Journal of Engineering Sciences and Information Technology (JESIT) • Vol 8, Issue 4 (2024) • P: 99 - 89
https://journals.ajsrp.com/index.php/jesit
ISSN: 2522-3321(Online) • ISSN: 2522-3321(Print)

Review on building energy effeciency through optimized building envelopes

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Received: 26/09/2024
Revised: 20/10/2024
Accepted: 03/11/2024
Published: 30/12/2024

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Citation: Bazaraah, M. O., Khodeir, L., & Gadelhak, M. (2024). Review on building energy effeciency through optimized building envelopes. *Journal of engineering sciences and information technology, 8*(4), 89 – 99 . https://doi.org/10.26389/AJSRP.R290924

Abstract: Energy-efficient building envelopes consider material thermophysical properties and wall section configuration to optimize energy consumption for cooling and heating in response to climate. A review of 80 papers revealed that published information on this subject is diverse, contains inconsistencies in findings, and shows contradictory results. Therefore, hypothesizing a suitable building envelope for efficient year-round performance per climate is difficult through published literature alone. The aim of this paper is to identify trends and gaps in studies regarding efficient year-round building envelopes. Relevant literature published from 1997 to 2023 was reviewed. A data extraction process was used to organize performance parameters of thermal insulation and thermal mass. The relationships between climate, wall configuration, and thermophysical properties in published experimental studies were then analyzed. Results of static thermal insulation investigations revealed a trend where the most common placement is interior or embedded, however inconsistencies in results were found depending on climate. Dynamic insulation is predicted to show promising results, although it is a novel solution under research. Moreover, multilayer walls of thermal insulation and thermal mass show better mitigation for thermal discomfort in climates with high diurnal fluctuation compared to other climates. Furthermore, latent heat storage using Phase Change Materials (PCMs) was found to be more advantageous than sensible heat storage. This study highlights future potential research on building envelopes in different climates and microclimates and their respective thermophysical properties requirements.

Keywords: Static Insulation; Dynamic Insulation; Sensible Heat Storage; Latent Heat Storage; Year-round Energy Efficiency.

مراجعة أدبية حول كفاءة الطاقة في المباني من خلال تحسين غلاف المبنى

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المستخلص: تأخذ الأغلفة الإنشائية للمباني ذات الكفاءة في استهلاك الطاقة في الاعتبار الخصائص الديناميكية الحرارية للمواد وتكوين الجدران بهدف تحسين استهلاك الطاقة للتبريد والتدفئة استجابةً للمناخ. كشفت مراجعة لـ 80 بحثًا أن المعلومات المنشورة حول هذا الموضوع متنوعة، وتحتوي على تناقضات في النتائج، وتظهر تباينات متعارضة، مما يجعل من الصعب افتراض غلاف بنائي مناسب للأداء الفعّال على مدار السنة بناءً على الأدبيات المنشورة وحدها. تهدف هذه الدراسة إلى تحديد الاتجاهات والفجوات في الدراسات المتعلقة بالأغلفة الإنشائية ذات الكفاءة على مدار السنة. تم مراجعة الأدبيات ذات الصلة التي نُشرت في الفترة من 1997 إلى 2023. تم استخدام عملية استخراج البيانات لتنظيم معايير الأداء المتعلقة بالعزل الحراري والكتلة الحرارية. ثم تم تحليل العلاقات بين المناخ، وتكوين الجدران، والخصائص الديناميكية الحرارية في الدراسات التجريبية المنشورة. كشفت نتائج تحقيقات العزل الحراري الثابت عن وجود اتجاه شائع في وضع العزل داخل الجدران أو دمجه فيها، لكن وُجدت تناقضات في النتائج حسب المناخ. يُتوقع أن يظهر العزل الديناميكي نتائج واعدة، رغم كونه حلًا مبتكرًا تحت البحث. علاوة على ذلك، أظهرت الجدران متعددة الطبقات التي تحتوي على العزل الحراري والكتلة الحرارية قدرة أفضل في تحسين الراحة الحرارية في المناخات التي تتميز بتفاوت حراري نهاري كبير مقارنةً بالمناخات الأخرى. كما تبيّن أن تخزين الحرارة الكامنة باستخدام مواد تغيير الطور أكثر فائدة من تخزين الحرارة المحسوسة. تبرز هذه الدراسة إمكانات البحث المستقبلي حول الأغلفة الإنشائية في المناخات والمناخات الدقيقة المختلفة ومتطلباتها من الخصائص الديناميكية الحرارية.

