

## An experimental investigation on the impact of lime and cement mortar/plaster material on the indoor hygrothermal environment of test spaces

Ayushi Singh<sup>1\*</sup>, Rashmin M. Damle<sup>1</sup>, Nikhil Bhesaniya<sup>2</sup>

1: CEPT University, Ahmedabad, India

2: Center for Advance Research in Building Science and Energy, CRDF, Ahmedabad, India

ar.ayushisingh@gmail.com

### Abstract

The study's objective was to investigate and quantify the heat and moisture transfer through two walls of a 1m<sup>2</sup> area facing south, located in Ahmedabad, Gujarat, India. One of the walls was constructed with lime mortar, and the other with cement mortar and XPS (Extruded Polystyrene) blocks of size 230 x 100 x 75 mm, coated with an inner plaster layer of the same materials. Other walls were made up of EPS (Expanded Polystyrene), thus limiting the heat and moisture transfer only through mortar layers. The mortar joints on the exposed wall accounted for 17% of the total surface area of the wall. The study monitored the temperatures, relative humidity, and surface temperatures inside the two identical test cells of 1 m<sup>3</sup> volume each for 54 days from 1st March to 23rd April 2023. Also, a 3-day moisture test was carried out to check the effect of vapor permeability. The research questions are as follows.

- Is the hygrothermal environment different for cement and lime mortar cells?
- Will the cement mortar produce higher heat ingress due to high conductivity?
- Will the higher thermal mass of cement make a difference in the hygrothermal environment of the cells?

**Keywords** - Lime plaster & mortar, hygrothermal behaviour, moisture buffer, thermal bridging, vapor transmission

### 1. Introduction

The world's energy consumption has been overgrowing in the construction sector, causing a 43% increase in CO<sub>2</sub> emissions over the last two decades. In India, Energy consumption has doubled since 2000 [1] (IEA,2021) and is expected to double by 2040 [2] (IEA, 2020). India is required to decrease its greenhouse gas emissions to 35% by 2030 in response to the challenges posed by climate change [3] (INDC,2022). Therefore, there is a need to adopt "green technologies" based on renewable or recycled materials in construction, to significantly reduce buildings' carbon footprint and energy consumption (International Renewable Energy Agency [4] (IRENA),2019).

The need for study can be justified through results found in studies based on thermal bridging and moisture buffering through mortar. Mortar has been a thermal performance deficiency in the masonry wall [5] (Ismail et al.,2022, p.529), as it reduces 12% thermal resistivity of the wall [5] (Ismail et al.,2022, p.533) and 38% in an insulated wall [6] (Al-Sanea & Zedan,2012, p.591). Mortar joints cause an 11% increase in cooling and heating loads [7] (Zedan et al.,2016, p.17). Ignoring thermal bridging overestimates, the wall R-value by 26% [5] (Ismail et al.,2022, p.545). Hygroscopic interactions of the material change the room temperature by 2-3°C [8] (Gaur & Bansal, 2002, pp. 15-16). Moisture buffering can help with a 20% reduction in heating energy [9] (Damle and Rawal's,2018, p. 478). Therefore, neglecting these phenomena can overestimate energy loads and wall R-value. Studies on the effect of heat and moisture transfer through exposed walls with lime mortar have not received significant attention in the literature. Also, simulation tools do not consider the moisture buffering capacity of materials, resulting in overestimated energy use. Thus, the present study considers the effect of thermal bridging through mortar layers and its moisture buffering capacity by carrying out, one-to-one comparison between cement and lime mortar.

## 2. Methods

### 2.1. Selection of methodology

From the literature, it was found that most biobased hygrothermal research was based on a wall scale - using a climate chamber. The studies not based on the experimental approach suggested that there is a need to carry out experiments for realistic observations and under real variable climatic conditions [10] (Moujalled et al., 2015, p. 535). Therefore, an experimental study was undertaken in this study. Thomas Busser (2018), [11] (p.16) suggested that the scale models can be validated using experimental data within test walls, i.e., the characteristic sizes of samples - 1 m x 1 m x 0.11m thick. It was also stated that for testing purposes, the walls can be exposed to controlled conditions in climatic chambers or to outdoor conditions on one side. Therefore, the scale of the model selected in the current study is 1 m<sup>2</sup>, and the models are tested in actual outdoor conditions. Experimental investigation study proves to be a better approach for this study as lime mortar composition varies with region, thus getting the exact values for its properties like conductivity, etc., is difficult. Hence a simulation approach would prove to be beneficial due to the uncertainty in the thermophysical properties. Moreover, for the comparison of two materials, getting two identical buildings with two distinct construction materials is difficult.

### 2.2. Test cell development

For the study, a location in Ahmedabad, Gujarat, India, has been selected. The city has a hot and dry climate. For this location, the shading mask of the two test cells was analysed using the Andrew Marsh Shading Box tool for any shadows falling on the cells. It was observed that the cells are not shaded by surrounding objects, there was no mutual shading, and both test cells have the same environmental conditions and solar exposure.

