Thermal performance of different construction materials used in New Zealand dwellings comparatively to international practice – A systematic literature review

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Abstract

New Zealand medium residential dwellings are mainly timber homes which form the predominant structural material with a historical market share of more than 90% in New Zealand residential dwellings. The attention to new construction materials such as cold-formed steel homes, concrete masonry, and recently precast concrete homes have been witnessed over the last decade. New Zealand homes are also categorized as very cold and thermally inefficient compared to other countries with similar climates. The national motive is to raise the thermal insulation standards and to regulate higher thermal resistance values for different house envelopes across the six (6) different climate regions in New Zealand. The regulation also comes to achieve energy-efficient homes in meeting the net-zero carbon motive in New Zealand. In this paper, a systematic literature review is conducted on thermal transmittance of different construction materials used in residential homes to seek their potentiality in fulfilling energy-efficient New Zealand homes. This paper reviews the timber, cold-formed steel, concrete, bricks and phase change materials and new systems. The review of over 190 journal papers has indicated that New Zealand has yet to catch new technologies, such as concrete for typical construction materials, phase change material for new materials, and thermally activated building systems for new systems. Composite materials are also found to be the focus of much current research which showed great thermal performance when used in insulation products. Most of the reviewed papers used thermal modelling instead of experimental testing, which strengthens confidence in using thermal computer modelling as an evaluation tool. The paper summarises conclusive points in the reviewed literature and their applicability to the New Zealand construction industry.

Keywords: Energy saving, Thermal performance, Thermal transmittance, Thermal insulation panels, Thermal insulation systems.

1. Introduction

When compared to other industry sectors like transportation or infrastructure, the construction industry's global energy contribution is expanding and increasing dramatically [1]. Internationally, more than 40% energy use is the estimation of European buildings from the overall energy consumption, at which 36% is from residential sector in 2010 [2-5]. Globally, the carbon emission percentage from the energy usage is 38% at where 35% come from construction industry [6, 7]. With the current net-zero carbon 2030 at the Paris agreement to reduce carbon emissions to 55% compared to 1990 levels [8], there has been an increasing concern to address the mission by incorporating latest approaches and techniques for energy efficient construction and homes [9-11]. NZ implemented new rules to aim for zero nett emissions by 2050, much like other nations, by raising thermal performance criteria for both new and existing homes towards energy efficient homes and less gas emissions, despite the fact that NZ's power is derived from renewable sources [12].

In New Zealand (NZ), the residential stock constitutes over than 1.8 million units [13]. The NZ commercial building forms of approximately 50,000 buildings in which 66% of those are used for offices or retail purposes [14]. This is relatively low compared to the residential portion, though it consumes over than 9% and 21% of NZ’s national energy and electricity usage, respectively [15]. Within New Zealand context, building industry contributes approximately 20% of the total energy and carbon emissions [16]. The majority of homes in NZ are constructed of timber, although new technologies like cold-formed steel and precast concrete structures are beginning to gain more attention [17]. Building sector in NZ realized the environmental impact of the construction activities and materials since 1990, yet further controlling measures to regulate how buildings are built, operated and what materials are selected are yet to be investigated [18].

NZ is composed of six climate zones with 74% warm regions towards the north and 26% cold regions towards the south through the year, however all regions undergo heating needs in winter [19]. It is also reported that more than 43% of NZ houses from different climate zones require heating during winter in a conducted survey in 2014 [20]. It is also reported that two thirds of NZ’s existing houses are poorly insulated [21, 22].

The adoption of thermal insulation in NZ houses was launched in April 1978 for all climate zones between the south and north, where the minimum insulation requirements were revisited in 2000 for floors [23], with recent amendment to raise the insulation levels towards energy efficient and warmer houses [19].

Houses in NZ are composed of several construction materials, for example surface envelopes such as floors, walls, fenestrations or roofs can be either timber, steel, concrete or bricks. Composite materials in the form of insulation boards are also becoming popular in the industry [24].

Basically, building envelope is defined as "building skin" which forms the building barrier between internal and external areas, which is used to define how much energy is dissipated from the internal areas to the external areas, where this can be walls, external doors, fenestrations, roof, subgrade interface, insulations and external shadings to form thermal bridges [7, 25]. On the other hand, thermal bridges are defined as "part of building envelope where otherwise uniform thermal resistance is changed by full or partial penetration of the thermal insulation by materials with lower thermal conductivities and/or when the interior and exterior areas of the envelope are different, such as what occurs at parapets and corners" [26, 27].

Improving thermal performance of building envelope is found to be a very efficient approach for reducing energy usage of approximately 31.4% for high rise apartments in Hong Kong through passive energy strategies such as adding insulating wall panels with extruded polystyrene (EPS) and reflective coated window glazing [28]. The building shape factor on the other hand plays a significant role in optimizing the overall thermal envelope, where the smaller the footprint area to the overall exterior wall surface area is recommended, and therefore ranks square shaped buildings to be optimal shape for new builds [25, 29].

The aim of this paper is to investigate the global insulating and thermal bridges prevention approaches for residential housings for the aim of transferring applicable knowledge to New Zealand industry. For this review, the aim is extended to cover several construction materials used in residential buildings, namely: timber, steel, concrete, and composite materials. Where applicable, all building elements will be elaborated on current literature works pertaining to each material.

Furthermore, this review contributes to the current re-evaluation of NZS4243:Part 1 [30] through providing a literature review on the international latest works pertaining to thermal bridging and insulation with different construction materials. The paper elaborates on the current practices in New Zealand in line with latest governmental energy legislations towards net-zero carbon emissions aims. The paper provides further recommendation for best practices adaptable to NZ and for future research works where needed. The reviewed literature has been limited to residential sector targeting the major building envelops that is walls, slabs on grade, and roofs within the residential industry.

2. Thermal bridging in timber structures

Globally, construction systems made of wood are mainly used for residential buildings [31-35]. Significant number of research studies have been conducted on the environmental, economic, structural, and internal comfort of such systems [36-42]. The current environmental scenario has created a pressing need for creating sustainable building systems and an extremely crucial parameter controlling such systems is the thermal efficiency of the building frame.

A recent research report published by Verney Ryan, Cuming [43] for building research association New Zealand (BRANZ) presented data gathered by surveying 47 dwelling units in NZ. It was seen that health and inefficiency issues related to housing were still prevalent and minimising the presence of thermal bridges increased manifold the thermal efficiency of timber structures. The overall R values of timber houses are heavily influenced by the percentage of framing as framing has a lower R value as compared to the wall panels made of bulk insulation materials. Another observation of the study was that provisions of insulation were not provided at the external wall junctions which also lowered the R-value of the building.

The study also showed that in recent times there has been a gradual increase in the proportion of timber framing in residential buildings resulting in an excessive increase in thermal bridging and leading to a non-conformance of NZBC clauses related to energy efficiency and internal moisture. The dwellings included in the study were spread across Auckland, Hamilton, Wellington and Christchurch and it was seen that average percentage of timber framing was 34 and that it varied from 24% to 57%. These values were significantly higher than the general values of 14-18% which are taken as by the concerned country's regulatory bodies for undertaking and doing compliance audits. It was suggested that this anomaly was due to the stringent regulations with respect to structure and weathertightness which lead to the increase in the framing percentage.

The same research group published a continuation [44] to the aforementioned study [43] in which it was seen that the overall R value of the building varies from 1.2-1.4 although the R value of the external wall is 2.8. The overall R value is much lower than the recommended values of 1.9/2.0 given in the NZ Building Code and this can be majorly attributed to the effects of thermal bridging. The study also identified five unique weak points marginally responsible for the lessening of the R value and on fixing of those points, the R value increased by 6% and 8% for buildings with insulation materials having R values of 2 and 2.8 respectively. The most substantial increase of 40% in R value was recorded when the edges of the floor slab were insulated.

In addition to the effects of thermal bridging a host of parameters ranging from movement of air at the sub floor as well as within the cavity in roof spaces affect the thermal efficiency of a structure [45]. The type of wood and its properties also substantially influences the thermal efficiency of a housing system and research studies in Australia have suggested that houses having partition boards made of mass timber recorded an average improvement of thermal performance varying between 1% to 6% and 4% to 9% for houses located in Launceston and suburban Melbourne climate respectively. Further calculations involving carbon sequestration showed that mass timber houses having high carbon sequestration values as compared to concrete block and clay brick systems. Among timber systems, the ones made of hardwood showed 1.5 times greater carbon sequestration values as compared to softwood [46]. Environmental moisture has a direct bearing on the thermal characteristics of wood and further insight can be gained into this phenomenon by studying the hysteresis of sorption of humidity and its interrelationship with temperature [47].

Viot, Sempey [41] concluded that common practices in estimating the overall thermal resistance of a building in European standards results in several errors due to rounding approaches by engineering offices. Alternative studies for timber studs were proposed to qualify the accurate thermal bridging occurred in timber walls, which depends on the timber studs inertia and overlapping zones.

Most of the proposed methods in estimating thermal bridges in different materials including wood account for the one-directional heat flow and neglects the dynamic effect of multidimensional heat flow. In most cases, this negligence can lead to doubling the heat flow in actual scenarios [48]. Santos, Sousa [49] proposed a new novel timber panel towards enhanced thermal insulation by adapting cross insulation arrangement with different thicknesses as demonstrated in **Figure 1**. Wood is found to incur variability in the thermal resistance due to the timber material thermal resistance.