الكلمات المفتاحية: العزل الثابت؛ العزل الديناميكي؛ تخزين الحرارة المحسوسة؛ تخزين الحرارة الكامنة؛ الكفاءة الطاقية على مدار السنة.

1. INTRODUCTION

The management of heat gain through thermal insulation and/or thermal mass is an important consideration in addressing energy consumption optimization in built structures. From a thermophysical engineering perspective, wall materials can be characterized by thermal conductivity, mass density, and specific heat capacity, which are all parameters are of great interest [1]. Thermal insulation of building fabric creates a layer of high thermal resistance between interior and exterior environment, thereby decreasing heat flow through building facade and decreasing energy consumption [2]. Static insulation has been well established and widely used as an energy-sustainable practice. Current literature expands on thermal insulation as a tool within energy retrofitting strategies.

However, the conventional notion that increased thermal insulation leads to energy efficiency has been challenged by recent studies [2], [3]. These studies suggest that static insulation can lead to higher energy consumption during certain times of the year, counteracting overall annual energy savings. For example, it may block heat gain in summer to prevent overheating, but in winter, heat gain would be beneficial for indoor thermal comfort [4]. Conversely, insulation designed for cold climates to retain heat in winter may neglect protection from heat gained through fenestrations in summer [5], [6]. This has led to a new research area: dynamic thermal insulation.

Dynamic insulation refers to the ability to control envelope's thermal resistance to control heat transfer to and from the building by switching between non-conductive and conductive states [7], [2]. According to [3], dynamic insulation can be achieved through air flow through permeable insulation, physically removable insulation, or changing pressure within nanomaterials. Other technologies include electronically influencing thermal resistance, introducing inert gases with variable thermal conductivity, or mechanically sliding or compressing wall assembly [8].

Thermal mass, in contrast, stores thermal energy during peak hours and utilizes it during off-peak hours by charging, storing, and discharging thermal energy. This process shifts peak loads and smooths out diurnal fluctuations [9]. The three main classifications of thermal energy storage systems are sensible heat storage, latent heat storage, and thermo-chemical heat storage [9]. Recent studies have been looking into phase change materials (PCMs) as latent thermal energy storage due to their ability to store energy at nearly constant temperatures. Their high storage capability makes them a competitive technology for reducing energy consumption in buildings [9]. The effectiveness of (PCMs) is largely dependent on its phase change temperature and thermo-physical properties. If these are not optimized, (PCMs) will store heat sensibly, offering no advantage over other materials [10]. Sensible heat storage materials, such as limestone and marble, for example, serve the same function. Nevertheless, (PCMs) can store and release latent heat during phase transition, offering 5-14 times higher storage capacity per unit volume compared to sensible heat materials [11].

The development of thermal insulation and thermal mass technologies improves the efficiency in energy utilization in buildings [12]. This paper aims to identify common trends and gaps in thermal insulation studies for designing efficient year-round building envelopes in different climates. The paper reviews studies on the integration of thermal insulation and thermal mass in building envelopes. The review is structured as follows:

- Section 2: Research Methodology
- Section 3: Results of Studies on:
  - Static thermal insulation
  - Dynamic thermal insulation
  - Multilayer wall where thermal insulation is combined with thermal mass
- Section 4: Discussion and Analysis of Literature to Identify Trends and Gaps

2. RESEARCH METHODOLOGY

The methodology of this systematic review follows the guidelines recommended by [13] and [14]. This methodology aims to ensure comprehensiveness and provide a clear framework for filtering, extracting, and analyzing of data. Data collection for this review was conducted through the Google scholar platform. The following section will explain each step of the methodology in detail.

