Examining Indoor Humidity Ratio in Response to Varying Window-To-Wall Ratio and Ventilation in Indian Climate Zones for Earth-Plaster Based Dwellings

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Abstract

Indoor Earth-based plasters in buildings offer indoor humidity regulation through moisture buffering. This study examines the applicability of using earth-based plaster indoors as a passive strategy for regulating indoor humidity for occupant comfort, using a simulation-based approach. BESTEST model geometry was used to simulate indoor T/RH conditions with varying window-to-wall ratio (WWR) and air changes per hour (ACH) for Indian climate zones using EMPD (Effective Moisture Penetration Depth) model in DesignBuilder tool. Experimentally derived material properties of earth-plaster were used as input to the model. The results revealed that the surface area available for moisture sorption/desorption or WWR is critical in determining the moisture buffering potential. High WWR leads to low surface area available for moisture buffering, resulting in high diurnal indoor Humidity Ratio peaks. Also, air changes per hour (ACH) have a significant bearing on moisture buffering. As the ACH increases, the peaks in indoor HR increase and become closer to the outdoor HR. In this chapter, monthly mean indoor HR for the given geometry was computed for the 5 climate zones of India. These results were examined vis-à-vis indoor comfort Humidity Ratio recommendations for comfort (accounting for thermal, skin, and respiratory comfort) for occupants in the rural Indian setup as reported in our previous work. The results suggest that earth-plaster for moisture buffering can be effectively used in Warm and Humid, Hot and Dry, and Composite climate zones of India. Using this strategy in Temperate and Cold climate zones was not found effective. Earth-based plasters are derived from natural soil, and their use can avoid cementitious (energy and carbon-intensive) material and support occupants' wellness simultaneously.

1. Introduction and Motivation

Earth is a hygroscopic material used as a surface finish in many traditional architectural styles. Apart from the thermal properties of earth, it also offers excellent indoor humidity regulation (Priyadarshani et al., 2021a, 2021b, 2022, 2023). Indoor humidity is critical to occupant comfort, particularly impacting thermal, skin, and respiratory comfort. Regulating indoor humidity passively can help significantly reduce the building heating/cooling load. Depending on building typology, indoor temperature and humidity vary diurnally and seasonally in response to the external climatic conditions. Diurnal variation in indoor humidity is also attributed to moisture buffering in the case of hygroscopic surface finishes. Earth-based materials have been examined in the light of thermal performance; however, their implication on indoor humidity is often overlooked in presently available design guidelines for comfort and energy efficiency, more so in the case of naturally ventilated buildings.

This study aims

1. To examine indoor Humidity Ratio in response to window-to-wall ratio and air change rates with the use of earth-based interior surface plaster.
2. To study the applicability of moisture buffering as a passive strategy for indoor moisture regulation in different climate zones of India.
3. To extend the adoption of earth-based plasters on conventional materials like fired-clay bricks masonry.

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2. Materials and Methods

2.1 Hygrothermal Characterization of Earth Plaster

Earth-based dwellings in India were examined for indoor humidity regulation and plaster samples from these dwellings were collected. These samples were subjected to lab-scale tests to investigate their hygrothermal performance. Measurement of density, thermal conductivity, and dynamic vapor sorption (DVS) for the samples was conducted. The experimentally measured values were then used as input parameters to a whole-building computational for further analysis. The average density and thermal conductivity of the earth-based plaster samples were 1150 kg/m^3, and 0.22 W/(m K), respectively. Further, the moisture transfer coefficients a, b, c, and d were calculated as 0.0139, 9.638, 0.025, and 0.676, respectively, based on the DVS. Material properties for the rest of the building materials were adapted from DesignBuilder material library.

2.2 Whole-Building Simulation

The ANSI/ASHRAE standard BESTEST (Building Energy Simulation TEST) case building was used to perform simulations using the DesignBuilder tool (see Fig. 1).