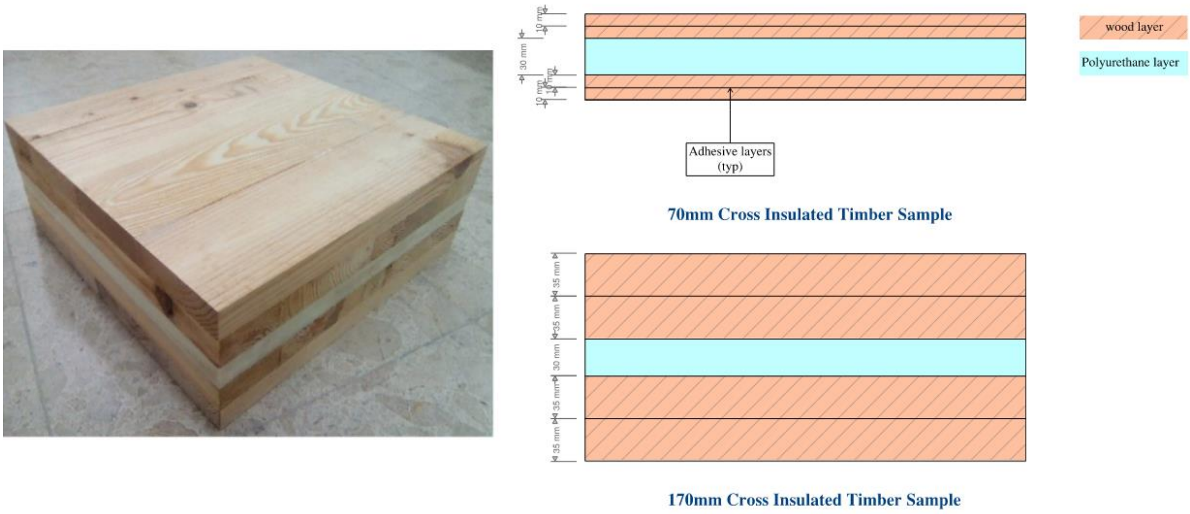

Figure 1: Proposed new Cross Insulated Timber panels by Santos, Sousa [49]

Timber energy performance has witnessed several research works that showed efficient thermal behavior compared to other materials. Khavari, Pei [50] investigated the thermal performance of solid cross glued laminated timber (CLT) panels arranged orthogonally for a multistory residential building application. The work included a simulation and sensitivity analysis of the CLT performance against light weight steel construction. CLT was found to provide an air-tight envelope that showed significant heating energy efficient compared to the equivalent light weight steel construction. Dodoo, Gustavsson [51] investigated the CLT carbon implications in multistory building systems, where low-energy designed houses showed significantly lower heating demand compared to conventionally designed. It is also recommended for efficient lower energy and carbon emission construction to adopt multistory timber building systems. Similarly, Wen, Qi [52] and Tam, Senaratne [53] concluded that timber results in thermally efficient envelopes compared to other materials such as concrete and steel in residential buildings.

The method of calculating thermal bridges in timber structures is also a debatable issue with several different methods being used having its own individual sets of limitations. Values of prefixed coefficients of transmissions do not mirror the actual physical conditions. EN ISO 13786 standard [54] states that the dynamic method of calculation should be used while assessing the performance of a building but concurrently it also states that EN ISO 10211 [8] should be used to do steady-state calculations in order to quantify thermal bridges. Martin, Erkoreka [55] acknowledges this contradictory tone. It is seen that though there are guidelines which prevent the loss due to thermal bridges, they end up not being applied. This may be due to the design methodology employed to create such guidelines. Ideally, the methodology should be able to accurately calculate the losses as well as its effect on comfort of the inhabitants. In the last two decades several studies have been carried out to mitigate through the challenges associated with the dynamic nature of thermal bridges.

In another study by Hassid [56], a simple model was presented in which it incorporated the effect of lateral heat transfer taking place due to the presence of thermal bridges in homogeneous as well as multilayer walls [57]. The model used the two-dimensional conduction equation and integrated it to form an expression which was then used to include the effect of thermal bridges in steady state calculation procedures. Another method to calculate the effect of thermal bridges on pre-engineered steel walls was proposed by Zalewski, Lassue [58]. They created a numerical model of the wall and validated the results with an experimental investigation involving a metallic stud fixed with an infrared camera, heat flow meters and thermocouples.

In a similar manner Tadeu, Simões [59] used devices to measure the temperature and heat flow to experimentally validate a numerical heat flow model based on an electrical analogy wherein the elements of the wall in question were associated with a resistance/capacity couple. The validation had a deviation of approximately 2%. Martin, Erkoreka [55] conducted a test in dynamic conditions where the work compared a concrete pillar and a hollow metallic pillar having a strong and a weak inertia respectively. Separate simulations were performed to identify the individual effects of different parameters. The study also showed that the level of inertia determined the effectiveness of a model.

Tadeu, Simões [59] employed a border element method to solve a frequency domain heat equation. The model was subsequently validated experimentally and was used to understand the effect of thermal bridging at three junctions under both static and dynamic conditions. From the results it was seen that the calculations done by using the steady state method yielded unconservative values. Déqué, Ollivier [60] modelled an apartment by representing its every junction by two-dimensional finite element models and further integrated them with the help of a dynamic simulation software which used default values given in the EN standard. Based upon all these studies it could be said that the value of coefficient of transmissions are underestimated by a majority of them and that the most accurate way of calculating them is to use a three dimensional model which can be reduced in order to be a made a part of different calculation tools to accurately simulate dynamic heat transfer [61].

Though this is not the norm in engineering offices where ideally the catalogues should divide thermal bridges into two categories e.g. high inertia and low inertia and all the provided values should be accompanied by three figures as is done in standards [41].

Sensitivity analysis has also been used to assess the energy efficiency of a timber structure. Maučec, Premrov [62] et al conducted a study through which it was observed that the weather conditions had a direct effect on the energy consumption of the building. It showed that the parameters that affect the heat energy requirement are the coefficients of solar heat gain, a set-point heating temperature and the overall U factor of a window. It is seen that these parameters have a comparatively increasing influence on the energy demand due to heating in cold, warm and moderate climates to the tune of 30%,88% and 39% respectively. The weightage of the parameters in determination of the demand for energy changes with the nature of the models with shading control playing a more dominant role in case of one box models while the thermal performance of two box models depends more on glazing-to-wall ratio [62].

Viot, Sempey [41] numerically investigated the impact of using the design code methods and rounding up practices by designer to have significant errors in estimating the thermal bridges in timber structures. The work covered both walls and junctions in conventional residential units. It is also concluded that each new structure should carefully evaluated on a standalone basis which could result in a tedious work which could be replaced by design catalogue with common boundary regimes to cover common details.

3. Cold Formed Steel structures

Cold-formed Steel (CFS) is an economical, energy-efficient, and flexible material with a number of many benefits [63-73]. The recyclability of cold formed steel structures gives it an advantage over other building materials. For instance, timber material tends to have shorten fibers when chopped for potential reuse, whereas steel maintains its molecular level qualities when recycled [63, 68, 74]. The CFS studs require thermal breaks to achieve similar thermal resistance to timber studs which have lower thermal conductivity [75].

Many researchers attempted possible areas of improvement in CFS towards optimising the thermal insulation performance [73, 76]. According to Roque and Santos' [75], the thermal resistance of steel structures can be overestimated by up to 50% when the influence of heat transmission is ignored. Thermal bridges caused by the CFS studs may significantly reduce the energy efficiency of the entire CFS structure, which can lead to higher energy demand within the interior environment to compensate the thermal energy lost through structure’s envelopes. Many researchers have worked hard to advance their understanding of the thermal performance analyses of steel framed structures as a result of the steel's ability to create thermal bridges [65, 68, 70, 74, 77-82], thermal resistance calculation methods [67, 69, 71, 83, 84], thermal performance improvement (or thermal bridge mitigation) [64, 66, 67, 73, 75, 85, 86].

Within a CFS building envelope, the option of using different CFS profile of different thicknesses as well as different insulation materials combined with makes it challenging to predict the thermal performance for all CFS details [69, 71, 85, 86]. According to De Angelis and Serra [86], compared to masonry constructions, evaluating the thermal performance of CFS buildings require more intricate and in-depth study. Santos et al. [77] assessed the impact of several factors on the thermal efficiency of CFS residential structures, including ventilation rate, thermal insulation level, overhang shading, window shading devices, and window glazing.

Similarly, Santos et al. [80] investigated the thickness of steel studs, stud spacing, the thickness and material of thermal break strips, the arrangement of the inner sheathing panels, and the thickness of the extruded polystyrene (EPS) external thermal insulation composite system (ETICS) were all evaluated for their effects on the thermal transmittance of CFS framed wallw. More recently, Santos and Poologanathan [65] evaluated the geometry variation of the steel studs on the overall CFS thermal insulation performance, where these parameters focused on CFS cross sectional geometries. The study investigated the effect of the stud section size impact on the wall’s overall R-value, then followed by introducing an indentation within the flange surface of varying sizes with a filling material as presented in **Figure 2**. The experimental work was reported to be later used for the 2D & 3D numerical works verification to investigate other parameters.

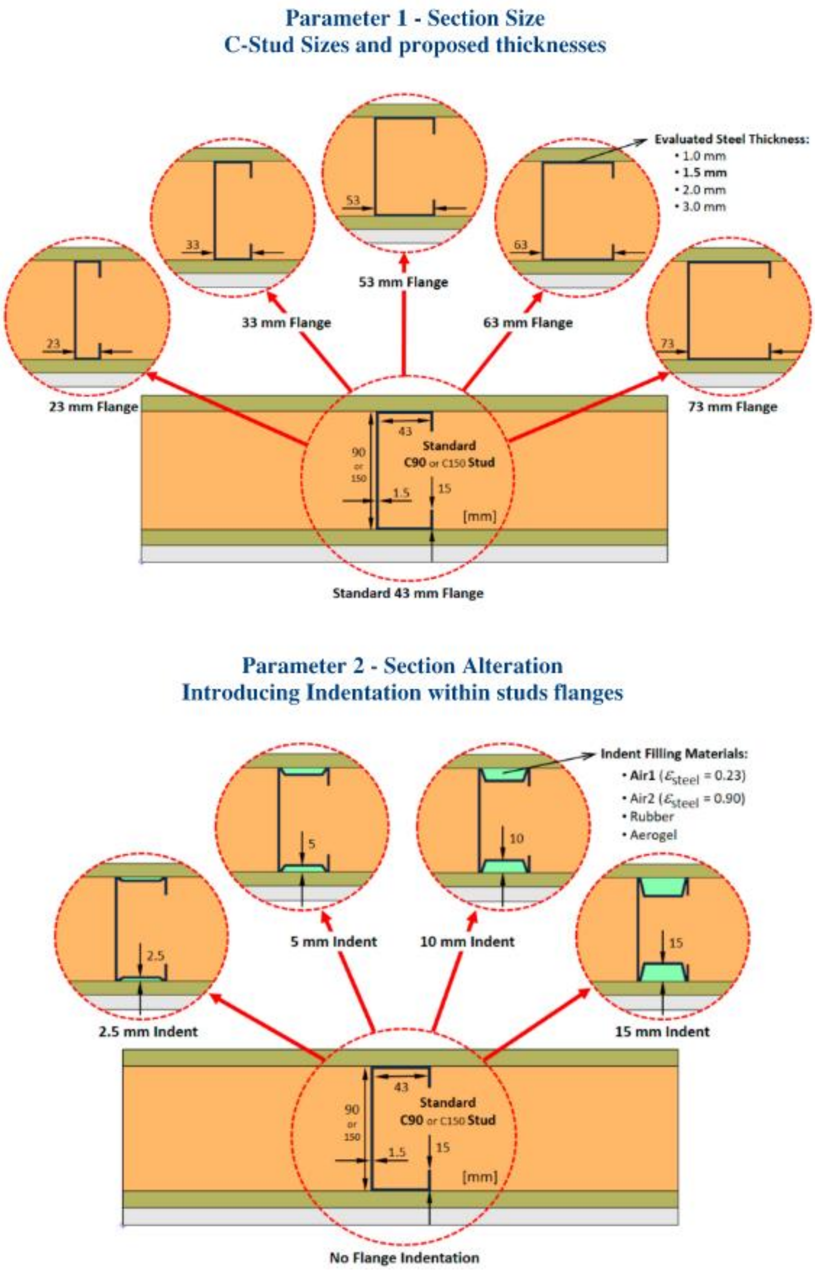

Figure 2: Impact of CFS studs on wall thermal performance parameters tested by Santos and Poologanathan [65]