To ensure that the walls are made of the same size and mortar is of the same area, a 12mm PVC frame was made. Inside this frame, a 75mm thick XPS layer was added to provide insulation from edges and prevent edge effects.

Along with that, layers of 12mm XPS were added on either side of the wall, between the outer frame and inner frame, to prevent direct contact of the outer frames with the wall. The outer frame was made of 8mm Plywood, and the inner frame was made of 17mm thick PVC, as seen in Figure 1. For the construction of walls, 120 XPS blocks were cut in the size of 230 \* 110 \* 75mm which corresponds to a typical brick size. A top and bottom groove of 10 mm was made in each brick for better bonding with mortar, as shown in Figure 2. Similarly, other EPS walls of 100mm thickness were also cut as per the requirement. The cutting process was followed by the laying of XPS blocks and mortar. Twelve layers of XPS block with a 10mm thick mortar layer between each layer were laid, as shown in Figure 3. A layer of 15mm thick plaster was given on the inside, as shown in Figure 4.

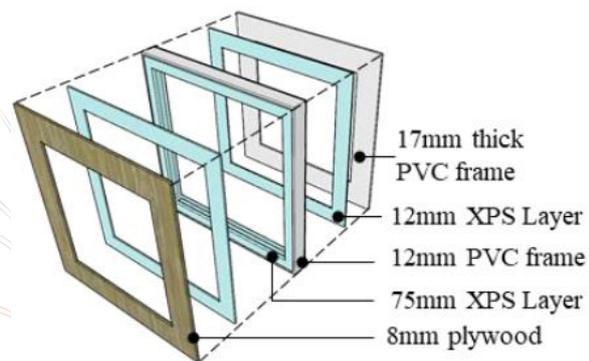


Figure 1: Schematic of the support frame

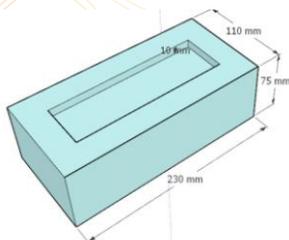


Figure 2: Size of one XPS block with 10mm groove



Figure 3: Laid blocks with mortar



Figure 4: Inner 15mm plaster in cement

## 2.2. Test cell development

As per IS 1661,1972, for a single layer of plaster, 10-15mm thickness of plaster is recommended with a mortar mix of 1:4 ratio of cement: sand. For lime, as per IS 2394, 1984, plaster thickness of 15mm is recommended. To keep the ratio the same in both test cells, lime mortar and plaster were also made with a 1:4 ratio of lime: sand. The exact mix ratio was used for plaster and mortar to maintain the same properties. The ready mix of lime mortar was delivered on site. To test the proportion of binder and aggregate in the lime mix, an acid dissolution test was carried out. The section in Figure 5, gives the entire detail of wall assembly. After wall construction, the cement and lime walls were cured for a period of 14 and 10 days, respectively (26th December to 8th January 2023). As per IS 456, 1978 curing period of 14 days in cement and 7 days for lime is sufficient. The walls were left to dry for 52 days before installing the loggers. The walls were transported to the site, and the test cells were assembled, as seen in Figure 7. Both the test cells have an inner volume of 1m<sup>3</sup>, and the exposed walls facing south have a 1m<sup>2</sup> surface area. The mortar accounts for 17% of the total south wall surface area. The assembled test cell model with wall composition is shown in Figure 6.

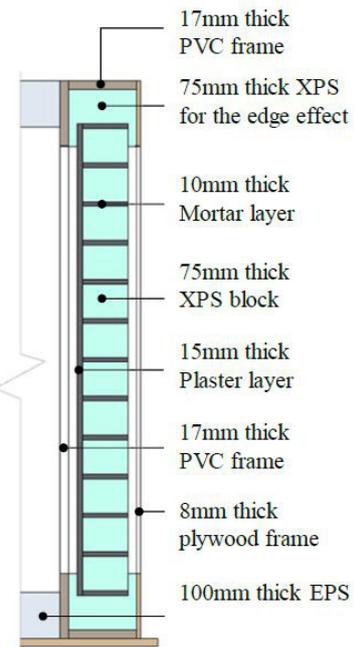


Figure 5: Section of test wall with outer support frame

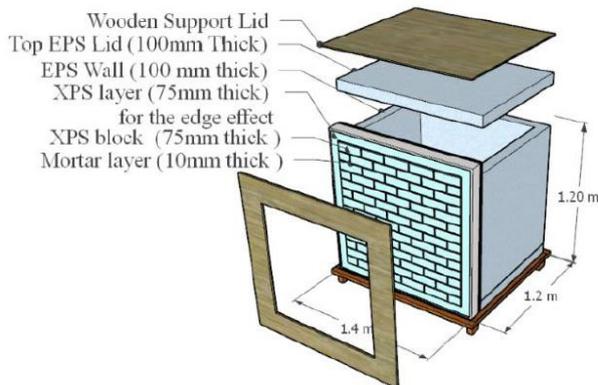


Figure 6: Experimental set-up showing wall composition.



