Influence of Hygroscopic Property of Lime and Cement Plaster on Building Energy Consumption for Five Climate Zones of India

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Abstract

Lime and cement are the commonly used walling materials in India. They are used as wall mortar and wall finish materials. Lime is a sustainable material with qualities such as breathability and better moisture transfer properties. Though it is a natural material, in contemporary construction practices, lime mortar or lime plaster has been replaced by cement mortar and cement plaster. To predict the impact of the moisture-buffering ability of building materials, hygrothermal simulations are carried out. It is a simulation-based study where the two numerical models of EnergyPlus are studied: Conduction Transfer Function (CTF) and Combined Heat and Moisture Transfer (HAMT). The study quantifies the annual energy consumption in a low-rise office building for five climate zones of India. Preliminary work shows that lime-plastered building has lower indoor relative humidity by 6 - 10% and the indoor conditions were 6% more comfortable. The results show that building having cement plaster is more energy consuming than lime. The moisture-buffering capacity of lime helped in reducing overall energy consumption by 12 – 23 kWh/m^2 for the five climate zones of India.

Keywords - Heat and Moisture Transfer, Lime Plaster, Cement Plaster, Energy Consumption.

1. Introduction

The building construction sector accounts for over one-third of global final energy consumption [1]. In India, 30% of the total electricity is used in space cooling [2]. The number of household air conditioners in the residential sector has increased by 50% in the last five years [3]. An increase of 10 - 45% in peak electricity load is expected by 2050 [2]. Therefore, to lower the environmental impact of buildings over their life cycle, energy efficiency has become a national and social imperative. The building envelope plays a key role in energy-efficient buildings. A well-designed building envelope responding to the external environment reduces the energy required for space conditioning. The construction materials and their hygrothermal characteristics affect both heat and moisture transfer across the building envelope. Additionally, the moisture-buffering capacity of internal finishes also affects the indoor relative humidity.

Several studies have established that the moderation of indoor humidity by interior finish materials results in energy savings. Qin et al. [4] found that potential savings in energy for heating and cooling were 4% and 7 - 30% respectively in 2009. In the case of a test building with an HVAC system to maintain indoor conditions, Zhang et al. observed a potential energy saving of 25 - 30% for temperate and semi-arid climates [5]. Few studies have emphasized designing the HVAC system based on the building envelope's moisture-buffering capacity [6]. Mendes et al. [7] predicts that ignoring the moisture effect may overestimate the conduction peak load by up to 210% and underestimate the yearly integrated heat flux by 59%. Boukhelf et al. [8] studied the hygrothermal behaviour of walls composed of eco-concrete made of glass powder to satisfy RE2020 requirements. Tran Le et al. [9] and Maalouf et al. [10] observed energy-saving potential with hemp concrete and hemp starch as interior finish, respectively. The overall impact of moisture-buffering depends on the hygroscopic property of the internal finishing material. In the long run, its contribution to the entire carbon footprint of the building would determine whether it is a sustainable material. In Germany and China, there is an increase in awareness of the need to maintain sustainable development using natural products [11]. Lime mortar or lime plaster is a natural organic material with a low carbon footprint in production and carbon absorption throughout its lifespan as a hardened material [12].

Lime plaster has been used as binding and finishing material since ancient times in India. The composition of lime deposits varies with the region due to different soil impurities [13]. There is a large variation in the preparation of lime mortar across India. Significant variation in lime plastering is also observed based on the addition of organic materials and application techniques mainly dependent on climate. Lime is a porous material that naturally absorbs ambient moisture and thus reduces dampness and pre-ageing of the building [14]. However, the decline in the use of lime was observed in the 18th century with the invention of Portland cement. Due to its ease of applicability and quick setting time, it replaced lime entirely in all aspects of the building. Cement also has low vapour permeability, which prevents the movement of penetrated water, causing the indoor environment prone to dampness. Unlike lime plaster, cement plaster is prone to cracking with varying outdoor conditions and is particularly not suitable for traditional and historic buildings.

Numerous simulations and experimentation-based studies have been reported on materials like hemp concrete, gypsum, spruce wood etc., and their moisture-buffering capacity [5,10]. However, studies of the hygrothermal behaviour of lime plaster or lime mortar have not received any attention in the literature. A lack of information on the hygroscopic properties of lime and cement plaster is also observed in the Indian context. Therefore, this research aims to bridge the gap, study the hygrothermal performance of lime and cement plaster, and quantify its impact on building energy consumption.