Santos, Gonçalves [71] compared CFS walls R-values obtained from numerical models against theoretical approaches defined in ASHARAE and ISO 6946 to conclude good agreement between the results [71]. In another study, Santos, Lemes [69] estimated the R-values of 80 different CFS framed wall models using six different analytical methods. The walls were then numerically modelled in THERM [69]. The obtained results from the numerical models agreed well with all of the nominated analytical methods, however higher accuracy was found with the Modified Zone Method [69].

External insulation has been proven to be an efficient method to reduce the thermal bridges within steel wall panels [67, 68, 74, 87]. The choice of appliable insulation has been the aim for several works. Expanded polystyrene is found quite efficient in both mineral and steel walls [85]. Other mitigation methods can be thermal breaks [80], studs with slotted webs [73, 85]. Additionally, lowering the heat transfer through radiation is an efficient technique to enhance the thermal performance of walls with air cavity. This is accomplished by applying foil or reflective low-emissivity paint to the air spaces between the building materials [66] [64].

Unlike traditional construction, CFS buildings' thermal performance is highly dependent on the applied thermal insulation [70]. Roque and Santos [75] indicated that the trade-off between embodied and operational energy must be taken into account if additional insulating material is employed to lower operational energy requirements. The use of thermal break on the external side of the CFS studs also allows the system to meet the appropriate energy performance standards [87]. Santos et al. [80] numerically estimated a reduction of 24% in the wall’s overall thermal resistance rating when thermal breaks are introduced. An alternative solution to mitigate thermal bridges is using slotted studs, in which staggered longitudinal penetrations are placed into the web of the stud during production. The slots allow the thermal energy to travel a longer journey, reducing the heat or cold that reaches the flange on the stud's opposite side [87]. Because of the additional manufacturing costs and lowered structural load capacity caused due to the presence of web penetrations, this solution has gained limited application [87].Error! Reference source not found. below summarizes literature works on steel thermal bridges inclusive of adopted numerical software where applicable.

Table 1: Literature novel works on efficient thermal insulation for steel

Reference	**Year**	**Scope**	**Research work**	**Key Observation**	**Software used**
[68]	2021	Thermal performance of a number of cold formed steel (CFS) assemblies.	Numerical	- The assembly's overall and component-level heat flow increased when CFS member thickness was raised. - The influence of the stud depth was minimal. - Heat transfer performance was enhanced by adding continuous external insulation outside the stud cavity.	HEAT3
[65]	2021	Investigate effect of CFS studs geometry on thermal performance within CFS walls.	Exper. & Numerical	When the flange length and steel stud thickness are increased, the R-value drops, and a moderate flange indentation size can enhance R-value.	THERM
[67]	2021	Numerical Investigation thermal resistance of available market CFS walls configurations against manual	Numerical	For wall assemblies with lower R-values, the NZS 4214 technique demonstrated acceptable applicability. The use of outer frame insulation and high resistance claddings was the most	THERM

Reference	Year	Scope	Research work	Key Observation	Software used
		thermal resistance estimation methods.		effective technique to reduce the impacts of thermal bridging.	
[66]	2021	In this study, different air gap thicknesses, ranging from 0 mm to 50 mm, with a step increment of 10 mm, are experimentally evaluated to determine how well a thermal reflective insulation system, consisting of an aluminum foil placed inside an air cavity between a double pane lightweight steel framed (LSF) partition, performs.	Exper. & Numerical	For wall assemblies with lower R-values, the NZS 4214 technique showed acceptable applicability. Applying outside frame insulation and high resistance claddings was the best solution to reduce the impacts of thermal bridging.	THERM
[64]	2021	Examining the use of aerogel thermal break (TB) strips and Aluminum reflective (AR) foils to double-pane lightweight steel-framed (LSF) walls to enhance their thermal performance.	Exper. & Numerical	- Aerogel thermal break strips were found to be less effective than metal reflective strips. - When compared to two aerogel TB strips, only one AR foil (either the inner or outer) increases thermal resistance by up to 19%.	THERM
[79]	2020	Analyze the thermal performance and energy efficiency of a Trombe wall in a compartment with a light steel frame.	Exper. & Numerical	If the Trombe wall device was properly constructed and operated to limit nighttime heat losses, it might greatly enhance the thermal behavior of a CFS frame compartment and lower heating energy usage.	THERM
[70]	2020	Investigate market existing envelope solutions for thin walled CFS systems. The study includes sustainable recycled materials. .	Numerical	The study revealed that for the same level of thermal insulation, the environmental impact of the recycled-PET thermal wadding-based system was smaller than that of the Mineral Wool (MW)-based system.	Graphisoft Archicad 21
[69]	2020	Estimating thermal resistance for several CFS walls with different analytical methods. Results are compared against numerical output.	Analytical & Numerical	The findings showed that the Modified Zone Method had the best accuracy performance. In contrast, the Gorgolewski Method 2 yielded the lowest results.	THERM
[80]	2019	Evaluating the impact of stud thickness, spacing, material, thermal break strips, inner sheathing panels, EPS thickness and external insulation on the thermal transmittance of CFS walls.	Numerical	The findings showed that the Modified Zone Method had the best accuracy performance. In contrast, the Gorgolewski Method 2 yielded the lowest results.	THERM
[81]	2019	Investigate the thermal influence for CFS façade systems.	Numerical	The variation in the U-value can be as much as 82 percent by altering the kind and placement of the frame in the wall. The efficacy of CFS framed walls' sound insulation is also impacted by the steel frame.	THERM
[71]	2019	Three different cold-formed steel (CFS) framed walls' thermal transmittance was evaluated using the Heat Flow Meter approach, 2D and 3D FE simulations, and the ASHRAE zone method.	Analytical & Numerical	For CFS framed walls with just vertical studs, a good agreement was discovered between the 2D FEM findings and analytical ISO 6946 techniques.	ANSYS, THERM
[83]	2018	For the measurement of in-situ thermal transmittance of CFS framed	Exper. & Numerical	The findings demonstrated that the Representative Points Method was consistently correct, while the	COMSOL

Reference	Year	Scope	Research work	Key Observation	Software used
		walls, new methodologies are suggested.		Weighted Area Method's inaccuracy did not exceed 2% for cold frame walls and 5% for hybrid frame walls.	
[75]	2017	Emulation of the introduced thermal bridges by CFS studs in a wall's overall thermal performance.	Numerical	There was a considerable variation in the outcomes. The effectiveness of the steel frame might be increased by applying thermal insulation outside of it.	THERM
[73]	2016	Proposing slotted CFS studs towards improving the thermal insulation of CFS walls.	Numerical	The quantity of heat flow passing the element and the perforated geometry of steel profiles were shown to be correlated. The energy efficiency of the wall increased as the distance between perforations, both vertically and horizontally, dropped, perforations were placed along the heart profile, profile thickness fell, rows of holes and their length increased, and perforations increased in size.	Abaqus, UNFORM
[85]	2015	Investigating mitigation strategies for introduced thermal bridges in CFS walls	Exper. & Numerical	Implementing the mitigation techniques can lower the U-value by 8.3 percent when compared to the reference example. A further reduction of 68 percent was achieved by the optimization of the insulation layers, including the use of novel insulation materials and the combination of mitigation strategies.	ANSYS
[86]	2014	Investigating thermal resistance of CFS framed walls	Numerical	Utilizing the technical data available from manufacturers, the variety of materials and the high frequency of metal studs might lead to an overestimation of heat resistance.	THERM
[74]	2013	Assess the impact of thermal bridging across enclosed envelope CFS building.	Numerical	The simulation's thermal peak load rose by around 10% above the reference scenario when metal frames were taken into account.	EnergyPlus
[78]	2013	Thermal efficiency of a lightweight modular steel. The impact of flanking losses induced during thermal transmittance is investigated in the paper.	Exper. & Numerical	For the exterior and interior surfaces, the predicted heat flow varied by nearly 222% and 50%, respectively. In the reference situation, where losses through the flank were assumed to be nil, thermal conductivity was equal to 0.30 W/m (m2 K).	ANSYS
[77]	2011	Explore at how different building envelope factors, such as air velocity, insulating level, ridges, lighting, and window glazing, affect the thermal resistance of CFS walls.	Exper. & Numerical	- Ventilation rate and windows glazing are the most influential parameters in a CFS wall thermal insulation during cooling season. - For various climate situations, an ideal building envelope and operating solution were suggested.	EnergyPlus
[84]	2007	Proposing a simplified method of estimating heat flow transmittance in CFS framed structures	Exper. & Analytical	A novel approach is suggested, and it was discovered that for a variety of 52 evaluated constructs, the mean prediction error using the suggested approach is less than 3%, with a maximum error of 8%.	-

4. Thermal performance of Concrete

As a most widely used material in the construction industry, concrete excels in thermal insulation compared to other materials. The inherited thermal resistance of concrete favours it as a cladding product which is experiencing a resurgence in industry applications [88]. The precast aspect of concrete increases its competency towards sustainable solutions in which considerable innovation has occurred in the last two decades [89]. In several systems, it is sandwiched with other composite materials to form different cladding types. The whole composite system can constitute weatherboard, thermal insulative layer and the structural concrete wall with interconnecting shear keys for the assembly with adjacent wall panels. The use of precast concrete systems is found in low rise industrial buildings and extending in medium to high rise buildings [90].