2.1 Data Search and Sample Selection

- The inclusion criteria of data for this review were:

- Investigations on how specific thermal insulation and/or thermal mass impacts the performance of external wall.
- Investigations on external wall thermophysical parameters.

In the interest of collecting data relevant to year-round building envelope performance, the data sample included studies where the target seasons are both heating and cooling.

- The investigation of this topic was conducted in two distinct phases:
  - Phase 1 encompassed a comprehensive examination of a general data set using a deliberately expansive search strategy to identify relevant publications.
  - Phase 2 involved examining two specialized data sets. After reviewing 80 documents in Phase 1, a preliminary understanding of the subject was developed. This led to the creation of more refined keywords, as shown in Table 1.

Table 1 Literature Identification Data Sets

Phase	Data set	Keywords	Aim	No. of Papers
1	Generic	Year-round, energy efficiency, thermal energy storage, thermal insulation, climate	To investigate current literature on this topic and to develop an understanding eligible for building a data extraction system.	80
2	Focused	Phase change material, energy efficiency, building envelope	To extract and examine relevant data	32
	Focused	Polystyrene, polyurethane, dynamic thermal insulation	To extract and examine relevant data	22

- To ensure the selected studies were relevant to this review, a multi-step filtering process was conducted. This process involved screening abstracts to exclude irrelevant papers and iterating the data search with more refined keywords. Ultimately, 54 studies were selected for the inclusion in this paper at this stage.
- After investigating the full text of the selected studies, 13 studies were excluded due to eligibility and relevance concerns. This resulted in a final selection of 41 studies for this review. With these studies identified, the topic and aim of the review paper were clearly defined, and a preliminary data extraction method was developed.

2.2 Data Extraction

- To achieve the paper's aim of identifying trends and gaps in building envelope performance, the selected literature was analyzed to establish a correlation between the investigations of wall performance, thermophysical properties of the materials used, and climatic context of the cases.
- A list of key parameters for a well-rounded review process were identified. These parameters are primarily organized in 3 groups as shown in table 2.

Table 2 Data Sets categorization per parameter.

Group	Parameters
Group 1: Wall thermophysical properties	U-value, latent heat, (PCM) melting point, amounts/thickness/encapsulation of solution materials, wall section composition
Group 2: Study context	Target season, climate, and building materials
Group 3: Study parameters	Study focus, type of experimental testing, type of experiment measurement, and measurement of solution efficiency

- Identifying the parameters facilitated the development of a more comprehensive data extraction process. This process involved creating tables that captured specific details of each reviewed experiment, including study data and the author's observations on the topic. To further enhance the analysis, additional data such as the Koppen climate classification for each study location was obtained through cross-referencing. The information regarding each investigation were systematically extracted as shown in Figure 1:

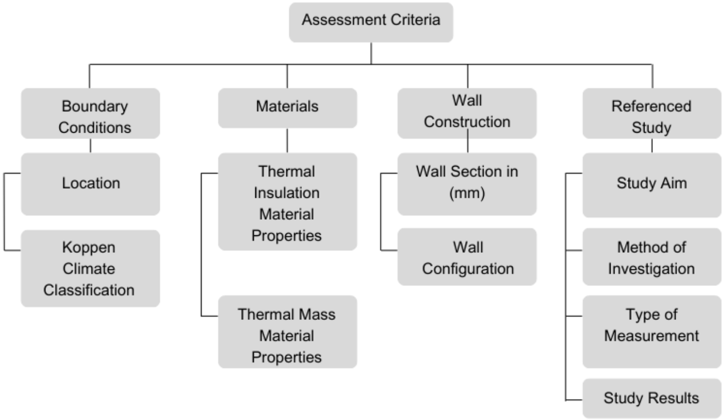

Figure 1 Data Extraction Criteria

- Then, study findings were analyzed for correlations between climate, wall configuration, and thermophysical parameters. Following this analysis, a comparative review was conducted, grouping the results according to findings that supported each other (complementary) and findings that disagreed (contradictory). This process facilitated the identification of common trends and gaps in studies regarding building envelopes for year-round thermal performance in different climates.

Having outlined the methodology employed to analyze the relationships between efficient wall design parameters, climate, and a year-round building envelope performance, Section 3 will present the results. This section will showcase the impact of thermal insulation and multilayer walls on building envelope performance.

3. RESULTS OF DIFFERENT THERMAL PROPERTIES ON BUILDING ENVELOPE

This section explores the findings from reviewed literature regarding the impact of thermal insulation strategies on building envelope performance. The effectiveness of static insulation, the potential of dynamic insulation, and the benefits of combining thermal insulation with thermal mass in multilayer wall configurations.

3.1 Static Insulation

Several studies have documented the energy saving potential of thermal insulation materials. One study reported that the energy savings range from 34% to 48% depending on the insulation material [15]. Similarly, a simulation of a typical residential building led to 37.85% energy savings, 50.53% reduction in cooling loads, and a 30% reduction in discomfort hours [9]. Another simulation testing the impact of thermal insulation on an existing building's energy consumption reported that insulation alone achieved 10% energy savings, while the whole retrofit design strategy achieved 33% energy savings [16]. Additionally, a study investigates combining wall and window thermal insulation in retrofitting through a simulation and reported an annual decrease of 47.6% in energy consumption [17]. Moreover, an experiment conducted through the course of 2008 and 2009 to test the impact and behavior of three insulation materials [18]. They reported that the most energy efficient material was polyurethane, as it achieved 64% energy savings in the summer, and 37% energy savings in winter.

However, the effectiveness of thermal insulation is not without its' limitations, where some authors expand beyond the benefit of conventional static insulation and studied potential drawbacks. In an investigation on the relationship between thermal insulation and overheating in southern European summers, it was concluded that solar heat gain through windows is not released out of the building due to thermal insulation, however appropriate solar shading is sufficient to prevent overheating [5]. Similarly, a study on the relationship between thermal insulation designed for heating season and its' consequential impact on overheating in cooling season in 5 different cities in China, reported that thicker insulation layers (125mm polystyrene) induced overheating in cooling seasons (22.5% compared to 6.9% with 60mm polystyrene) [6].

3.2 Dynamic Insulation

As research on thermal insulation parameters and performance expands, multiple publications highlight the importance of a flexible R-value for its' ability to adapt to external conditions. For example, the concept of designing fixed thermophysical properties of a wall to adjust to the year-round varying seasonal conditions was investigated in [19], comparing it to humans changing clothes in response to different seasons. Dynamic insulation is believed to achieve better year-round thermal performance, meaning investigations are not limited to cooling or heating seasons only. A study on the impact of dynamic insulation on heat flux and reported that dynamic insulation has significant potential for all climates [20]. Another study investigated the impact of dynamic insulation on peak load and annual energy consumption in the UAE, reporting that dynamic insulation can achieve 25% decrease in peak load energy consumption, and a 3.8% decrease of annual energy consumption. [21]. The lower amount of annual savings compared to other studies could be due to the novelty of concept, on-going research on its parameters, challenges in simulation, or due to that most studies focus on summer seasons in hot desert climates instead of annual energy consumption neglecting the impact of energy consumption in winter season on annual energy consumption. Additionally, a study on a novel smart insulation system where u-value is variable reveals that its' efficiency exceeds static insulation, however authors predict fabrication challenges [7]. Finally, a comparison of dynamic and static insulation in three different climates (Cairo, Naples, Munich) showed a greater temperature decrease with dynamic insulation (3.2%, 4.7%, 7.2%) as opposed to conventional insulation [22].