2. Objective

The primary objective of this work is to compare the hygrothermal performance of lime and cement plaster. The influence of both walling materials in building energy consumption for five climate zones of India is also studied.

3. Methodology

In this work, simulations are carried out with the EnergyPlus 9.4.0 version simulation tool to study the hygrothermal performance of lime and cement plaster. Preliminary simulations are carried out to re-establish the difference between an only thermal and thermal-hygrothermal model to ascertain the appropriateness of calculating the annual energy consumption in a building.

3.1. Properties of Lime and Cement Plaster

Measurements were carried out to determine hygrothermal properties of lime and cement plaster. Sorptionisotherm, vapour diffusion resistance, thermal conductivity, specific heat, and density were estimated as per the respective ASTM standards. These properties are not available for typical building materials employed in India. Table 1 shows the hygrothermal properties of lime and cement plaster determined for this research. Figure 1 shows the measured sorption-isotherm for lime and cement plaster.

Table 1: Hygrothermal properties of lime and cement plaster

Property	Lime	Cement
Thermal Conductivity (W/m-K)	0.16	1.58
Density (kg/m³)	1636	2252
Specific heat (J/kg K)	814.26	927.89
Porosity	0.276	0.164
Vapour Diffusion resistance	5.74	25.18

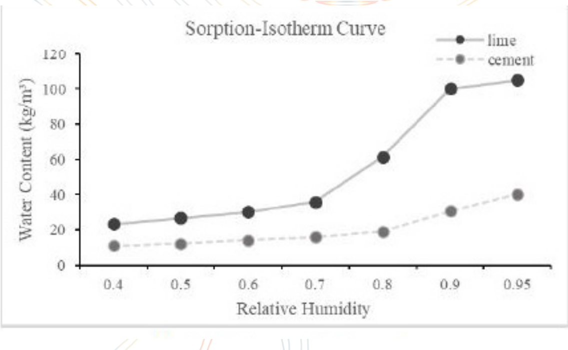

Figure 1: Sorption Isotherm Curve

3.2. Test case details for model applicability

A simulation-based study is carried out to observe the hygroscopic behaviour of lime and cement plaster. EnergyPlus has three different models for simulating heat and moisture transfer in buildings [5]. Conduction transfer function (CTF) model is the default model and provides quick results. Although it considers heat transfer of the building envelope with indoor and outdoor environments, it doesn't account for the moisture transfer across the wall surface. The indoor relative humidity is calculated by mass balance without considering the wall interactions. On the other hand, the combined heat and moisture transfer (HAMT) model considers detailed moisture interaction with the envelope. It considers the hygroscopic characteristics of the building materials, such as sorption/desorption curves, porosity, water absorption, and water vapour permeability. Qin & Yang [12] evaluated the building energy consumption for three different climate conditions to compare the accuracy of different models of EnergyPlus. They concluded that the HAMT model is the most accurate model for simulating heat and moisture transfer across the envelope. From the literature, it is understood that detailed and intensive simulation studies have been carried out worldwide. However, such hygrothermal studies are lacking in the Indian context with typical and new construction materials. One reason for fewer studies with the HAMT model is the lack of detailed hygrothermal properties. Lime and cement plaster are the commonly used finishing materials in India. Studies on moisture-buffering effects of lime and cement plaster, especially in Indian climatic zones are lacking. In this work, both CTF and HAMT models are employed to compare the performance of lime and cement plasters.

The CTF and HAMT models of EnergyPlus have been previously verified in the literature [12]. However, a primary verification of these models is carried out to check if physically realistic results are obtained in case of lime and cement plaster. The verification is carried out by simulating the BESTEST geometry [15] to avoid complex construction details and represent a test case to study the fundamental physical behaviour of lime and cement plaster. Several authors [11,16,17,18] have considered this model for hygrothermal analysis. The BESTEST geometry is 6m x 8m x 2.7m in dimension with no openings. The exterior wall assembly is of clay-brick with internal and external wall finishes such as lime plaster or cement plaster. The composition and configuration of the envelope chosen in this work are shown in Figure 2. A constant air change rate (ACH) of 0.5h-1 is maintained in the building throughout the day. The indoor condition (indoor air temperature and relative humidity) is not maintained in this case.