It has a successful track of envelope in different types of structures such as schools, warehouses and offices buildings with good encasing strength and insulation performance that comes of more than four decades of advancement [91]. The concrete walls/precast cladding benefits outnumber common cladding materials due to aspects such as the durable resistance to fire stresses and durable performance under weathered conditions [92]. In hot climate countries, concrete is a preferred material due to the low thermal conductivity it carries and serving as an insulation material towards lower electricity dependence for balancing the inner atmosphere with cooling means. Concrete bricks are a form of construction in high ambient air temperature zones that are mainly for building walls [93].

Al-Awadi and Alajmi [94] used numerical modelling to investigate thermal bridge behaviour in residential building envelopes during hot climates, validating initial models against work by Quinten and Feldheim [95]. The wall envelope, in conjunction with other envelopes, such as interior floors and corners, showed autoclaved aerated concrete (AAC) to have lower thermal performance compared to exterior insulation and finish system (EIFS), confirming the efficiency of EIFS in enhancing the building envelope with less heat exchange with the outdoor.

The thermal performance of a concrete wall is influenced by the type of material used in concrete, including the dynamic thermal properties of the external outdoor environment. Mohammad and Shea [96] investigated the building envelope dynamic properties of heat capacity, density and thermal conductivity for six different concrete walls arrangement of hollow clay blocks (two types) HCBC, light expanded clay aggregate LECA (two types) and autoclaved aerated concrete (two types) of varying thicknesses between 200mm to 300mm. The type of walls varied in performance between winter and summer time, where LECA (330mm thk.) performed reliably in both summer and winter time.

In a response to sustainable call for the concrete industry, Alayed, O'Hegarty [97] researched the impact of solar flux on exterior building envelope for concrete structures under hot climates. The project created a physical monitoring system for the existing building for a set period of time, and the results were validated numerical through FEA models. The study was extended to explore new wall options for efficient thermal insulation. The work recommended an exterior layer of insulation with varying thickness between 65 and 80mm for a thermally efficient concrete envelope in hot climates. The behaviour of RC walls with inter-floor slabs in multi-story buildings was investigated by Basiricò, Cottone [98] to demonstrate the great heat losses based on the number of the floors. The study provided regression models to predict the thermal loses between RC walls, slabs, and junctions. It is also noted that the type of slab (i.e. hollow) influences the heat loss in junctions. **Figure 3** illustrates the proposed PCPCPs model which achieved efficient thermal insulation.

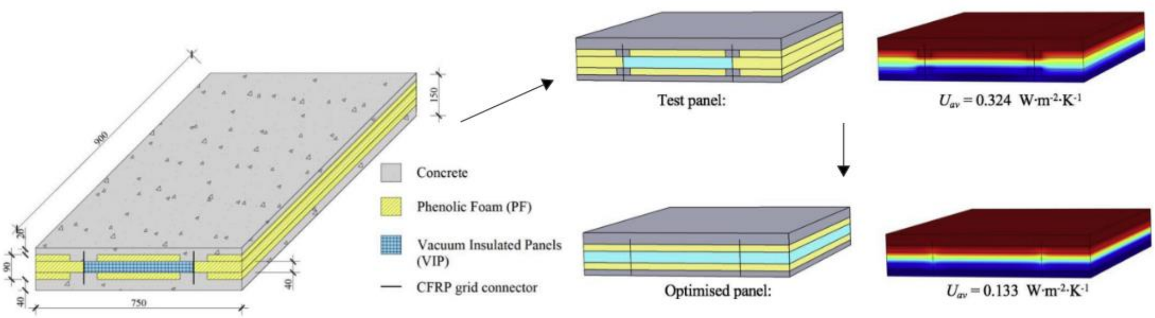

Figure 3: Experimental PCSPS model validated and optimized by O'Hegarty, Reilly [92]

2.1 Precast Sandwich Panels (PCSPs)

As a comparable material, the use of concrete in light weight systems and masonry walls is receiving wider attention from research and industry work. Precast sandwich panel comes from the intention of providing light weight system with high thermal mass material type such as concrete. The base components of a precast sandwich panels (PCSPs) are two wythes separated by intermediate higher insulating material. The panels are frequently used on the exterior buildings and can serve as bearing or shear walls. They can be precast hollow core or ribbed section. The first configuration had two concrete wythes connected by ribs to ensure the inplace shear stresses, where was followed by replacing the ribs with solid square concrete zones in order to break the direct thermal bridge introduced by ribs [91].

The common arrangement is also maintained at two wythes of the same thickness, and the flexibility of the exterior wall can be used for architectural aesthetic design, such as having strips for a desired appearance. In addition, the insulation located within the two wythes provides superior moisture protection compared with other wall systems [90]. The thermal performance of PCSPs is mainly achieved by the insulation material provided in between the wythes, while the strength is achieved by the concrete wythes. Several experimental works such as those shown in [99-101], have been dedicated to this gas in research, while many have used numerical means, such as [99-104].

The thermal performance of sandwich wall panels can be reduced by up to 40% through the concrete block shear connectors between the front and back wythes that penetrate the separating insulation [105]. Through hot box testing, Van Geem and Shirley [106] investigated the thermal bridging of stainless-steel anchors connecting a double-layer concrete sandwich wall. The steel anchors between the wythes reduced the thermal conductivity by 7%. The replacement of steel anchors with fiberglass composite times did not show measurable thermal resistance improvement.

O'Hegart and Reilly [92] experimentally investigated the impact of thin concrete wythes in precast sandwich panels (PCSPs) as a response to the increased popularity of these systems in thermal insulation. The hot-plate experiment was then validated numerically to show high level of agreement. Starting from a common 300mm thick wall encompassing all the composite elements, the study reduced thickness by 50% to 150mm with (20-40mm) concrete wythes. **Figure 3** shows the experimentally tested PCPS model as well as the optimized specimen.

The methodology was extended to localized improvement such as local thickening areas of connectors. The results of the study showed a significant improvement in the overall wall thermal transmittance U ($W.m^2k^{-1}$) when combining effects of continuous vacuum insulation, local thickening at connectors, and reducing the connector area. It is concluded that 150mm of thin concrete wythes is 16% more insulative than a standard 315mm thick with 100mm insulation foam. **Table 2** provides a review on literature for different examined PCSPs and their associated findings.

Table 2: PCSPs previous research works

Reference	Year	Scope	Material	Key Observation
[96]	2013	Understanding modern wall thermal behavior between different wall materials in new builds	AAC Wall, Light Expanded Clay Aggregate (LECA) Autoclaved Aerated Concrete (AAC)	Steady state thermal analysis is not sufficient to provide full understanding of modern wall thermal performance. It is crucial to include local environment data for understanding the building envelope thermal performance.
[99]	2014	Investigating thermal response of PCSPs with different arrangement of steel connectors between the front and back wythes	Concrete Steel	Different steel connectors of W, Z ad J shapes are experimentally tested for their influence on the overall thermal performance of PCSPs. The heat flux of J-shape the connection with higher heat flux followed by W and Z shape.
[100]	2017	Exploring the of fiberglass connector influence in PCSPs overall thermal performance through numerical and experimental work.	Glass fiber reinforced polymer (GFRP) Precast Concrete	Ten (10) test sample were prepared with varying number, size and dimensions of connectors. The overall wall thermal resistance R-Value for a number of walls was measured showing an improvement of up to 70% by using larger FGRP connectors.
[101]	2006	Thermal Performance of PCSPs formed up of three concrete wythes sandwiched together with expanded polystyrene in between.	Light weight concrete	A new detail is proposed by using three concrete wythes. The R-value is improved significantly due to the inclusion of more insulation in the three wythes arrangement.
[103]	2014	Incorporating vacuum insulated panels within precast concrete elements to develop thin composite concrete elements with higher thermal insulation.	Vacuum insulated panels (VIPs) Concrete	New composite insulation panels format are proposed with varying thicknesses between 15, 30 and 60cm increments.
[107]	2022	Presenting a new precast concrete walls details towards efficient thermal insulation performance	Concrete Steel EPS	A multilayered wall made u of EPS separated by transversal steel truss. The concrete fine aggregate is replaced with fine EPS granular. The use of S-shape truss reduced the thermal bridge path.

2.2 Concrete flooring

The contribution of literature works on heat loss on reinforced concrete slabs on grade has been a continuous concern for the overall heat conservatism within the building envelope. In a survey conducted in United States [108], it was suggested that heat transfer to the ground accounts for $5 -$15 billion year. It was also documented in US that basement structure in contact with earth accounts for 67% of the heat loss of the total envelope load when the above ground part of the building is insulated. Furthermore, heat loss to the ground accounts for up to half of total heat loss in cold climate zones [109, 110]. The provision provided in ISO 13370 [111] aims to predict the heat loss via ground through penetration is detailed in the code. The recommended calculation methods in ISO 13370 [111] are based on simplified assumptions on the building's geometrical boundaries. The mathematical approach is also restrained to a constant heat flow assumption with constant thermal properties that does not represent the complex non-stationary scenarios found in real cases.

Roots and Hagentoft [112] addressed the lack of addressing the heat loss calculation moel ru to the floor heat system in ISO 13370 [111]. The findings show the influence of the heat pipes on the overall heat loss, where it is controlled by the design of foundation and has minimum influence from junctions. Rees and Adjali [113] provided an provided an overview work for heat transfer between ground to structure in contact with earth envelope, where it was demonstrated the ground thermal conductivity is dependent on the ground water content.

Dos Santos and Mendes [114] addressed the influence of three-dimensional asymmetrical influence in the soil moisture effect on the ground heat transfer. It was also shown that the mesh refinement on the top surface (in contact with air) has an influence on the accuracy of the results irrespective of the time step. Borelli and Cavalletti [115] adopted FEA models, validated against EN ISO 10211:2017 [116], to evaluate ground thermal bridges in a steady state thermal model against different foundation topologies and parameters. The study proposed a regression model for different foundation to ground interaction models and node configurations. The FEA results showcased an influence from the choice of materials, thicknesses, and geometry effects to stress out the importance of ground foundation detailing.

Larwa [117] addressed the temperature distribution in ground through mathematical model that was influenced by solar flux and surrounding environment. The study showed the conductive flux is controlled mainly by the daily solar radiation flux and has little influence from the remaining parameters. Pokorska-Silva, Kadela [118] demonstrated numerically and through experimental works the efficiency or PCPS when combined with different materials.