Figure 7: Experimental set-up on-site

## 2.3. Material Selection Criteria

The main objective of the material selection is to make all the surfaces adiabatic and keep the mortar layer as the only element through which heat and moisture transfer occur. Also, for the wall, to nullify the effect of the masonry unit, XPS blocks have been used, which have low conductivity for minimum heat transfer. Both cells are identical, differing only in mortar material. This ensures a fair basis for comparison. Any differences observed can then be attributed to the plaster and mortar material. Simulation software does not capture the physics entirely due to the limitation of numerical models and uncertainty in hygrothermal properties of materials due to variable compositions. The experimental approach also gives an advantage over simulation as the models are exposed to real dynamic weather conditions.

## 2.4. Data gathering

Heat transfer and moisture transfer were studied by measuring variables like inside air temperature, inside and outside surface temperatures, and relative humidity using Hobo Loggers MX1104. Identified variables and instruments are shown in Table 1.

Table 1: List of variables and instruments used.

Legend	Variable	Instrument Used	Measurement
●	Air Temperature and Relative Humidity	Onset HOBO (MX1104) Analog/Temp/RH/Light Data Logger	10 Minutes Logging
●	Indoor Surface Temperature		
●	Outdoor Surface Temperature		

## 2.6. Measurement protocols

After calibration, the loggers were installed in the test cells, as shown in the perspective sectional schematic Figure 8. The surface probe was placed at the center of the inside and outside walls at a height of 480 mm from the finished floor level. This avoided the edge effect from the ceiling and floor as marked in red and yellow. The logger for measuring indoor conditions like air temperature and RH was placed at a height of 100mm above the finished floor. The logging period for the study started on 1st March 2023, with a logging interval of 10 minutes for each parameter. The readings for indoor conditions, relative humidity, and surface temperatures were taken till 23 April. While taking the measurements, the surface probe was covered with a foam layer, so that it does not get affected by air temperature or solar radiation falling on it. The outdoor logger was placed inside a well-ventilated box in the shade such that it was protected from direct sunlight, rain, and local effects.

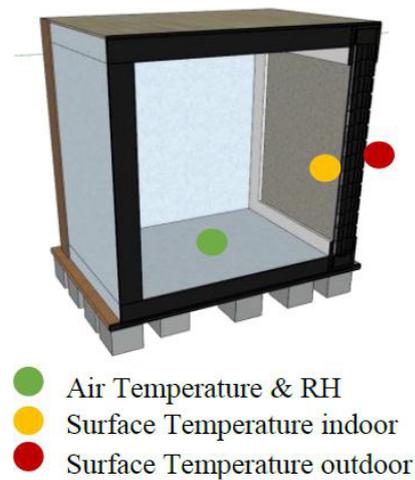


Figure 8: Perspective section of the cell, showing the placement of loggers.

## 2.7. Moisture test procedure

In this test, an equal amount of water was sprayed on the mortar layers of each test cell, using a spray bottle. The pressure of the spray and the distance of the nozzle from the wall were kept constant to have an even distribution of water on the entire wall. To ensure an equal quantity of water, the number of sprays on each mortar layer was maintained. The exact amount of water was filled in the bottle for each round of spraying. This test was carried out for 3 consecutive days from 10th April to 12th April in the evening hours starting from 5:30 pm. Figure 9 shows the spraying of water with the help of a spray bottle.



Figure 9: Spraying of water on the mortar layers.

## 2.8. Testing Properties of Material

Six samples (size of 9cm x 9cm x 2cm ) of lime mortar and cement mortar were made and tested at CARBSE. The material properties were tested as per ASTM standards. Table 2 shows the properties derived from experiments.

Table 2: Material properties

Sample type	Density (Kg/m <sup>3</sup> )	Thermal Conductivity (W/mk)	Thermal Diffusivity (mm <sup>2</sup> /s)	Specific heat (kJ/kg.k)	Thermal Mass (kJ/m <sup>3</sup> .K)	Permeance of the test specimen (ng·m <sup>-2</sup> ·s <sup>-1</sup> ·Pa <sup>-1</sup> )	Permeability (ng·m <sup>-1</sup> ·s <sup>-1</sup> ·Pa <sup>-1</sup> )
Cement Plaster	1875.5	1.14	1.09	0.57	1081.80	1763	33
Lime Plaster	1571.2	0.77	0.78	0.64	1011.70	2626	48

From the results, the conductivity and thermal mass of lime mortar were 32.45% and 6.5 % less than cement mortar, respectively. Water vapor permeability in lime mortar was 31.25% higher than in cement mortar.