3.3 Multilayer Walls of Thermal Insulation and Thermal Mass

Building envelope performance is often optimized through its u-value. However, other literature assesses the thermal efficiency of multi-layer walls containing thermal mass and thermal insulation on building thermal stability [23]. Authors suggest that the combination of an appropriate u-value and thermal inertia strongly influence envelope thermal performance by mitigating daily exterior fluctuations [24].

For example, a study that combines thermal insulation and wall cavity as thermal mass achieved 22% energy savings [25]. Another study testing the impact of sensible thermal storage and thermal insulation on thermal comfort reported a 7.2% energy savings [26]. Similarly, a study on wall configurations containing sensible thermal storage and thermal insulation achieved an 11% reduction in annual energy consumption [27].

However, another investigation studying the impact of Phase Change Materials (PCM) and insulation on thermal comfort revealed no significant temperature decrease unless it is paired with passive ventilative cooling [28]. On that note, an experiment studying the impact of (PCM) on an insulated wall's performance achieved a 1-hour peak load shifting and a decrease in temperature by 2 degrees Celsius [29]. Moreover, a similar study was conducted and reported a decrease of 6 degrees Celsius in mean radiant temperature and 4 degrees Celsius in air temperature [30]. In a study on phase change materials and thermal insulation, it was revealed that a 2-hour peak load were shifted [28]. A study on the impact of (PCM) on the decrement factor, which is the rate of change of temperature inside a space and is used as a measure of thermal comfort, reported that (PCM) achieves a decrease of 30-40% [31].

With the emergence of dynamic insulation, authors began to integrate thermal mass and dynamic insulation to achieve optimal efficiency. For example, a study on the impact of phase change material and dynamic insulation on thermal efficiency reported that it eliminates overheating risks [32]. Another study compared the impact of a multilayer wall configuration containing (PCM) and dynamic insulation to dynamic insulation alone, (PCM) alone, and static insulation alone on the thermal performance. This study reported a 15-72% reduction in heat gain and 7-38% reduction in heat loss depending on climate [8].

Having explored the results of different thermal properties on building envelope performance, Section 4 will present the impact of climate, configurations, and thermophysical properties of materials used in each study.

4. DISCUSSION ON WALL THERMAL PROPERTIES FOR EFFECTIVE YEAR-ROUND BUILDING ENVELOPE PERFORMANCE

This section explores the influence of climate on the effectiveness of static and dynamic thermal insulation, as well as multilayer wall configurations containing thermal mass, for building envelope performance. Studies investigating a wide range of climates, including hot desert, mediterranean, and continental variations, were analyzed to evaluate the impact of context and wall thermal properties of each case on its' performance as an effective building envelope.

4.1 Building Envelope and Climate

Six climate types, as shown in figure 2, are covered in studies investigating static thermal insulation's impact on building envelopes. While Static thermal insulation effectively reduces cooling loads in hot desert climate (BWh) [15], [17], [9], a study by [18] reports a reduction in both heating and cooling loads in Mediterranean climate, without specifying whether its' hot-summer Mediterranean (Csa) or warm-summer Mediterranean climate (Csb). Furthermore, it was found that static thermal insulation as a sole tool in a hot-summer Mediterranean (Csa) achieved less energy savings compared to when it was used in hot desert climates [16]. Adding that [21] achieved lower results on cooling load reduction using dynamic insulation in a hot desert climate (BWh).

Static thermal insulation can have negative consequences, such as overheating, in summers in Monsoon-influenced climates (Dwa, Dwb, Cwa), where it is designed for retaining heat in colder months [6]. Larger window-to-wall ratio to allow passive heating in winters, however in summers it results in the opposite outcome by allowing heat and insulating it inside. Nevertheless, [5] reported that controlled solar shading can prevent overheating during a year-round thermal comfort analysis.