2.3 Concrete novel insulation contributions:

The novel contribution of new systems towards efficient concrete insulative materials has been attempted by several authors. Del Coz Díaz, García Nieto [119] [120] examined numerically and experimentally a new proposed wall made up of concrete hollowed slotted bricks, ARLIBLOCK. The work targeted the impact of tying mortar between bricks on the overall thermal bridging performance. The first parameters considered were relevant to the geometry possible modification, such as different slit arrangements. It also included different insulation layers arrangements. The experimental works were scoped to a wall element of 3.80m×3.65m for a duration of 38 days. The experimental works confirmed a good agreement between the overall performance of the numerical and experimental works with a margin of error of up to 2.6%. The descriptive shapes of the proposed new slotted bricks (ARLIBLOCKS) for all the specimens investigated in the study are shown in **Figure 4**. The same work was extended to investigate numerically the impact of major parameters influencing the thermal conductivity of wall due to the efficiency of FEA in attending to cumbersome modelling.

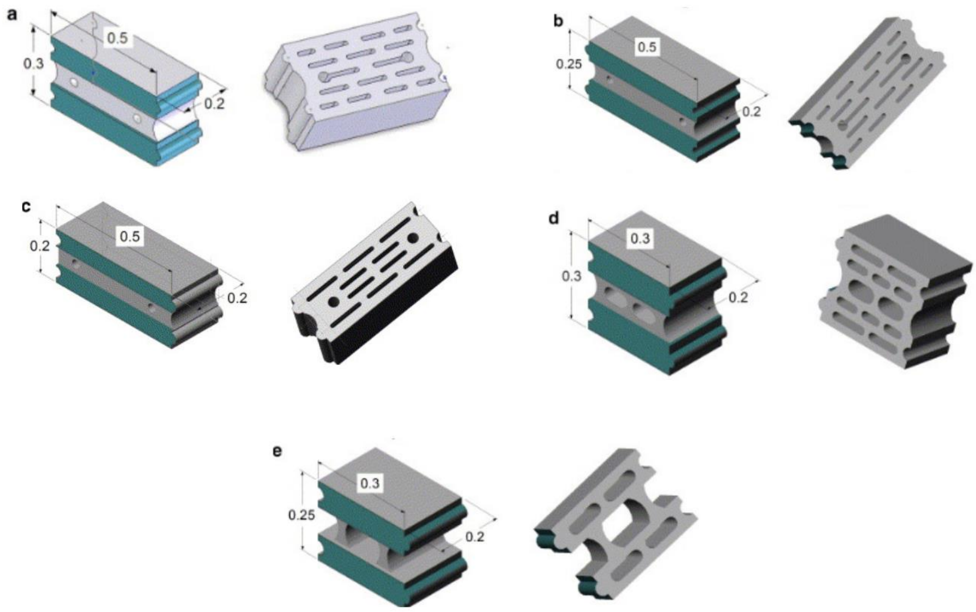

Figure 4 Slotted bricks patterns introduced by Del Coz Díaz, García Nieto [119]

The impact of clay concrete in the same brick described above was attempted in another research work by the same authors [121], which comes as a response to knowing the best recess geometry boundary between the bricks forming the wall as well as best mortar materials. Upon defining the six (6) types of proposed brick geometries, the same authors del Coz Diaz, Garcia-Nieto [122] extended the work for further optimization through response surface FEA methodology after giving the product a seven years of industry experience. The work came as a response to the emerging concern of sustainable calls towards efficient systems with lower environmental impacts. The proposed floor systems are shown in **Figure 5**.

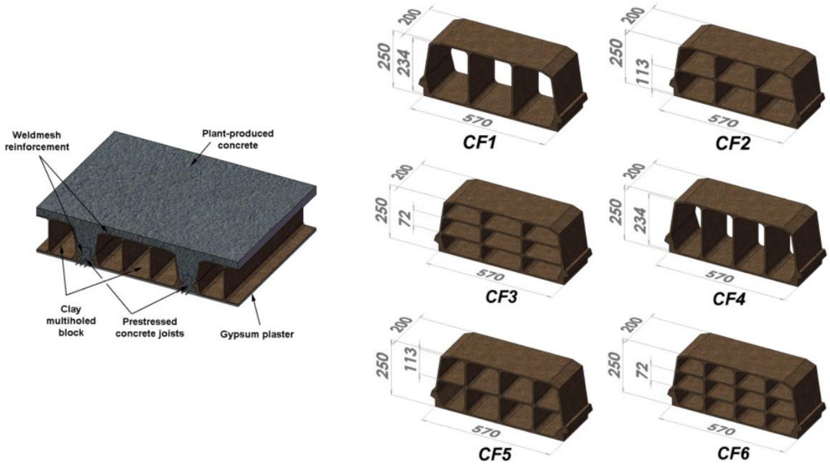

Figure 5: Proposed new composite floor system with efficient thermal insulation behavior del Coz Díaz, García Nieto [121]

It is found that finite element models (FEM) can predicate the mechanism for heat flow. Furthermore, it is concluded that the use of highly insulative mortar can enhance the wall's overall insulation significantly. Geometry-wise, the increase in recesses length enhances the thermal behavior when formed with a width between 28 and 30mm. The thermal bridge behaviour varied according to the adopted slit pattern as shown in **Figure 6**. The work provided a direction for housing designers in accordance with the provided brick types demonstrated in the study.

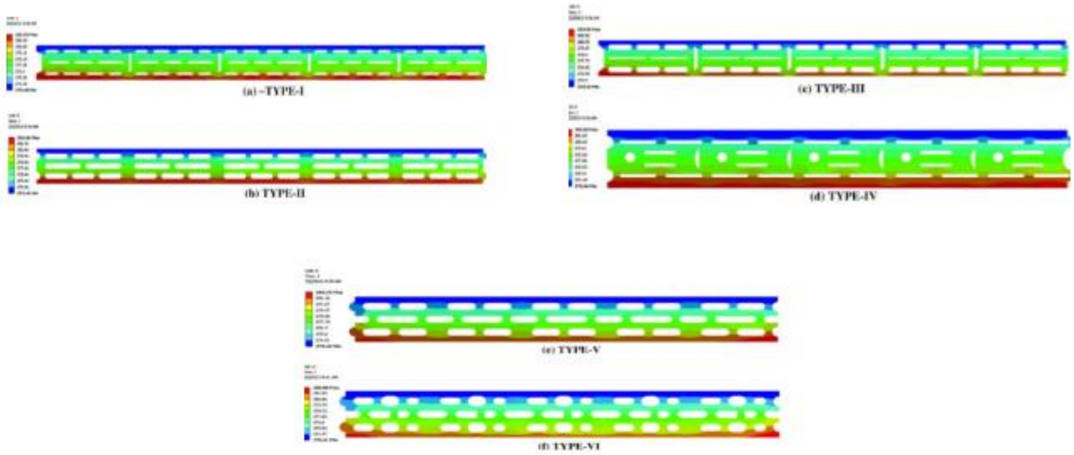

Figure 6: Thermal bridge behavior in proposed thermal slitted bricks introduced by del Coz Diaz, et al. [119-122]

In a recent study, Gencel and del Coz Díaz [123] investigated the potential of composite wall made of concrete wythes and expanded polystyrene (EPS) layer with predefined cavities as shown in **Figure 7**. The work is on a numerical basis, adopting different parameters of the new wall composite shape. The thermal modeling study of the composite blocks formed by cavity and separated by EPS, converged on a certain geometry shape incorporating corner junctions. The models accounted for the material type and size of aggregates involved in the formation of concrete mix. Critical wall parameters were targeted to achieve an efficient construction cost, such as wall thickness, EPS thickness, size and shape of cavities, and material thermal conductivities. The thickness of the wall significantly controls the thermal transmittance with inverse relationship. Internally, the concrete wythes thicknesses also dominates the amount of heat flux between the interior and exterior surface. The thicker the concrete wythe, the larger the heat flux. The cavity thicknesses on the other had has an impact on the wall overall heat flux more due to length than thickness.

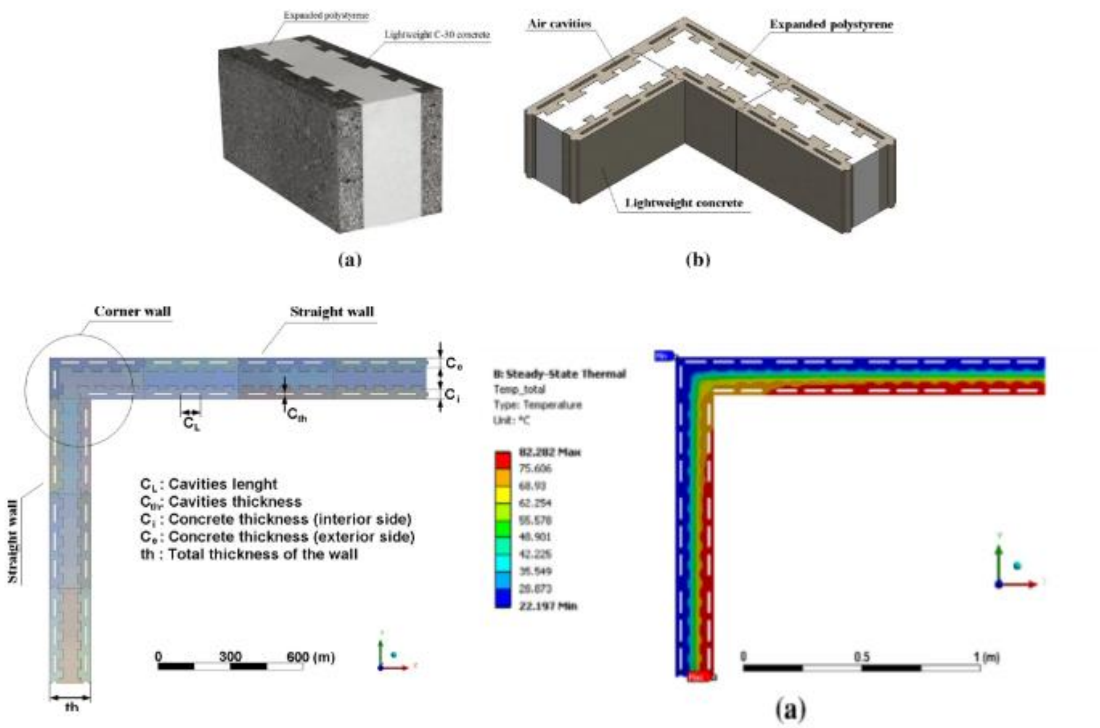

Figure 7: Composite wall proposed by Gencel, del Coz Díaz [123] towards efficient thermal

Bricks dominates a large sector of wall assemblies in the construction industry [124]. Improvements to its thermal insulation properties is of a significant impact on heat loss controls through wall heat bridging issues in houses [125]. The introduction of slitted bricks is a key approach in achieving that goal, where mechanism on that is of a common method since early ages [126]. The addition of waste material into brick making process is receiving a research attention in an aim to enhance the thermal behavior. Sutcu, del Coz Díaz [127] examined creating a microporous bricks by adding clay raw material, where paper waste was used to produce the pores through numerical response surface methodology (RSM). The study examined three different walls made of different bricks with different cavities arrangements. The inclusion of paper waste in the fired bricks showed an improvement in the thermal insulation up to 40% among the different slitted patterns shown in compared to conventional brick. The proposed composite paper shapes from the study is illustrated in **Figure 8** below.