### 2.9. Data analysis

The two test cells have identical geometry and construction, except for the plaster and mortar material. Thus, a student's t-test was employed to detect any differences in the behaviour of the two test cells. The t-test determines if there is a significant difference in the data being analysed. If the value for the calculated p-value is less than 0.05, then the data sets compared are considered significantly different. The gathered data from the instruments was analyzed by variance, which could be either unequal or equal. Outliers in the data were eliminated by utilizing the interquartile range (IQR) method.

## 3. Results & Discussion

In this section, observations from the measurements carried out for a period of 54 days from 1st March till 23rd April 2023 have been recorded and discussed. The results and observations have been covered in 3 sections, air temperature, surface temperature, and relative humidity. In the last section, indoor conditions of the test cells have been compared with the IMAC band for calculating comfortable hours.

### 3.1. Air temperature in test cells

To see the daily trend of the air temperature inside the test cells, two peak days with high outdoor temperatures were chosen in March month and compared with respect to the outdoor temperatures, as seen in Figure 10. By analyzing data from these 2 days, the inside air temperature peaks at around 40 °C whereas the outside temperature is around 35 °C. In comparison to the cement cell, the lime cell consistently displays indoor temperature readings that are 1 – 1.4 °C lower. Cement reaches a peak temperature of 40.5°C at 5:20 p.m., whereas lime reaches a maximum temperature of 39°C at 5:30 p.m. Both cells have a 10-minute difference. Looking at the 2 triangles under the curve, the heating rate is higher than the cooling rate in both cells by 4 hours. During the day, the temperature increases rapidly after 7:30 a.m. and decreases gradually after 5:30 p.m. A similar trend can be observed for other days. Figure 11 shows the difference in indoor air temperatures between cement and lime test cells that were analyzed and compared for two months. The positive values for both months show that the indoor air temperature inside the lime test cell stays cooler than the cement cell for the entire period of measurement from March to April. The maximum difference in the air temperature between the two cells is 1.44° C and 1.0° C. The average difference in the air temperature of both cells is 0.6 and 0.4 ° C for March and April, respectively. A t-test was conducted to examine the variation in indoor temperature between the lime and cement test cells, and the resulting p-value was found to be 0.0. As the p-value is less than 0.05, it can be said that the difference in the indoor temperatures of the test cells is significant.

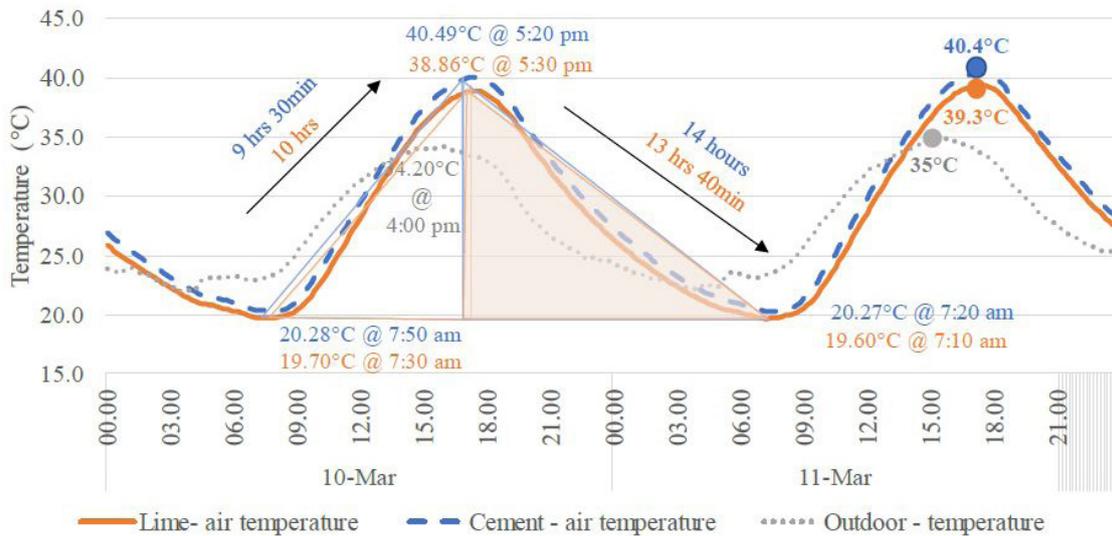


Figure 10: Comparison of air temperatures of both cells for 2 peak temperature days in March

From the above observations, lime cells consistently display indoor temperature readings that are 1 – 1.4°C lower than cement cells. With the higher temperatures during peak summer, higher differences are expected in the air temperatures inside the cells. Also, the rate of heating and the cooling of air temperatures inside the cement cell is higher than in the lime cell. The lime cell has 3% higher temperatures falling between 15 to 25 °C as compared to cement. This shows that lime cells stay cooler than cement cells. Therefore, cement cell has shown more heat ingress and more heat storage till date due to its 6.5 % higher thermal mass and 32.45% higher conductivity than lime. Therefore, the overall indoor.