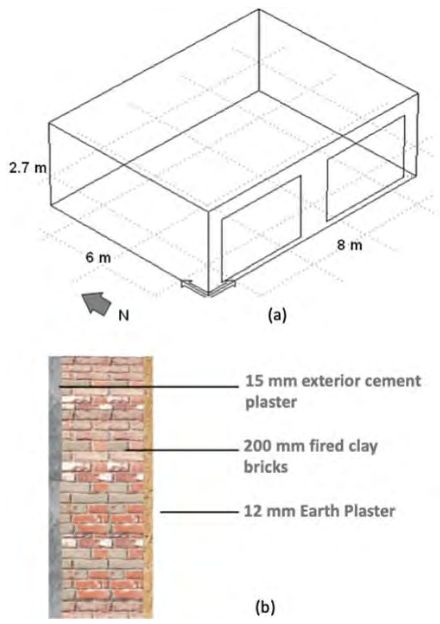

Fig. 1 – Building geometry used for simulation (a) BESTEST case geometry (b) Wall assembly details

The simulation model was set up with the envelope material being a burnt clay brick wall with cement concrete plaster on the exterior side and earth plaster interiors. The floor and roof material were set as Reinforced Cement Concrete. The Moisture Penetration Depth Conduction Transfer Function (EMPD) solution method was used for computations. Multiple simulations were performed with Air change rates (ACH) varying from 0.5 (infiltration only) to 4 (highly ventilated) and with window-to-wall ratio (WWR) ranging from 0-100 were performed for five cities representing different climate zones of India as per the National Building Code of India (2005) (see Fig. 2). The results were then comfortable humidity ratio (accounting for thermal, skin, and respiratory comfort) for occupants of composite climate zone of India reported in our previous study (Priyadarshani et al., 2023).

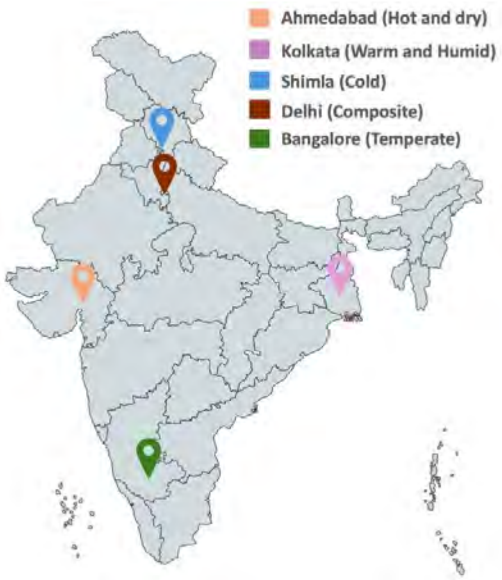

Fig. 2 – Representative cities for different climatic zones selected for simulations

3. Results and Discussions

3.1 Comparing Humidity Ratio With and Without Moisture Buffering

Indoor humidity ratio peaks depend on the moisture buffering offered by the surface material. The diurnal peaks of indoor Humidity Ratio (HR) are regulated in the case of hygroscopic earth-based plaster material compared to the less hygroscopic cement-based plaster materials for the same outdoor conditions. The indoor HR trends resulting from earth-based and cement-based indoor plasters are shown in Fig. 3 for different months of the year. It clearly indicates dampened indoor HR in the case of more hygroscopic earth-based indoor plasters.