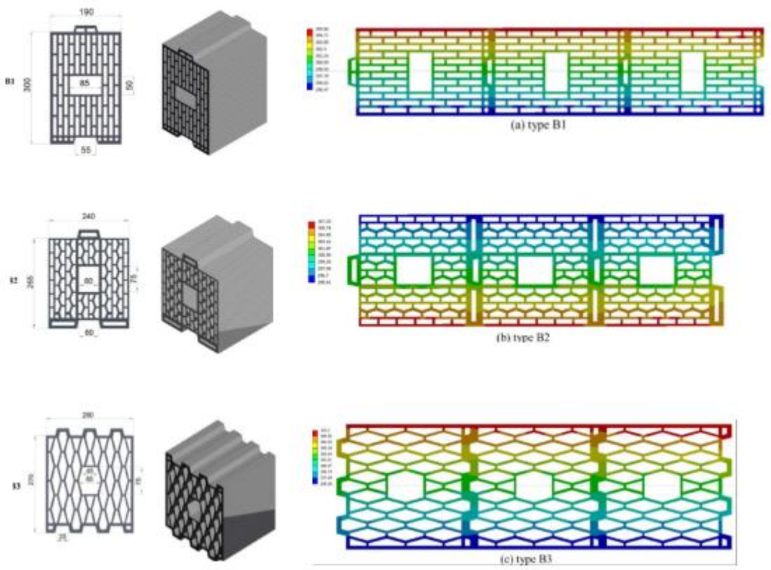

Figure 8: Wall types made of composite paper materials with thermal contour performance proposed by Sutcu, del Coz Díaz [127]

From the approach defined in earlier works [119, 120], FEA is concluded to constitute a good approach for predicating further optimization impacts when it comes to heat transfer in walls compromised of cumber shapes. del Coz Díaz, García Nieto [121] investigated concrete blocks with a total of 18 models with all the six shapes of varying geometry details made up different materials such as plain, light weight concrete and clay to provide a comparative finding when composed with different recess dimesons. The composition of the new floor system is of concrete with rebar reinforced steel mesh atop hollowed blocks covered with gypsum plaster. The investigation work scoped the FEA models to different recess arrangements. It is concluded that CF1 and CF4 samples showed poor performance compared to other configurations due to the direct thermal path found between the top and lower fibre. Geometry-wise, CF5 and CF6 showed 0.05% improvement from the CF1, however they are associated with difficult construction details. CF3 performed the best among others with very close performance to CF6, and hence is found a suitable constructable sample. It is also important to highlight that all changing the material from normal concrete to light concrete showed more than 0.27% improvement in the thermal performance for CF3.

Yesilata and Isker [128] incorporated the addition of polymeric materials into the concrete mix to enhance the thermal performance of concrete. The concrete mix was defined as two types of samples. The first is the addition of scrap rubber pieces and the other is the addition of waste polyethylene terephthalate (PET) bottle pieces. Both mixes were compared a the conventional concrete mix that formed the third category. It is concluded that thermal conductivity of concrete is enhanced, notably in both samples (with scrap robber, and with PET). Depending on the percentage of addition, the thermal insulation improved up to 18.52%.

Yoon and Lim [129] inspected the addition of nano aerogel materials within foam concrete with the aim of developing the thermal and moisture performance. The addition of nano aerogel materials comes as a replacement of EPS insulation layers due to the associated environmental impacts that it has. The findings of the study proved that the addition of nano aerogels improved the thermal performance between 13% for Methyltrimethoxysilane (MTMS) and 18% when MTMS is combined with tetraethyl orthosilicate (TEOS). However, the concrete compressive strength is slightly compromised by 3% for the MTMS+TEOS sample. Table 3 below summarizes the reviewed literature works with concrete novel works towards efficient thermal insulative building envelopes.

Table 3: Literature novel works on efficient thermal insulation for concrete

Reference	Year	Scope	Material	Key Observation	Limitations
[119]	2007	Investigating thermal insulation of hollow concrete brick walls through numerical methods	Light weight concrete.	The impact of mortar has an influence on the thermal insulation performance of wall insulation, as it acts a direct thermal bridge. Including perforations within a brick in a manner to increase the thermal path.	The work is based on a mathematical model through numerical FEA only. Five bricks shapes are investigated with thickness variation as the key parameter.
[120]	2006	Numerical and experimental work for new hollow bricks thermal insulation performance	Light weight concrete ARLIBLOCK	Numerical results constitutes a reliable agreement with heat transfer experimental work with a margin of 2.6%. The increase of mortar conductivity compromises the overall wall thermal resistance.	Certain number of brick shapes and dimensions were covered.
[122]	2014	Parametric optimization through response surface numerical methodology	Light weight concrete	New thermal conductivity predicting models are developed for the covered bricks shapes. Recess width between	The work is limited to numerical optimization.

Reference	Year	Scope	Material	Key Observation	Limitations
		for hollow concrete bricks		vertical bricks has a potential thermal optimization when used with less thermal conductive material.	Caped to number of bricks arrangement corresponding to those developed through [119, 120].
[121]	2010	Understanding the floor thermal bridge behavior due to brick shape and recess variation. The scope is also extended to different materials effect on brick's thermal performance.	Clay Concrete Lightweight Concrete	The overall wall thermal resistance is dependent on both the brick material and number of brick intermediate bulkheads. The reduction of recesses number between bricks reduces the amount of heat flux through the wall. The higher the material thermal mass of the floor, the a better thermal insulation which can be used to reduce floor's size.	The work is limited to numerical modelling. The work is limited to concrete material with clay blocks.
[130]	2021	An experimental work for phase change materials (PCM) mixed with concrete samples to investigate the thermal conductivity influence of the new mixed material.	Phase change materials. Normal and Lightweight Concrete	The effect of PCM is witnessed to perform better in normal weight concrete than lightweight concrete. During cooling, PCM layer can enhance a temperature reduction by 5.4°C.	The work is based on experimental observation. The work targeted cooling behavior of walls in hot areas.
[131]	2022	Investigating thermal insulation of aerogel foam concrete as a wall material.	Aerogel-enhanced foam concrete (AEFC)	Aerogel is foreseen as a new emerging novel materials towards efficient thermal insulation purposes. The AEFC samples test results showed a significant improvement in the heating and cooling thermal flux.	The work is based on experimental observation.
[127]	2014	Inclusion of paper waster as a new material within concrete hollow bricks constituents materials.	Paper waste Clay bricks	The inclusion of porous material within bricks can enhance the thermal resistance significantly. The new microporous brick has an improved conductivity by 70% compared to a normal clay brick.	The work is based on numerical modelling.
[123]	2021	New lightweight concrete wall blocks combined with EPS to form a new composite blocks towards sustainable and thermally efficient construction	LWC EPS	A new arrangement of wall with slotted pattern and combined embedded with EPS insulation. The new wall detail showed a 50% of thermal improvement without cost impact.	The work is based on numerical modelling.

2.4 Concrete application in NZ

The historical line of NZ industrial expansion coincides to the colonial settlement and development which occurred following the Second World War and up to the 1990s, where a substantial infrastructure concrete development was witnessed. Other materials expanded in NZ in the mid of 1990s, increasing diversity of construction technology and the economy. Due to the global influences such as transportation hardships, local materials in NZ emerged within the late 1990s. The sustainable measures in NZ are tightening up towards the zero-net carbon motive announced by MBIE for the 2050 vision [16].

Since the early 1900s, concrete has been the primary choice for ground floor constution in NZ. Due to the availability of ready mix-concrete, concrete floors were preferred to be used for floors, thereby eliminating the need for high foundation wall. It achieved a design win by being a vermin-proof and, to some degree, are considered warmers, quitter and less draughty than suspended timber floors. The adoption of concrete floors in residential housings extends for further benefits such as a structural bridge over minor weak soil zones with the flexural capacity and shear stiffness it contains, as well as the good resistance from the uplift forces resulted from lateral actions due to its mass [132].

Besides the main function of the ground slab in providing a working surface for imposed activities, it contributes to the moisture resistance of the whole flooring system through capillary break from soil moisture provided by a well compacted hardfill. In NZ, this is enhanced with the provision of a damp-proof membrane (DPM) that is laid below the slab for additional insulation and protection. Another layer of expanded polystyrene protection is added below the slab and above the landfill soil to enhance the thermal insulation for the entire flooring in contact with the soil [132].

Furthermore, NZ incorporates precast concrete as a cladding system in medium to large commercial buildings. The precast method favoured concrete for controlled conditions when working with builders for better quality finish. It also allowed concurrent operations in which the tile band was prepared in the factor and the panels were delivered to the site to complete the openings frames. The advantage of concrete for the internal environment comes from its thermal mass. The ability of concrete to absorb and store heat due to its inherited high-density rates concrete as greatest thermal quality for cladding systems. Furthermore, the embodied footprint of precast cladding is considerably less than a lightweight cladding system of a different materials such as aluminium, and has shown a better thermal performance in different NZ conditions. [133].

In moderate to large buildings, where most of the energy demand is due to cooling resulting from internal heat generated from several sources such as humans or machines, solar gain through the exterior envelope is an essential element that has been of concern in NZ. The introduction of light weight glazing to resolve this issue by letting the sun heat passes more easily is what disadvantages concrete cladding due to the delay it causes for the heat to pass in the building [134].

The first recycled concrete house composition in NZ was witnessed in 2009 in East Tamaki by incorporating waste glass (called glasscrete) as a replacement for fine aggregate. The attempt comes from continuous research work since 1980s. Due to the risk of silica content in glass compromising concrete strength, several testing regimes were conducted to confirm the right proportion to be added. The proportions were then standardized in Australia as a common practice between both regions [135].