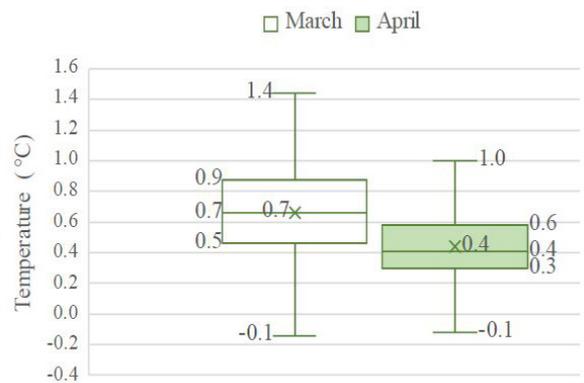


Figure 11: Difference of air temperature between temperatures are higher in the cement cell. cement & lime cell (Cement - lime)

### 3.2. Surface temperatures in the test cells

The difference in the air temperatures, as discussed in section 3.1, can be explained by the study of surface temperatures. It was observed that the air temperature is linearly in relation with the inside surface temperature in both the test cells. Therefore, as the inside surface temperature changes with respect to outdoor conditions, the air temperature inside cells is also being affected. To study the trend of surface temperatures, a week in April was selected. It was observed that the outside surface temperatures stayed higher than the inside surface temperatures for all the days. The outside surface temperatures reached up to 45°C during the day, due to solar radiation falling on the wall. The inside surface temperature stayed around 40°C during the day. There was a reduction in the amplitude of the inside surface temperature curve compared to the outside by around 5°C.

To understand the trends of outside and inside surface temperatures, as seen in Figure 12, the daily trends for 2 days in March month were selected. 10th and 11th March were the warmest days of March month, with the maximum outdoor temperatures of 35°C. From Figure 12, it can be observed that for 10th March, the maximum outside surface temperature (marked at point B) is 47.9°C and 47.65°C in the cement wall and lime wall, respectively. For the same day, the maximum inside surface temperature (marked at point D) is 41.18°C and 39.55°C in the cement wall and lime wall, respectively. Thus, having a reduction in amplitude of 6.7°C and 8.1°C in the cement wall and lime wall, respectively, which shows lime has a more damping effect (reduction in amplitude) than cement. A similar observation can be made for the 11th March. Also, the outside and inside surface temperature curves have a horizontal shift, showing the time lag. The maximum outside surface

temperature (marked at point B) in the cement wall was at 3:10 p.m., and in the lime wall, it was at 3:00 p.m. The maximum inside surface temperature (marked at point D) in the cement wall was at 5:20 p.m., and in the lime wall was at 5:30 p.m. This shows that the time lag in the cement cell was 2 hours 10 minutes, and in the lime wall was 2 hours 30 minutes. The two cells have a 20 minute difference. This trend could be seen for all the other days, where lime always had more time lag than cement. The downward slope in both curves shows the cooling rate. It was observed that the cooling rate in the lime wall was slower than in the cement wall. The upward curve shows the heating rate. It was observed that the heating rate (from point C to D) for inside surface temperatures was slower in the lime wall as compared to the cement wall.