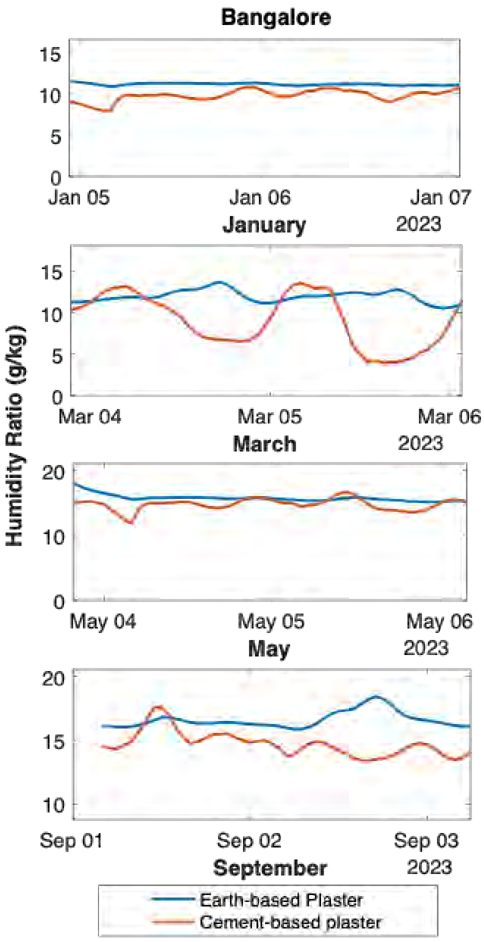

Fig. 3 – Indoor Humidity Ratio for earth-based (hygroscopic) and cement-based indoor plasters

3.2 Relationship between Outdoor and Indoor Humidity Ratio

The indoor HR variation in an enclosed space diurnally depends mainly upon the hygroscopicity of the indoor surface through moisture buffering. The extent of moisture buffering determines the amount of humidity that can be released/or adsorbed by the material in a situation of surface moisture concentration perturbation. Therefore, the difference between indoor and outdoor humidity is crucial to examine the effectiveness of moisture buffering in a given building enclosure.

The difference in humidity ratio between outdoor and indoor with varying ACH for Bangalore is shown in Fig. 4. The humidity excess/deficit (Indoor HR – Outdoor HR) between outdoor and indoor changes with season, consistently being higher when the air change rates are lower. This occurs because of a moisture source (occupancy) present indoors, and the absence of air change led dilution to reduce indoor air humidity.

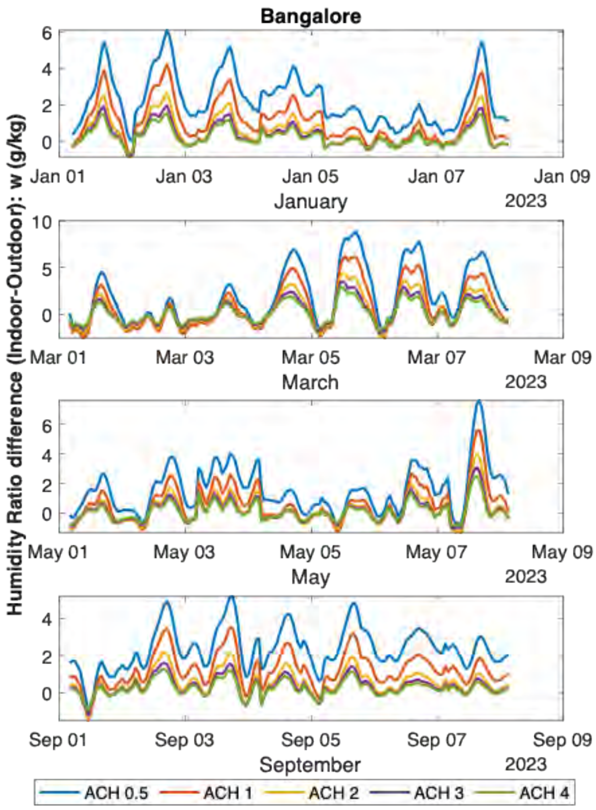

Fig. 4 – Variation in humidity deficit/excess (Indoor-Outdoor HR) for a typical week in Bangalore (temperate climate zone) with varying air changes per hour

The indoor humidity excess is higher during the winter (January) and monsoon (September) weeks, with a difference of ~5 g-wv/kg-da in winter and ~3 g-wv/kg-da in monsoon (low infiltration rates). As the air changes per hour become higher, the indoor humidity approaches outdoor humidity levels. Interestingly, the variations in humidity deficit/excess are higher at low ACH (say infiltration, ACH=0.5), suggesting high buffering capacity. The difference in diurnal variation in Bangalore is ~6 g-wv/kg-da. In the case of Ahmedabad, the variations are highest in May, and the differences in outdoor and indoor humidity are as high as 10 g-wv/kg-da.