5. Composite and alternative materials

Building thermal envelope forms an important key for efficient passive house system.

The literature works on thermal insulations for buildings have involved composite materials and new systems combined of sub-systems. The net-zero carbon encourages recyclable building materials such as timber or bamboo. These materials have shown advantages over other construction materials due to their strength, weight, costs and ductility [136-138].

Combining bamboo with other stiffer and lighter materials such as light weight steel was investigated by Li, Yao [139]. The work aimed to study the energy performance of a novel lightweight steel-bamboo wall configuration with cementitious mortar and expanded polystyrene as shown in **Figure 9**. The work involved both experimental and numerical work. It witnessed an improvement in the energy performance of up to 41%. On the other hand, it had a drawback with capsulating the internal heat in a building during peak summer when compared to conventual walls.

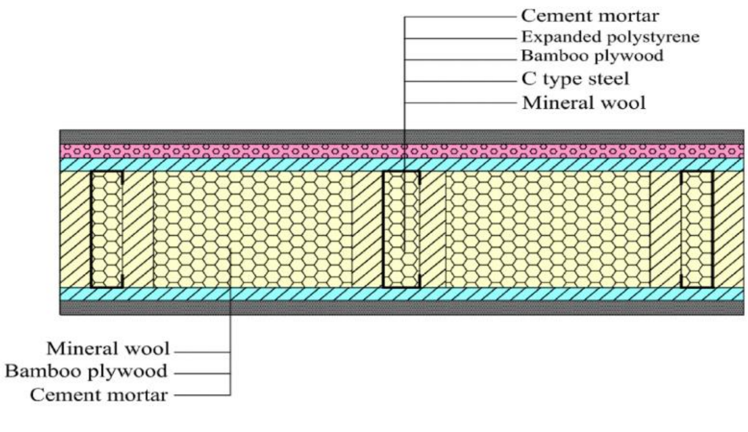

Figure 9: Proposed Bamboo-Steel composite wall by Li, Yao [139]

The use of other materials such as light weight steel as a composite material as stubs filled with slag strong concrete (SSC) was found of an interest towards thermally efficient structures [140]. The findings of the study showed SSC filler in light steel structures to less heat loss compared to equivalent conventional concrete structure by a range of 48%. It did not improve the thermal performance only, but indicated a level of sustainable development by adopting recyclable materials.

Xia, Xia [141] investigated a composite wall arrangement of concrete wythes of a constant thickness separated by diagonal steel brace embedded within insulative layer. The proposed wall arrangement, as shown in **Figure 10**, performed well in the varying temperature levels compared to the reference sample (steel framing wall) and is recommended in precast cladding.

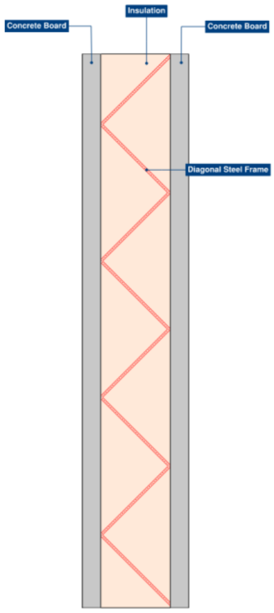

Figure 10: Proposed composite wall arrangement [141]

5.1 Phase Change Material

Phase Change Material (PCM) promises a good dampening effect to temperature fluctuations to absorb heat, and hence is foreseen to bring unique solutions in the thermal insulation within buildings [142-144]. Comparatively to concrete, it is estimated that 5mm PCM wall is capable to provide a similar thermal insulation as 80mm concrete wall [145], and a 15mm gypsum based PCM wall has a similar performance to 120mm thick conventional residential wall or 75mm of typical gypsum boards [146]. Furthermore, the passive application of PCM in the form of relatively macro-capsulated systems within wall insulations shows up to 31% reduction in energy in cold regions of Canada [147].

The last two decades have witnessed several forms of encapsulated PCM in the market for both active and passive solar applications, where melted PCM due to radiated solar energy can become a barrier for heat flow from exterior to interior envelope [148]. Several research works on different wall configurations towards architectural applications were found [149-

152]. The Oak Ridge National Laboratory (ORNL) has been investing on several projects towards thermal energy storage concept with octadecane wax capsulated wallboards [153].

The PCM integration methods in the building insulation products varied from direct methods such as immersion of the product into PCM baths known as imbibing method [154-158], which was associated with leakage problems or induced porous surfaces susceptible to moisture transfer issues across the envelope [159, 160], or encapsulating PCMS within the new material in a method called microencapsulation [161].

PCM has been shown to be very efficient with gypsum wallboards and can be sufficient to enable a large solar heating fraction in buildings [162, 163]. Athienitis, Liu [164] investigated the building's thermal performance with PCM gypsum boards placed interiorly forming up to 25% of the total building structure. The study was experimental and numerical, where the results showed that the PCM boards can be 6°C less than the ordinary boards when exposed to solar heat. Similarly, in exterior cold climate, the house was found to be 4°C higher than ordinary boards which proved noticeable improvement in the building's thermal comfort.

5.2 Thermally activated building systems

Adopting composite materials in building walls is found to have an efficient influence in the thermal insulation of the overall thermal resistance. In other systems, this is combined with mechanical approaches by embedding pipes within walls with circulated water inside to provide either heating or cooling influence on the surrounding space leading to less energy needed for heating or cooling the house [165-168]. The water activated systems has been implemented in buildings since the early 1990s in Switzerland to provide warmer houses with minimum heating energy [169].

Thermally Activated Building Systems (TABS) is known with other names such as slab cooling/heating system, concrete core conditioning system, thermo-active building systems, thermally activated buildings slabs, thermally activated building components, thermally activated constructions, active building storage systems and embedded hydronic pipe systems [169-176]. These systems have received enormous attention in several countries including in regions such as Europe, Canada and Asian countries [177-179]. The concept behind these systems is using radiators or floor heating emitters in transporting the energy from central plant to the desired place. These systems can exist in different structural elements, mainly ceilings, walls (mainly external), storey slabs and slabs on grade. The heating equilibrium is achieved by radiation between the heated surfaces trapped between the installed pipes in the envelopes.

Figure 11 demonstrates the typical water pipe locations embedded within a building envelope operated by TABS heating/cooling operating philosophy .

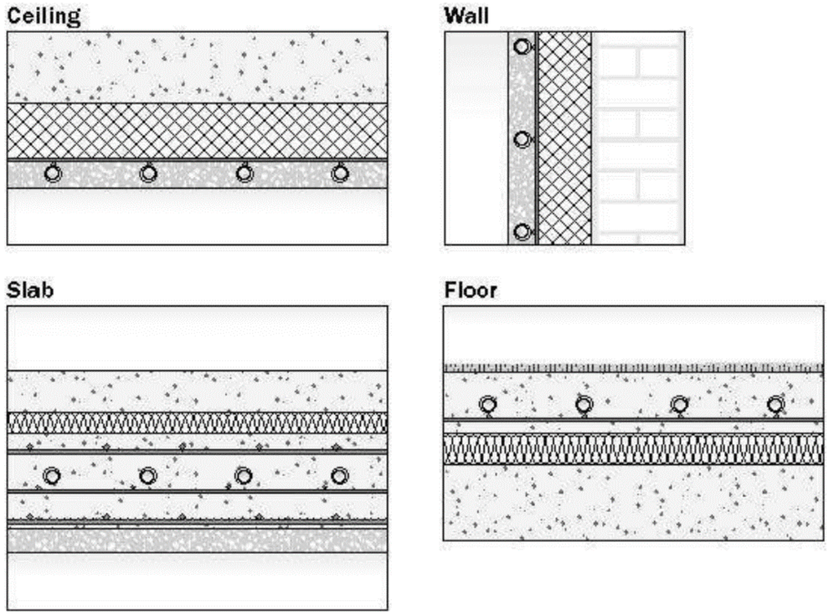

Figure 11: Typical location of water pipes within TABS buildings envelopes [171]

5.3 Thermally activated walls with phase change material as composite walls (TAPCW)

Combining TABS with PCM material is of an efficient solution found in several literature works and systems. Lin, Zhang [180], [181] introduced new PCM floor plates subjected to electrical heating flow as an output of experimental and numerical works. The work included a full-scale experiment on a house (3m × 2m × 2m h) with a window opening in one side. The 120mm thick floor systems consisted electric heaters, PCM, timber frame and insulation boards. It was found that not more than 15% was the heat dissipated through the insulation during the peak and the off-peak period of the year, where this was completed in a total of six (6) days monitoring scheme.

Chen, Yang [182] investigated the impact of macro-encapsulated PCM in composite TABS walls numerically. The wall arrangement aimed to relocate the pipes to the exterior load bearing layer. The numerical work explored the influence of several parameters such as pipe spacing, PCM layer thickness and location. The 360mm thick wall specimen constituted 240mm clay bricklayer, 20mm plasters (exterior and interior), 40mm extruded polystyrene foam boards (XPS), 40mm PCM layer with embedded 20mm inlet water pipes as shown in

Figure 12 . The comparative study against normal wall and a wall with PCM only (no inlet pipes) demonstrated the effectiveness of TAP composite walls (TAPCW) with a daily heat loss reduction of up to 106% depending on the solar direction exposed to the wall. The study showed that the TAPCW applied in the north orientation is more effective, which has the highest value of interior temperature increase (1.8 °C), effective PCM utilization ratio (14.14%), reduction size of PE (64.98%) and reduction size of C (34.43%). Overall, the proposed TAPCW presents a satisfactory thermal performance in the heating system and could contribute to the progress of energy saving in large buildings.