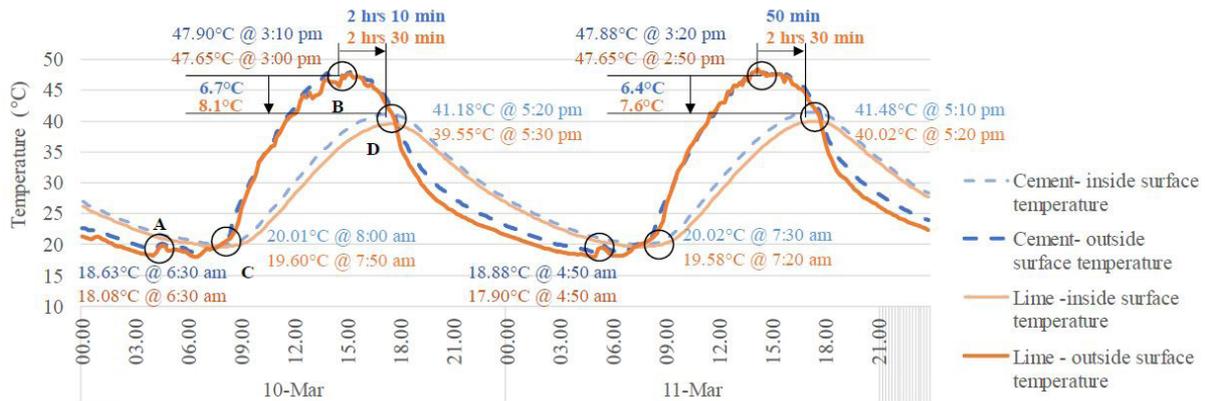


Figure 12: Comparison of cement and lime surface temperatures for 2 days

The difference in outside and inside surface temperatures of both cells for the entire period of measurement were observed. During the daytime, the maximum difference between outside and inside temperatures was 13°C in the cement cell, while the same for the lime cell was 15°C. At night the maximum difference between outside and inside temperatures was 8.7°C in the cement cell, and 10.8°C in the lime cell. Thus, lime walls always had a higher difference between outside and inside surface temperatures than cement walls. Figure 13 shows the surface temperature differences between the cells. Even though both cells were exposed to the same environmental conditions and facing south direction, the outside surface of the cement wall got heated up more than the outside surface of the lime wall. It can be observed that 75% of values lie above zero. This shows that cement wall surfaces remain warmer for more than 75% of the time than lime wall surfaces.

From the above observations, it was found that there was more time lag (horizontal shift of temperature curve) and more damping (amplitude reduction) observed in the lime cell. Lime walls always had a higher difference between outside and inside surface temperatures than cement walls. Also, the outside surface temperature in the lime wall was lower than the cement wall (Figure 13). These observations can be attributed to 32% lower conductivity of lime mortar than cement mortar. Therefore, the rate of heat transfer in cement mortar wall was higher than in lime mortar wall. Inside surface temperatures of lime mortar wall are 2.7°C lower than cement mortar wall. This difference in surface temperatures would affect the MRT (Mean radiant temperature) and occupant comfort.

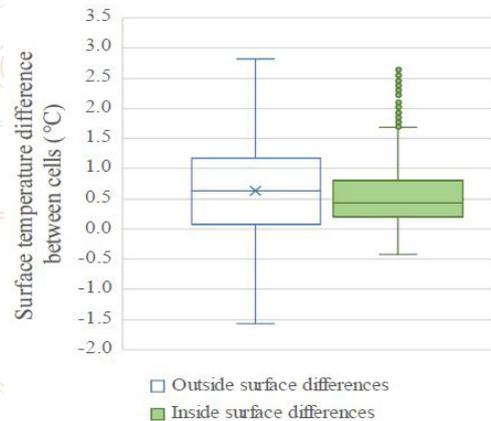


Figure 13: Difference in surface temperatures

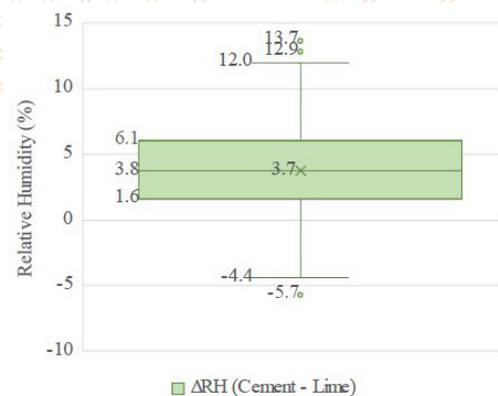


Figure 14: Difference of RH between cement & lime

### 3.3. Relative Humidity in the test cells

Figure 14 shows the difference between the RH of both cells for the entire period of measurement. The difference is calculated by subtracting lime RH from cement RH. The lime cell had a lower RH than the cement cell by a maximum of 13.7% and remained less than cement for more than 75% of the time. Figure 15 shows the RH evolution for 2 days. The same two days, 10th and 11th March, have been considered for analysis. It can be observed that the RH trend of lime cell and cement cell was similar for both days. The  $\Delta$  RH line in the graph shows the difference between the RH of both cells, which stays above zero. This indicates that cement has 9% to 4% higher RH than lime cells throughout the day. Similar observations can be made for all the days. As lime mortar is more porous and less dense, it can absorb and release moisture better than cement mortar. The consistent lower level of RH inside the lime cell shows that lime mortar has more moisture buffering than cement mortar.