Kolkata is situated in the warm and humid climate zone, and the difference in outdoor and indoor humidity is the lowest (<2 g-wv/kg-da) in most of the months. Composite climate zone is characterized by cold winters, hot summers, and humid monsoons. In the case of Delhi, the difference between outdoor and indoor humidity in winter reflects the cold indoor environment, causing very low indoor humidity (less than outdoors). The humidity difference variations in the warmer months of March, May, and September are similar with a humidity difference of ~3 g-wv/kg-da at low ACH/infiltration.

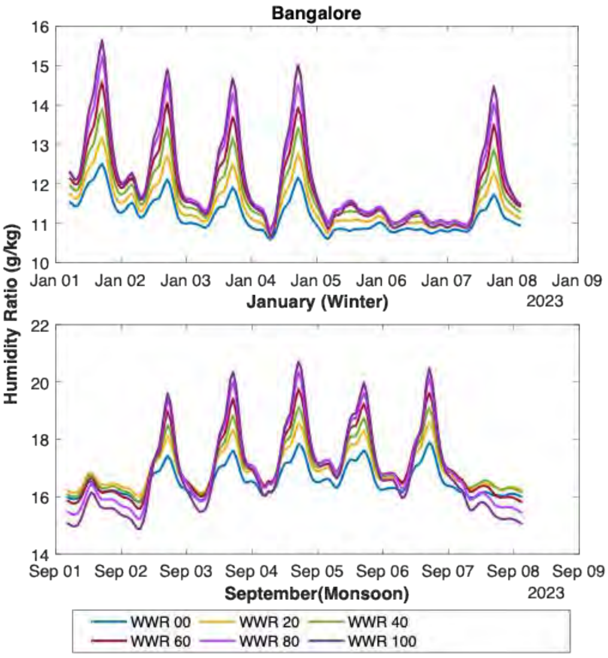

Fig. 5 – Indoor Humidity Ratio with changing Window to Wall Ratio at ACH=0.5 (only infiltration) for Bangalore during winter (low humidity) and monsoon season (high humidity)

In the cold climate zone, Shimla, with low air temperatures, the capacity of air to hold water vapor is also low. Also, the range of humidity variations in the colder conditions, specifically below 10 °C is very narrow. This is reflected in a very low moisture loading rate, correspondingly leading to less difference between the indoor and outdoor air humidity ratio (<2g-wv/kg-da) even at low air change rates.

3.3 Impact of Window-To-Wall Ratio

Window-to-wall ratio (WWR) is the ratio of the area of windows/openings to the ratio of the wall surface. Since wall surfaces are hygroscopic in nature, the surface area exposed to the indoor air impacts the diurnal variations of indoor humidity ratio through moisture buffering.

Table 1 – Details of Building geometry (Surface Area and Volume) for the simulation case building

	Wall Surface Area (m^2)	Volume (m^3)	Wall Surface Area/Volume (m^2/m^3)
WWR00	75.6	129.60	0.58
WWR10	68.04	129.60	0.53
WWR20	54.44	129.60	0.42
WWR30	38.1	129.60	0.29
WWR40	22.88	129.60	0.18
WWR50	11.44	129.60	0.09
WWR60	4.58	129.60	0.04
WWR70	1.36	129.60	0.01
WWR80	0.28	129.60	0.00
WWR90	0.04	129.60	0.00
WWR100	0	129.60	0.00

For the same rate of moisture generation introduced in the simulation model (occupancy), the peaks are best regulated in the case of WWR=0% and have maximum diurnal variations when WWR=100% (see Fig. 5) for the case of Bangalore. Window to wall ratio is critical for the design of buildings. A WWR that is too low can result in no natural daylighting, and a WWR that is too high can result in excessive radiative heat gains through windows, leading to high cooling loads.