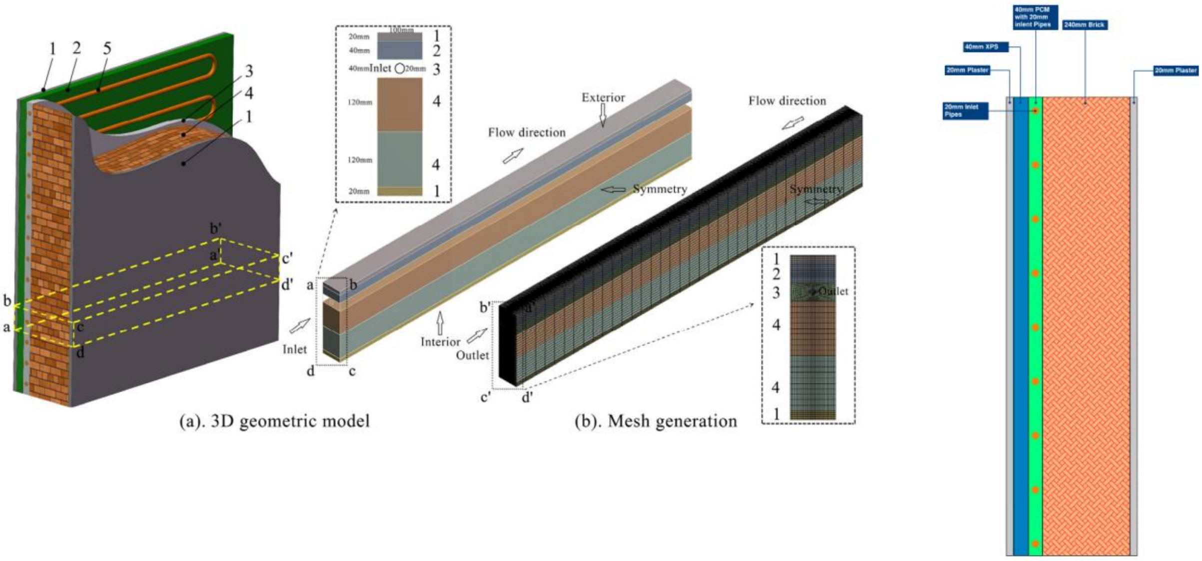

Figure 12: Proposed TAPS Composite Walls Arrangement [182]

Zhang, Zhuang [183] introduced a new hollow block for typical structural walls composed of PCM placed in a multiform arrangement with different configurations. The performance of the wall was investigated for the overall thermal resistance through hot-cold chamber. The works showed an improvement in the amount of temperature decrement in the wall by up to 5°C compared to conventional wall capable of resisting 1.5°C, indicting an improvement of approximately double the thermal resistance capacity.

Ramakrishnan, Wang [184] replaced 80% of concrete fine aggregate with phase change material integrated cementitious composites in an aim for interior applications, where experimental thermal testing of the new composite material within the interior temperature in hot climates was increased by up to 4.43°C. Lee, Medina [185] experimentally assessed the ideal location of the PCM shields within walls cavities, where an improvement of more than 50% was witnessed in overall heat flux. Kong, Lu [186] numerically investigated the thermal behavior of PCM wall panels that employed validation works in different reference rooms. The work targeted roof and walls to explore different analysis methods of thermal energy savings at comfort levels.

Schmerse, Ikutegbe [187] investigated the effect of PCM in a lightweight single and double residential units in NZ to showcase the thermal performance of PCM. The numerical simulation showed promising performance with an improvement between 30% to 50% of annual energy saving.

6. Other systems

In an attempt for new material, Ouhaibi, Gounni [188] introduced a new classical material "Poncebloc" that is incorporated in the Moroccan construction industryse as shown in **Figure 13**. The work involved both experimental and numerical work to showcase the effectiveness of the new material that can reduce cooling energy by 66% in hot climates and heating energy by 44% in cold climates. Similarly, Lamrani, Mansour [189] investigated a number ecological material using date palm fibers, olive waste and straw for thermal performance of building envelope using transient and steady state heat flow methods. The experimental work showed that the composite material reduced the thermal conductivity by 60%. Leang, Tittelein [190] studied the thermal efficiency of energy storage systems in building industry using composite solar walls combined with PCM materials known as Trombe walls. Their work showed significant improvement in the latent heat demand with greater thermal comfort.

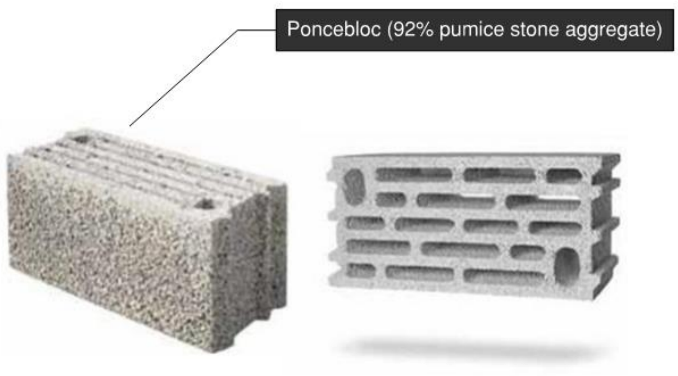

Figure 13: Proposed new material by Ouhaibi, Gounni [188] for thermal efficient walls.

A Trombe wall (TW) is a passive solar device that can be installed on the facade of a building to absorb solar heat while enabling natural ventilation to improve its thermal and energy performances [79]. Lohmann and Santos [79] investigated a Trombe wall's thermal behavior and energy efficiency in a CFS frame using in situ measurements . According to their research, the Trombe wall system can significantly improve the thermal behavior of a CFS structure while also lowering the heating energy consumption. For example, a 27% reduction in heating energy was found for an office at 18 ℃ set-point due to the TW systemdevice [79].

7. Summary towards NZ thermally efficient homes

The housing industry in New Zealand is presently in crisis. While affordability and housing shortages are the main points of contention, the quality of housing is also gaining traction with reports that poorly insulated houses cost New Zealand health-related issues annually. Furthermore, NZ dwellings have been categorized as cold, damp and miserable shabby behaviour when compared to healthy homes standard [191]. The fact that old NZ housing is constructed with poor ventilation makes it difficult to refurbish it towards healthy home requirements [192]. The healthy homes concept was first launched in NZ in 2013, covering the Auckland region, then was extended to cover more regions to provide a healthy environment for low-income families [193]. NZ introduced healthy homes standards as a law in July 2019 to cover rental properties with minimum requirements for thermal comfort, ventilation, moisture ingress and drainage [194].

+The level of insulation across NZ zones has been revisited by to include an interim increase in the house envelopes (walls, floor, roof and windows) starting from November 2022 [195]. In order to make recommendations for NZ, this study attempts to give a review of recent literature on house insulations and thermal comfort in the residential sector. The paper also assessed proposed solutions for efficient insulated envelopes from a practical employability within NZ industry. The following conclusions have been drawn from the reviewed literature to incorporate best practices and areas of exploration that can be of a reference to NZ hosing industry:

- Concrete structures have been limited to mainly non-residential buildings or within propriety systems in NZ. The workability of concrete and having the capability of embedding different materials have obtained the interest of much research in which novel works were suggested. The thermal insulation performance of concrete when combined with other materials can outperform timber and steel houses which can offset the use of insulation materials within timber and steel building envelope. The fact that concrete comes in thicker envelope, to account for durability cover and reinforcement placed within, compromises the thermal performance unless additives are added. Nevertheless, the implementation of concrete as a secondary structural element is found quite efficient in precast sandwich panels insulation wyths/boards in several applications. NZ, similarly to many regions, has been implementing PCSPs as a cladding insulation in mainly commercial and industrial projects and less in residential sector.

- Flooring systems in NZ is mainly formed with concrete material that is layered on a damping material sheets against moisture from soil. The interaction between soil and concrete is a direct contact with damp proof material in which no insulation means are provided. This agrees well with several international practices, however several novel works of combining concrete flooring system with other material that come in slitted or perforated shape have shown great performance in insulating the subfloors. The authors forecast composite floors to be of viable solutions towards healthy homes motive in NZ.
- New proposed geometries for bricks by including more perforations are found to be efficient for thermal insulation, or when combined with other materials such as concrete mortar as a filler materials. The proposed bricks geometries can be adopted within NZ since bricks forms a primary building product within NZ construction industry..
- Incorporating composite materials for insulation is found to be a good area for NZ's residential house. Composite concrete wythes with EPS layers showed good thermal insulation performance as well as less risks towards moisture development in walls when compared to steel or timber walls. .
- Steel houses, mainly cold-formed steel, forms another primary material in the NZ industry. It started to attract attention in NZ over the last decade and more over the last few years due to the erection speed it brings in order to compensate construction lag resulted from COVID-19 recession within in the building industry. The adoption of more steel houses in NZ triggers the concern of healthy homes requirements and the regulations with thermal comfort, despite old houses made of timber are categorized as an aging, cold, damp and of serious health concerns. The literature suggests several solutions for efficient thermally insulative steel houses mainly through geometrical

alteration to the steel profiles. The authors find those solutions to be possible in NZ industry too.

- Furthermore, NZ steel houses adopts thermal breaks in house envelopes to compensate the drop in the R-value, which makes it an expensive approach and relatively a near cost to timber houses. The authors believe that further research for steel houses thermal insulation is a critical step, particularly with industry moving towards steel as recyclable materials towards sustainability calls.
- Composite systems of different materials have been found to be a new area of investigation in recent literature for thermal insulation purposes. Bamboo for example is recommended as an efficient system when combined with steel framed walls. Other approaches such as in slag stone concrete fillers for steel closed sections is found to provide good thermal insulation. These approaches provide an insight to be adopted in NZ commercial projects where heavy hot rolled steel closed sections are used.
- Phase change material is found to be a major investigation part in the literature towards thermally efficient building envelopes. PCM forms the basis of many new insulating boards (i.e. gypsum boards) due to the low material thermal conductivity. The authors trust these solutions can be well incorporated in the NZ housing industry particular for external and internal building envelope boards
- Other systems found in European countries is the Thermally Activated Building Systems which proved to be a potential systems especially for large non-residential projects. These systems have no boundaries in getting adopted to NZ buildings towards sustainable solutions. The literature suggest that TABS can come in partial systems and in combination with PCM to provide good thermal insulation resistance.
- Trombe walls is another system that is found to be associated with great passive energy and thermal mass storage at low costs compared to other systems. NZ has the potential of adopting these systems for the new to-built houses for resolving the housing crisis in the country. These systems can provid great energy saving for the annual energy usage and hence can ensure another positive factor towards sustainable developments.
- The majority of the literature works reviewed are found to depend majorly on numerical modelling than laboratory tests for thermal assessment of buildings. The challenges in conducting laboratory tests is associated with several boundaries such as accurate laboratories atmospheric control. On the other hand, FEA means are found to provide reliable results for steady state thermal analysis and are recommended for thermal investigations.

The literature review shows intensive works on attempting efficient insulative systems for residential sector in different countries, however little is found to NZ aspect, where the authors recommend further research works on residential houses thermal comfort and efficient insulations systems incorporating suggested solutions from the above recommendations.

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