Another solution is dynamic insulation, which allows the wall to change its' u-value to adjust to external conditions. As proven by [22], demonstrates effectiveness in decreasing temperature in cooling seasons in hot climates, such as, hot climates (BWh, Csa, Dfb). While, [20] and [7] have developed technologies with "promising results" and "exceed static insulation methods", they lack quantification of energy efficiency benefits or specifics on climate data, relying solely on claims of adaptability to a wide range of climates.

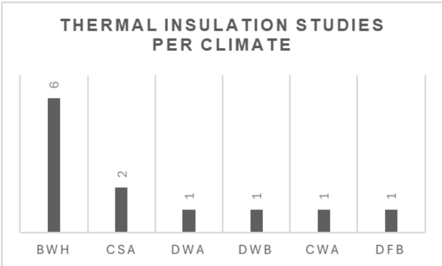

Figure 2 Number of thermal insulation studies sorted by investigated climate.

Multilayer wall studies that mention climate cover 9 climate types (Figure 3). Investigations by [30] and [29] report significant indoor temperature decrease during cooling contexts in Warm-summer humid continental climate (Dfb) and Hot-summer Mediterranean Continental climate (Dsa). However, [26] achieved relatively lower energy savings with a multilayer wall solution (thermal mass and thermal insulation) in hot desert climate (BWh) compared to other studies in similar climates.

Conflicting findings appear in literature regarding the impact of Phase Change Materials (PCM) in multilayer wall solutions. Studies by [33], [28] and [34] suggest that (PCM) in multilayer wall solutions does not reduce net heat gained in summers, only shifting peak loads. A possible justification is that the heat gained and stored is equal to heat released indoor, which highlights the importance of the use of (PCMs) in climates with high diurnal fluctuations where the heat gain during the day is delayed being conducted internally at night during a temperature drop to mitigate internal temperature fluctuation. This aligns with [30]'s suggestion that locations with large diurnal temperature fluctuations require a significant thermal mass.

However, [27], [35], and [25] report that thermal storage achieves significant energy savings, suggesting its effectiveness. It is important to note that [33], and [34] did not specify the type of climate that they factored in their study for year-round thermal comfort. While, [34] reported that (PCM) was effective in reducing heating load by releasing heat indoors at night, [31] reports a 30-40% decrease in discomfort hours in temperate climates. In addition to a study that tested the combination of thermal mass and thermal insulation in a cold arid climate and reported that it shifted peak cooling load by 2 hours [28].

In response, [36] clarified through simulation across different climates, that (PCMs) are more effective in semi-arid climates than subtropical Mediterranean climates. Given the efficiency of thermal storage as thermal comfort solution in [35], [25] and [37] studies in an arid climate, and lack thereof in [28], [34], and [33], agrees with the theory that arid climates with longer daytime duration and higher diurnal fluctuation are a factor in the success of thermal storage as a thermal comfort solution.

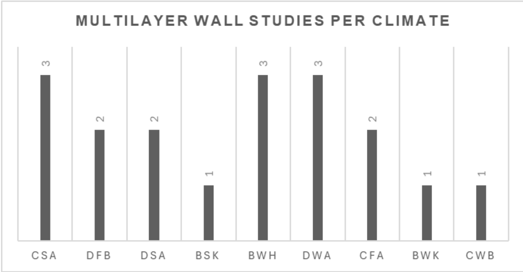

Figure 3 Number of multilayer wall studies sorted by investigated climate.

4.2 Configuration of Wall

While several studies featured in this review did not mention the placement of thermal insulation as a sole tool within the wall section configuration, most authors that mentioned the placement of the insulation material to be interior with the exception of [17] who embedded the insulation within the wall and achieved relatively high energy savings.