Given the role of WWR in the thermal performance of buildings, the optimum WWR is suggested to be between 20-30% (Ahmed et al., 2023). Therefore, to employ moisture buffering, it is critical to examine the indoor humidity ratio levels vis-à-vis climate zones.

The higher the surface area available for adsorption/desorption for a given air volume, the higher the moisture buffering potential of an enclosure. The peaks in indoor HR are lowest in the case of low WWR.

HR variation with varying ACH for WWR between 20-40% (for both daylighting and thermal comfort) is found comparable. Therefore, it is fair to consider an average of WWR 30 to examine the impact of ACH. Correspondingly, the presented results are applicable for a Wall surface/ Volume ratio of 0.18-0.42 (see Table 1).

Further, as stated previously, the impact of ACH and WWR varies as the outdoor environmental conditions vary. At lower temperatures, the air can hold less humidity when compared to higher temperatures. Therefore, this phenomenon varies with seasons.

The simulations pertaining to different climate zones for ACH=0.5,1,2,3, and 4 and WWR=30 have been shown in Fig. 7. It can be seen that the mean Humidity Ratio Levels vary seasonally. It is, therefore, critical to assess the applicability of moisture regulation as offered by the application of earth plaster for comfort in different months of the year. Fig. 7 also shows the mean indoor HR values expected vis-à-vis recommended Humidity Ratio values suggested in literature (De Dear & Brager, 2002; Kong et al., 2019; Li et al., 2019).

Indoor Humidity Ratio Vis-à-vis Recommendations for Comfort

Recommendations for upper limits of HR have been viewed from both buildings' and occupants' health perspectives. In cold climates, the wall surfaces become cold frequently (with temperatures lower than the dew point temperature); therefore, the risk of interstitial condensation causing dampness on walls is higher. This is an essential reason for ASHRAE-55 standards suggesting an "upper limit" for indoor humidity ratio, focusing on preventing moisture-associated defects like surface condensation, mold growth, etc.

However, this upper limit being comfortable concurrently for occupants' health needs careful examination. Recent occupant comfort centric studies suggest a higher value of indoor HR for comfort (>17 g-wv/kg-da) (Kong et al., 2019; Li et al., 2019). Therefore, in tropical regions, the comfort standards applicable for examining humidity in buildings are unclear.

It can be observed that the applicability of hygroscopic earth plaster as a passive design strategy for indoor humidity-related comfort is dependent on the benchmarking comfort values. There is a wide variation when indoor HR is examined for prescribed recommendations.