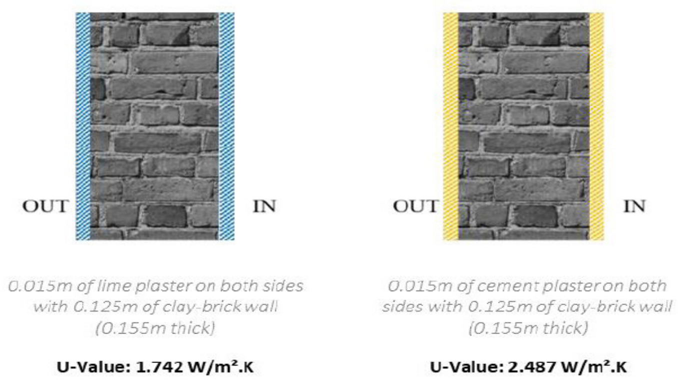

Figure 2: Typical sections of the envelope: lime plaster and cement plaster space

3.3. Test case details for parametric study

After verifying the model appropriateness, parametric studies are carried out in free-floating and air-conditioned modes to evaluate the impact of moisture-buffering on building energy consumption. The indoor air temperature range of 26 – 32°C and relative humidity range of 30 – 70% is considered for defining the comfort band. The commercial sector accounts for 8.6% of total electricity consumption in India and it is increasing rapidly due to urbanization [19]. Therefore, a test model of a low-rise commercial building model is considered for the parametric study. The low-rise office building model details and specifications are taken from the ASHRAE reference building [20]. The external envelope construction has clay-brick as masonry material but differs in the type of plaster. One case has lime plaster, while the other has cement plaster. However, this work does not consider the mortar, as EnergyPlus is incapable of modelling thermal bridging [21].

To study the indoor environment in free-floating mode, the comfort hours are compared with both the plaster materials. In the air-conditioning mode, variable refrigerant flow (VRF) with a coefficient of performance (COP) of 3.49 is used as the cooling system to maintain the indoor air temperature. An electrically heated steam humidifier with a fan is used to maintain indoor relative humidity. To observe the impact of five climate zones, five cities in India are selected based on NBC 2016. The same is:: Ahmedabad (23.02° N, 72.57° E): Hot-dry, Tiruchirappalli (10.79° N, 78.70° E): Warm-humid, Bangalore (12.97° N, 77.59° E): Temperate, Delhi (28.70° N, 77.10° E): Composite and Dehradun (30.31° N, 78.03° E): Cold [22].

4. Results

4.1. Model applicability

Annual simulations are carried out with the BESTEST case [15] as mentioned in Section 3.1. The cases considered are i) clay-brick wall with cement plaster in an only thermal model (C-CTF) ii) clay-brick wall with cement plaster in the hygrothermal model (C-HAMT) iii) clay-brick wall with lime plaster in the hygrothermal model (L-HAMT). These cases are simulated for cities in hot-dry (Ahmedabad) and warm-humid (Tiruchirappalli) climate zones. Figure 3 shows the results for these cases in the respective climate zones.

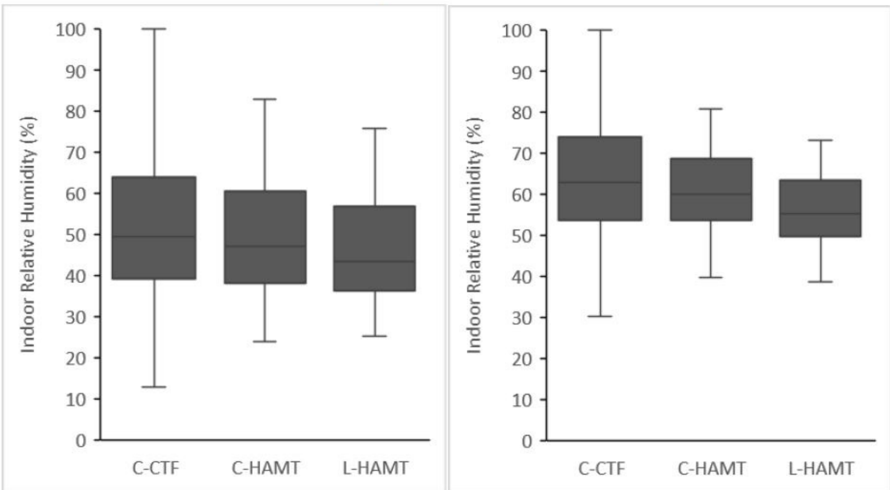

Figure 3: Indoor relative humidity comparing CTF and HAMT model (a) hot-dry (b) warm-humid