For multilayer walls, configurations of wall sections containing two or more layers hold many possible configurations. Studying the placement of thermal insulation and/or thermal storage near external or internal environment is important because it impacts their efficiency. A study by [27] compared six wall configurations containing sensible thermal storage and thermal insulation. They revealed that the best performance is achieved when thermal mass is on the interior side of the wall.

The majority of multilayer wall studies in this paper investigate a configuration where thermal mass is interior and thermal insulation embedded. However, a study by [23] investigated 12 different wall configurations of insulation and thermal mass to reach the best configuration for thermal comfort. They concluded that the most efficient configuration, as shown in Figure 4, is one where thermal insulation is on outer layers and thermal mass is in the center (Wall 2b as referenced in the paper).

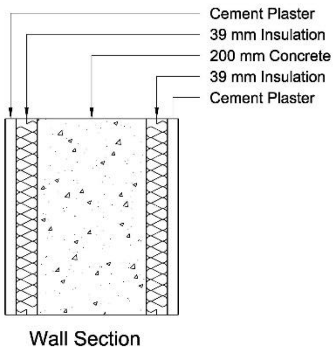

Figure 4 conclusion of the most efficient configuration as referenced in [23].

While a study [8] investigated a similar wall configuration with the exception that thermal insulation was dynamic not static, and thermal mass was PCM as shown in figure 5. In contrast with [34] where there are two layers of (PCM) with different melting points to respond to both heating and cooling seasons enclose thermal insulation as shown in figure 6.

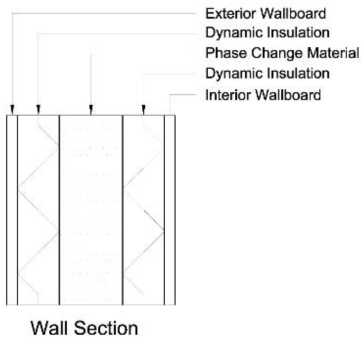

Figure 5 wall configuration as studied by [8].

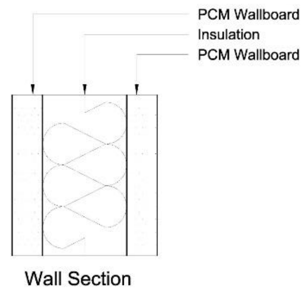

Figure 6 wall configuration as studied by [34].

Moreover, an investigation by [22] studied the impact of location of (PCM) on its' impact on energy savings, along with thermal insulation. They reported that (PCM) external plaster achieved 7.2% energy savings in semi-arid climates, however it achieved less than 3% in subtropical mediterranean climates [22].

4.3 Selection of Thermal Mass Parameters

Having established the benefits of thermal mass on thermal comfort. Literature suggests various sensible thermal storage material such as marble, concrete, hollow blocks, limestone, and cavity walls. However, a study by [1] highlights the advantage of Phase Change Materials due to their superior volumetric heat capacity compared to sensible thermal storage materials. Another study by [28] suggests that (PCM) thermal inertia is more efficient than Trombe-wall, further supporting the research interest in (PCMs).

For latent heat thermal storage materials using (PCM), materials specified in literature include paraffins and fatty acids. Selection criteria for building applications highlight a melting temperature close to human comfort temperatures(as suggested by [12], [24], [33], [38]). Complimentary to this finding, a study [39] concludes that in theory, the optimum (PCM) melting temperature is the heating setpoint to reduce heating demand, and the cooling set point to reduce cooling demand, which explains the reason why the choice of (PCM) melting temperature varied greatly in the span of studied literature. Authors used (PCMs) with melting points ranging from 27 to 47 degrees Celsius in cooling contexts, and 16 to 23 degrees Celsius in heating contexts. The variation of ranges of melting temperature selection between heating and cooling contexts might relate to the different thermal comfort needs in winter and summer.