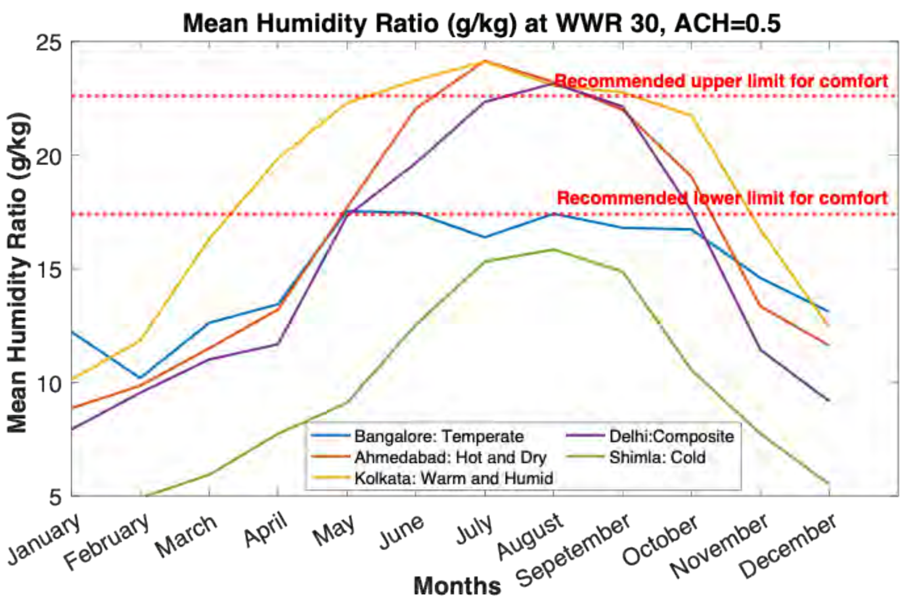

Fig. 6 – Mean monthly indoor HR vis-à-vis comfortable HR limits based on (Priyadarshani et al., 2023)

It can be seen that with comparatively lower HR recommended by ASHRAE-55, i.e., 12 g-wv/kg-da, the indoors can be categorized as comfortable, unlike in other recommendations. Another important observation is that in a cold climate zone, irrespective of the recommendation values used, the indoor humidity is very low and mostly uncomfortable.

In temperate climate zones, the mean HR values conform to the ASHRAE-55 standards. Still, they are consistently in deficit by nearly 5-7 g-wv/kg-da with recommendations of the studies done in tropical areas. In ascertaining the applicability of the design strategy explained in this work, comparing the values with a "comfortable" indoor HR for local occupants is essential. Our previous work suggests the optimum humidity ratio levels for occupant comfort in rural India (composite climate zone) range from 17.4-22.6 g-wv/kg-da (Priyadarshani et al., 2023). Mean monthly HR ranges using hygroscopic earth-plaster indoors vis-à-vis comfortable HR values for the study participants have been shown in Fig. 6. Also, Fig. 8 shows the monthly applicability of earth-based interior plasters and illustrates the need for appropriate moisture regulation for comfort. Results indicate that it can be a potential strategy in warm and humid, hot and dry, and Composite climate zones when existing recommendations are followed; however, its use in temperate and cold climate zones needs further scrutiny. The need for a comfortable HR for local occupants is critical in proposing guidelines for using moisture buffering as a passive design strategy for indoor comfort.