In hot-dry climate, 'C-CTF' predicts the highest indoor relative humidity of 96%. In 'C-HAMT', the highest predicted indoor relative humidity is 81%. Therefore, a reduction of 15% compared to the CTF model. While using lime plaster (L-HAMT), the maximum humidity is 78%. That is a difference of 3% more indoor humidity between cement and lime-plastered space. The difference between maximum and minimum values of indoor relative humidity for 'C-HAMT' is 10%, while 'L-HAMT' is 18% compared to 'C-CTF'. Thus, the overall range in the 'CCTF' case shows a wide distribution of data, whereas, in the other two cases (C-HAMT and L-HAMT), it is less dispersed and further reduced with lime (L-HAMT). While comparing the interquartile ranges, the difference in third and first quartile values of indoor relative humidity reduces from 25 in 'C-CTF' to 23 in 'C-HAMT' and 21 in 'L-HAMT'. In warm-humid climate, a reduction of 19% in indoor relative humidity is observed in 'C-HAMT' compared to 'C-CTF' model. Similar to hot-dry, the amplitude of lime plaster 'L-HAMT' is 7% less than cement plaster 'C-HAMT'. An absolute difference of 10% and 3% relative humidity between 'C-HAMT' and 'L-HAMT' in warm-humid and hot-dry climate. This is because, with a decrease in the vapour diffusion resistance factor of the finishing material, the moisture-buffering effect increases. Therefore, cement plaster has a high-water vapour diffusion resistance factor of

25.18 and that of lime is 5.74. The above results show that the HAMT model accounts moisture-buffering effect on the building walls compared to the CTF model. This reinforces the need for the HAMT model over CTF for evaluating the detailed analysis of energy consumption by walling systems. Also, it establishes that the moisture-buffering effect increases with the hygroscopic nature of lime plaster.

4.2. Parametric analysis

In the HAMT model, the effect of heat and moisture movement was prominently visible in the previous section. HAMT model is further applied to conduct parametric analysis. It is carried out in two modes: free-floating and air-conditioned mode. This study of heating and cooling energy demand has been carried out to ascertain the degree of influence of hygroscopic materials (lime and cement plaster) on energy demand for five climate zones of India. As mentioned in previous section 3.2, the low-rise office building has been carried forward for the parametric analysis [20].

4.2.1. Free-floating

Free-floating mode is considered with a constant air change rate and with no mechanical equipment. Air temperature and relative humidity are compared based on the aforementioned comfort band setpoints. Figure 4 shows the influence of porous and moisture-absorbing materials on annual comfort hours for warm and humid climates. A typical climate type is studied for analysing free-floating conditions in lime or cement-plastered buildings.

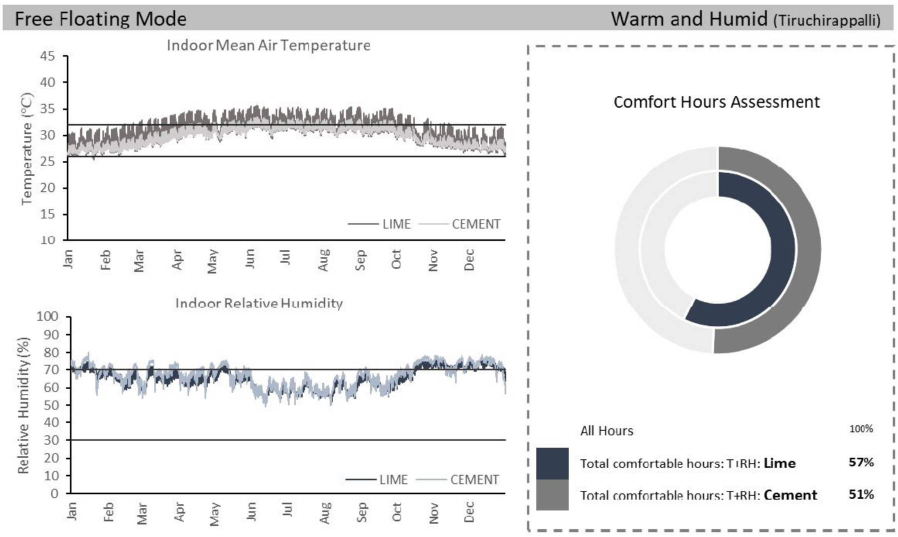

Figure 4: Free-floating Mode: Hourly analysis (L) and Comfort Assessment (R)