Importantly, the selection of (PCM) melting point is influenced by factors such as rate of air change per hour, and/or methods of active heating/ cooling, and u-value of external walls [38]. A study by [40] investigating PCMs in multilayer walls report that the shift in heating load only occurs if an internal heating source melts the (PCM).

In recognition of the correlation between season and (PCM) melting temperature, a study on a novel wall system [34] reported a reduction of peak cooling loads by 35.4%, and heating load by 12.8%. However, mathematical simulations proved that total cooling load is only reduced by 1% since the heat that charged (PCM) is discharged back into interior space.

The physical properties of (PCM) in multilayer walls can differ based on their incorporation method. Whether impregnated within a wallboard or macro-encapsulated in sheets, their thickness within the wall section ranged from 10 mm to 15 mm [30], [31], and [29]. Moreover, an investigation by [22] studied the impact of layer thickness of micro-encapsulated (PCM) on its' impact on energy savings, along with thermal insulation. They reported that 3 cm of (PCM) external plaster is the optimum thickness [22].

4.4 Selection of Insulation Parameters

Hot climates clearly require lower conductivity (U-value) walls for thermal comfort, as proven by literature. A study [41] tested the impact of polyurethane on the u-value of an external wall, reporting a potential decrease of u-value of the wall up to 45%. Most common insulation materials chosen by authors in previous literature ranged between glassfibre wool, rockwool, polystyrene, and polyurethane.

While lower u-values are beneficial for thermal comfort, studies have evolved towards dynamic insulation, where thermal conductivity adjusts to external climate conditions. Studies by the [19], [5], [6], [7], [2], [4] and [3] all conclude that a fixed u-value is not ideal. Instead, the u-value should be a function of the variation of external environment, diurnally and seasonally. A numerical simulation was conducted by [19] suggest that the U-value of an external wall should be square-wave function of external temperature, meaning the U-value of the wall should be its' lowest during summer and winter days, and its' highest during summer nights and transient seasons. The achievable u-value range is a key finding in dynamic insulation for adaptive building envelopes, tailoring insulation properties to climatic context. Therefore, a solution similar to dynamic insulation might be a promising research area. Complimentary to this finding, [3] and [21] study the achievable range of R-value/U-value of the dynamic insulation concept on the R-value limits of an exterior wall. They report that dynamic insulation can achieve up to 50% reduction in R-value, and a 41% decrease in u-value.

5. CONCLUSION

This paper investigates the correlation between thermal insulation, thermal mass use in walls, and their impact on building envelope performance. Results were analyzed based on climate, wall configuration and thermophysical parameters to identify trends and gaps. The accuracy of the results of this review's findings is influenced by several factors. These include the data sample size (41 papers), the methodologies employed in the reviewed studies, the level of climate detail in mathematical calculations, the inclusion of both heating and cooling seasons and its' impact on annual net efficiency, and material properties considered. The inherent complexity of factors such as microclimates, occupancy, context variations pose a challenge for this type of study. This can result in a range of discrepancy between simulation/ mathematical results and actual results. Static thermal insulation revealed a trend of interior or embedded placement. However, a gap exists in consistency of energy efficiency results depending on climate. Dynamic insulation shows promise for maintaining thermal stability. Nevertheless, it is a novel solution under research for year-round performance with respect to climate.

Multilayer walls incorporating thermal insulation and thermal mass show better mitigation for thermal discomfort in climates with high diurnal fluctuation compared to other climates. Latent heat storage using PCM has prominent advantages over sensible heat storage, where the best use of phase change materials is when melting point is close to indoor thermal comfort.

It is important to note that due to varying climates, wall configurations, and thermophysical properties investigated in the review studies, a direct comparison of energy savings between these groups would be inaccurate.

Overall, this review highlights the need for further research to address the limitations identified. By addressing these knowledge gaps, a year-round, energy-efficient building envelope can be designed.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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