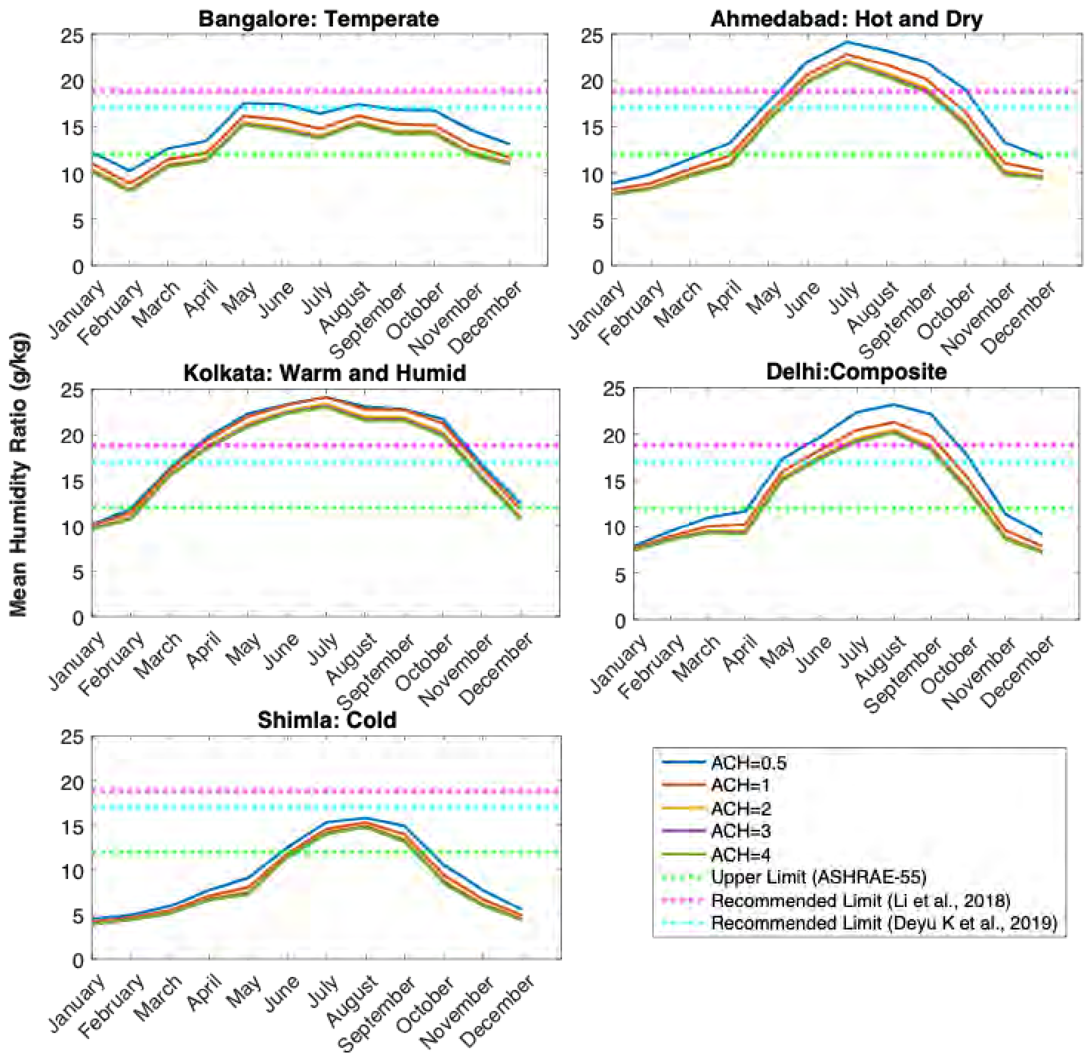

Fig. 7 – Mean monthly indoor HR for different climatic zones with varying ACH vis-à-vis prescribed recommendations for optimum HR by ASHRAE-55 (Li et al., 2019) and (Kong et al., 2019)

4. Conclusion

The study highlights the importance of moisture buffering indoors provided by hygroscopic earth plaster and its implications on indoor Humidity Ratio. Experimentally derived hygrothermal properties of earth materials were appropriately relied on to simulate its impact at a whole-building level. The study highlights that ACH and WWR are critical parameters influencing moisture buffering as a passive strategy to regulate moisture in naturally ventilated buildings. Further, its applicability in different climate zones has been examined. Results indicate that indoor earth-based plaster can regulate indoor humidity, dampening the HR peaks, which is beneficial both from energy efficiency and occupants' comfort and health (thermal, skin, and respiratory) perspective.

This strategy is most effective in warmer months in warm and humid, hot and dry, and Composite climate zones. A major challenge associated with the use of this strategy in temperate and cold climate zones corresponds to low surface temperatures leading to condensation risk. From the occupant's health and IAQ perspective, earth is naturally derived, does not pose a risk of exposure to harmful chemicals like VOCs, and ensures occupants' wellness.