The summer indoor air temperature in both lime and cement-plastered spaces lies above the upper limit of the comfort band of 32°C. Whereas in winter, the temperatures lie within the comfort range for both materials. As lime-plastered space has higher peak temperatures during summer and monsoon season, cement-plastered space is 10% more hours in the comfortable range of temperature. For 73% of the hours, the lime-plastered space is in the comfortable range of indoor relative humidity of 30 – 70% while the cement-plastered space is comfortable only for 63% of the total hours (Figure 4(L)). Here with a constant air change rate and no mechanical air-conditioning system, 57% and 51% of 8760 hours are in the combined comfortable range of indoor air temperature and relative humidity for lime and cement respectively (Figure 4(R)). Overall, the hours with comfortable indoor air temperatures and relative humidity in lime are 6% higher than in cement-plastered space. The above observation confirms that lime has the potential to reduce energy requirements to make the space comfortable.

4.2.2. Air-conditioned

The impact of moisture-buffering through building walls was seen in the previous section (4.2.1.). A variation in indoor air temperature and relative humidity and the number of comfort hours was noted. This section assesses the impact of moisture transfer on annual energy consumption. The objective is to identify the magnitude of possible savings due to lime or cement plaster. The reduction in overall cooling load is shown in Figure 5 (L). With lime plaster, the reduction in cooling load is between 5% - 15% for all climate types. This is due to the lower thermal conductivity of lime plaster (0.16 W/m-K) than cement plaster (1.58 W/m-K). The reduction in overall heating load for all climates is shown in Figure 5 (R). For HD, WH, and TE climate, heating load savings are in cement-plastered space by upto 21%. Whereas, in CO and CD climates, lime-plastered space has higher heating energy savings.

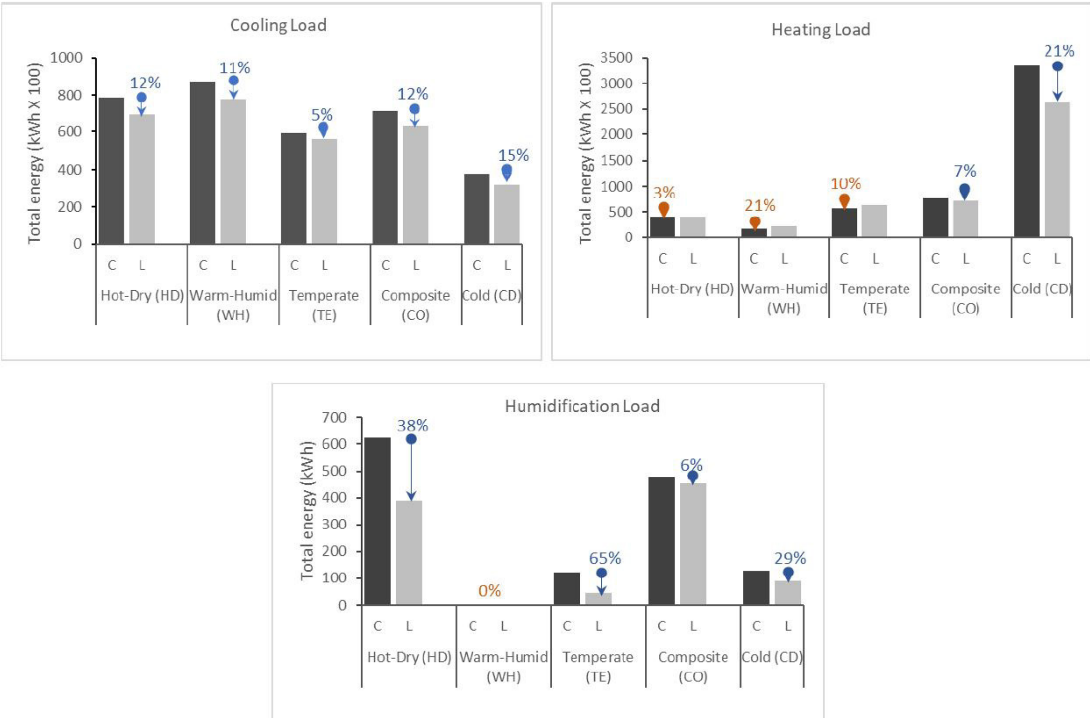

Figure 5: Comparison of energy requirement in lime and cement plaster

The humidification loads are 38% and 65% higher in cement-plastered space in HD and TE climates. Figure 5 (B) shows the reduction in humidification load in lime-plastered space to maintain indoor comfort. This is because heating and humidification loads are related to the moisture-buffering effect of the finishing material in the respective climates.