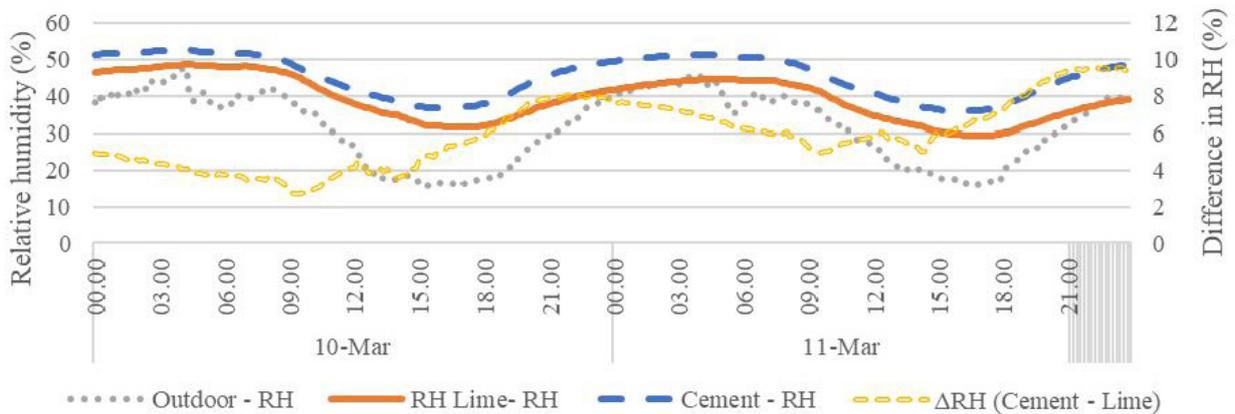


Figure 15: Comparison of RH in cement & lime cells for 2 days in March month

Figure 16 shows the result of a moisture test, which was carried out for 3 consecutive days, that is on 10th, 11th and 12th April. Before the test, the cement cell had more RH level than the lime cell throughout the day as can be seen on the 9th April trend in Figure 16. After the test, the lime cell shows 6 to 13% more RH than the cement cell for the next 7 days. After the 7th day from the test, the moisture in the lime cell reduced below the cement RH level. Even after the moisture test, the maximum RH level in the cement cell reached only till 50% whereas in the lime cell it reached 63%. This clearly shows that lime mortar has more vapour permeability than cement mortar.

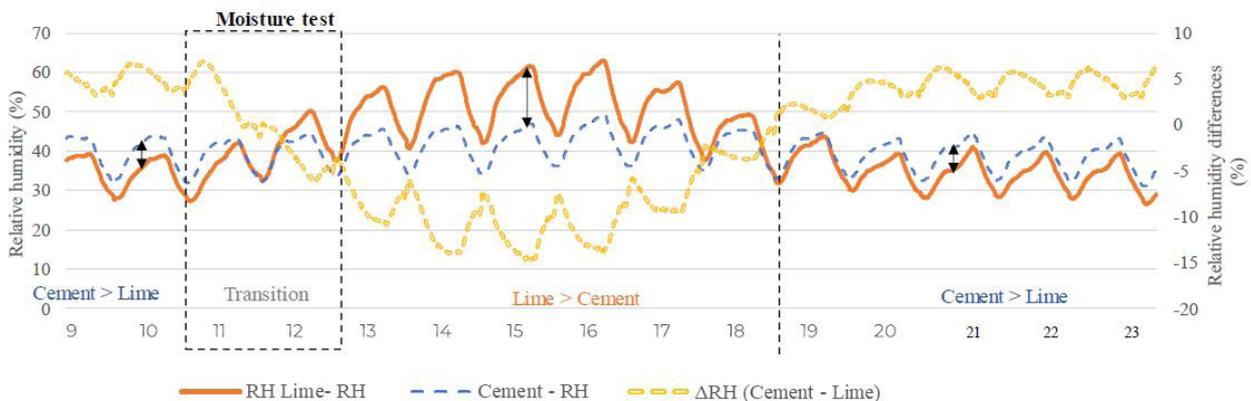


Figure 16: Comparison of RH of cement & lime cells for a period 12 days (moisture test from 10th to 12th April)

The above observations show that lime cell had lower RH than cement cell by a maximum of 13.7% and remained less than cement for more than 75% of the time. Also, the mean RH in lime remains lower than in cement by 6.5%. Lime has 24% more RH values falling between the band 20 – 40% and 24.7% lesser RH values falling between 40 -60% RH as compared to cement cell showing that

and 24.7% lesser RH values falling between 40 -60% RH as compared to cement cell showing that lime moderates indoor RH. Thus, the RH inside the lime cell remains lower than the cement cell. From the moisture test, it could be seen that the lime cell reached more RH levels than the cement cell. This is because the lime mortar allowed the water to pass through the surface (more vapour diffusion) as it had 31% more water vapour permeability than cement mortar.

### 3.4. Limitations & Future scope of work

The study had a few limitations like the indoor surface temperature was measured only at the center of the plastered wall, assuming a homogenized distribution of temperature over the wall surface, due to the limitation of the number of instruments. The unstable weather conditions with rain, thunderstorms, and overcast skies did not allow higher ambient temperatures. The results were expected to increase with higher ambient temperature during peak summer months. For Future scope, to understand the hygroscopic nature of lime, the same experiment needs to be carried out during monsoon months or maybe in a warm and humid climate. Temperature sensors may be installed for each of the EPS walls to measure their contribution to the indoor conditions. Globe temperature may be measured to see the effect of MRT, for better assessing the indoor conditions.