Temperate Climate: Bangalore					
ACH	0.5	1	2	3	4
Jan	12.23	11.00	10.41	10.22	10.14
Feb	10.19	8.85	8.24	8.05	7.95
Mar	12.62	11.43	10.88	10.71	10.64
Apr	13.44	12.12	11.51	11.32	11.24
May	17.53	16.11	15.47	15.28	15.19
Jun	17.45	15.74	14.91	14.68	14.58
Jul	16.38	14.75	14.02	13.82	13.73
Aug	17.42	16.17	15.53	15.34	15.25
Sept	16.80	15.28	14.52	14.31	14.21
Oct	16.73	15.14	14.49	14.32	14.24
Nov	14.59	12.92	12.20	11.99	11.90
Dec	13.10	11.65	11.12	10.97	10.90

Composite Climate: Delhi					
ACH	0.5	1	2	3	4
Jan	7.93	7.67	7.53	7.49	7.46
Feb	9.54	8.98	8.72	8.64	8.60
Mar	11.01	10.05	9.58	9.43	9.36
Apr	11.68	10.26	9.57	9.34	9.23
May	17.32	15.98	15.33	15.13	15.02
Jun	19.65	18.25	17.59	17.39	17.29
Jul	22.34	20.43	19.56	19.29	19.17
Aug	23.15	21.28	20.48	20.24	20.14
Sept	22.14	19.77	18.69	18.36	18.20
Oct	17.55	15.22	14.24	13.96	13.83
Nov	11.43	9.63	8.97	8.77	8.68
Dec	9.17	7.90	7.41	7.27	7.20

Hot and Dry Climate: Ahmedabad					
ACH	0.5	1	2	3	4
Jan	8.86	8.18	7.80	7.66	7.59
Feb	9.86	8.90	8.43	8.28	8.21
Mar	11.50	10.42	9.90	9.73	9.64
Apr	13.20	11.80	11.10	10.87	10.75
May	17.69	16.46	15.90	15.73	15.65
Jun	22.05	20.63	20.02	19.85	19.77
Jul	24.14	22.82	22.15	21.94	21.83
Aug	23.21	21.68	20.79	20.49	20.34
Sept	21.98	20.17	19.21	18.92	18.79
Oct	19.04	16.62	15.60	15.30	15.15
Nov	13.34	11.08	10.22	9.95	9.82
Dec	11.61	10.19	9.65	9.48	9.40

Cold Climate: Shimla					
ACH	0.5	1	2	3	4
Jan	4.49	4.18	3.98	3.91	3.88
Feb	4.92	4.63	4.49	4.44	4.42
Mar	5.93	5.44	5.20	5.11	5.08
Apr	7.74	7.10	6.79	6.69	6.64
May	9.10	8.06	7.53	7.36	7.27
Jun	12.53	11.83	11.56	11.49	11.46
Jul	15.31	14.57	14.20	14.08	14.02
Aug	15.84	15.28	14.94	14.82	14.76
Sept	14.87	13.96	13.40	13.21	13.11
Oct	10.54	9.40	8.77	8.56	8.45
Nov	7.74	6.71	6.20	6.04	5.96
Dec	5.51	4.84	4.52	4.41	4.36

Warm and Humid Climate: Kolkata					
ACH	0.5	1	2	3	4
Jan	10.11	10.02	9.70	9.61	9.56
Feb	11.84	11.44	10.94	10.80	10.73
Mar	16.30	16.10	15.65	15.53	15.49
Apr	19.85	19.50	18.87	18.68	18.59
May	22.29	21.98	21.21	20.96	20.85
Jun	23.30	23.23	22.60	22.40	22.31
Jul	24.11	24.13	23.37	23.10	22.98
Aug	23.05	22.76	21.93	21.66	21.53
Sept	22.76	22.69	21.92	21.66	21.55
Oct	21.73	21.25	20.30	19.99	19.83
Nov	16.72	16.27	15.46	15.20	15.09
Dec	12.41	11.79	10.97	10.74	10.63

Humidity Deficit:
External Humidification Required

Comfortable Humidity Ratio
(17.4-22.6 g-wv/kg-da)

Excess Humidity :
Dehumidification / Ventilation Required

Fig. 8 – Mean Indoor Humidity Ratio with earth-based plaster used as interior surface finish for Wall surface to volume ratio 0.18-0.42 m^2/m^3 (WWR =20-40%) for different climate zones in India

Acknowledgment

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