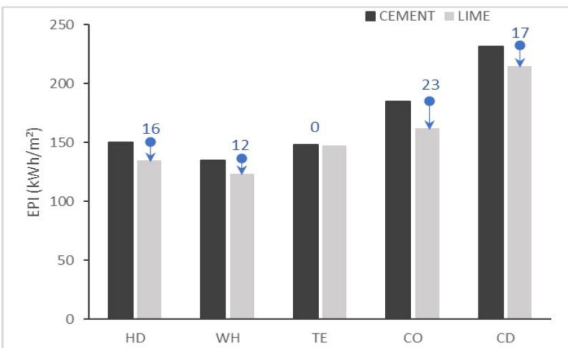

Figure 6: Energy Performance Index (EPI) reduction between cement and lime plastered buildings.

The potential for annual energy saving for the five climate zones is shown in Figure 6. An absolute difference of 12 – 23 kWh/m² is observed between lime and cement-plastered low-rise buildings around five climate zones of India. The maximum reduction is observed in composite, cold and hot-dry climates. Therefore, a substantial reduction in energy consumption due to lime plaster.

5. Discussion

In India, major parts of the country still rely on conventional finishing material, cement plaster. This study focuses on two plastering materials which are available in the Indian construction industry. Lime plaster was a heavily used material in the housing sector before industrialization [13]. The energy saving potential of lime plaster creates an opportunity to bring back lime to the market. This study is limited to wall finish, but the mortar is a prominent binding layer in the walling system. It is a thin layer between the bricks (usually 1-3 cm), therefore in a 1sq.ft. of wall construction almost 17 - 20% would be mortar. Due to the limitation of EnergyPlus in modelling thermal bridging, the energy consumption due to the mortar in the walling system is not considered in this study. Hence, the aspect of mortar needs to be studied to calculate its impact on energy savings due to lime plaster over cement. If there is an overall energy reduction, there would be a reduction in estimating peak load requirements in system design. Also, the conventional method of calculating the peak loads of a building is only through heat transfer calculation. The moisture-buffering phenomenon is not considered, which also contributes to the higher estimation of the peak load of an air-conditioning system. A more detailed study is required in calculating load requirements would help in reducing system sizes. Further research needs to be conducted to analyse the savings potential in annual energy consumption over ease of construction technology.

6. Conclusion

The conventional method of annual energy-used calculation is only dependent on one variable i.e., heat flux with the indoor and outdoor surface of the walling system. It does not calculate the moisture transfer with the surface of the walling system. It is observed that the CTF model, the conventional method predicts upto 15 - 26% higher absolute relative humidity than the HAMT model. This established the need to study both heat and moisture transfer for building energy assessment. Comparing the moisture-buffering factor between lime and cement-plastered space, a reduction of 6 - 10% in absolute relative humidity in lime-plastered space is observed. This is because lime plaster has a lower vapour diffusion resistance factor and higher porosity. Further, a low-rise office building with internal loads is studied for parametric analysis. In free-floating mode, the lime-plastered building shows the addition of 6% hours in annual comfort hours i.e., 536 hours out of 8760 hours. This implies that cement plaster is an energy consuming material. To quantify the energy savings for the five climate zones of India, the indoor condition is controlled with an air-conditioning system to maintain indoor air temperature and indoor relative humidity. It shows an overall energy reduction of 12 – 23 kWh/m² in the lime-plastered building while comparing five climate zones of India. Overall, lime as a wall finish material plays a substantial role in moderating indoor relative humidity. This helped in the reduction in energy requirement for space conditioning. The analysis proves to revive lime as a finishing and binding material for a sustainable future. It also evokes, along with focussing on ease of construction technology, a data-informed decision regarding the walling system for respective climate zones can help in making an informed decision.

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