## 4. Conclusion

The objective of the study was to investigate and quantify the heat and moisture transfer through two walls of a 1m<sup>2</sup> area facing south. One of the walls was constructed with lime mortar, and the other with cement mortar along with XPS (Extruded Polystyrene) blocks, coated with an inner layer of plaster of the same materials. Other walls of the cell were made up of EPS (Expanded Polystyrene), thus limiting the heat and moisture transfer only through mortar layers. The mortar joints on the exposed wall account for 17% of the total surface area of the wall. The study monitored the temperatures, relative humidity, and surface temperatures inside the two identical test cells of 1 m<sup>3</sup> volume each. The test cell has been located in Ahmedabad, Gujarat, India. The city has a hot and dry climate. The measurements were carried out for a period of 54 days from 1st march to 23rd April 2023.

The results showed that in the cement mortar wall, which had 6.5% higher thermal mass and 32% higher conductivity than the lime mortar wall, allowed the heat during the day to flow quickly through the mortar layers, and high thermal mass enabled the material to store the heat. Consequently, cement mortar wall showed lower differences between the inside and outside surface temperatures than lime mortar wall. The higher surface temperatures in the cement wall directly impacted the indoor air temperatures of the cement cell, which were 1 to 1.44°C higher than the lime cell. At night the cement mortar slowly released the stored heat, leading to a warmer indoor environment. On the contrary, the lime cell maintained a cooler temperature throughout the day and night and showed more time lag. As a result, the inside surface temperatures of the lime wall were 2.7°C lower than the cement wall. Surface temperature directly impacts the Mean Radiant Temperature (MRT) and the overall comfort experienced by occupants. Also, lime cell showed lower relative humidity (RH) than cement cell by a maximum of 14% and remained less than cement cell for more than 75% of the time during the measurement period. The mean RH in lime cells remained 6.5% lower than cement cell. This was due to the higher moisture buffering in the lime wall, which allowed the mortar to absorb and release moisture over time and regulate indoor humidity levels in the lime cell. The 31.25% higher vapor permeability of lime mortar than cement mortar also allowed the water vapor to pass through mortar layers more easily. When the indoor conditions, with an indoor temperature above 30°C and with optimum RH of 30 to 70 %, were compared in both test cells, the lime test cell was 9% cooler than the cement cell.

## 5. References

1. International Energy Agency. (2021). Buildings. IEA, Paris. Retrieved from <https://www.iea.org/reports/buildings> (CC 4.0)
2. Hans, N., and Prasad, G. (2020). India 2020; Energy Policy Review. International Energy Agency (IEA). Retrieved from <https://www.iea.org/reports/india-2020-energy-policy-review>

3. India's Intended Nationally Determined Contribution. Retrieved from <http://www4.unfccc.int/submissions/INDC> (May 15, 2022)
4. International Renewable Energy Agency. (2019). Renewable energy in the construction sector. Retrieved from [https://www.irena.org/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA\\_REmap\\_Construction\\_2019.pdf](https://www.irena.org/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_REmap_Construction_2019.pdf)
5. Ismaiel M, Chen Y, Cruz-Noguez C, Hagel M. Thermal resistance of masonry walls: a literature review on influence factors, evaluation, and improvement. *Journal of Building Physics*. 2022;45(4):528-567. doi:10.1177/17442591211009549
6. Al-Sanea, S. A., and Zedan, M. F. (2012). Effect of thermal bridges on transmission loads and thermal resistance of building walls under dynamic conditions. *Applied Energy*, 98, 584-593. doi: 10.1016/j.apenergy.2012.04.038
7. Zedan, M., Al-Sanea, S., Al-Mujahid, A., and Al-Suhaibani, Z. (2016). Effect of Thermal Bridges in Insulated Walls on Air-Conditioning Loads Using Whole Building Energy Analysis. *Sustainability*, 8(6), 560. <https://doi.org/10.3390/su8060560>
8. Gaur, R. C., Bansal, N. K., (2002), Effect of moisture transfer across building components on room temperature. *Building and Environment* 37, 11-17 , doi:10.1016/s0360-1323(00)00094-9
9. Dale, A. and Awal, K. (2017). 'Hygrothermal performance of a Building across Diverse Climates of India. Centre for Advanced Research in Building Science and Energy, CEPT University, India Abstract HMT Model verification'
10. Moujalled, B., Aït-Oumeziane, Y., Samri, D., Stéphan, E., Moissette, S., Bart, M., & Lanos, C. (2015). Experimental and numerical evaluation of the hygrothermal performance of a hemp-lime building. *Academic Journal of Civil Engineering*, 33(2), 534-541. <https://doi.org/10.26168/icbbm2015.83>
11. Busser, T., Berger, J., Piot, A., Pailha, M., and Wołoszyn, M. (2018). Experimental validation of hygrothermal models for building materials and walls: an analysis of recent trends.