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# Moisture Buffering and Mould Growth Characteristics of Naturally Ventilated Lime Plastered Houses.

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## Covering Letter

Lime plaster is one of the key sustainable building materials that is also effective as a passive cooling strategy. It has good vapour permeability that moderates the indoor relative humidity inside a space. The moisture buffering quality of lime and its permeability results in adsorption and desorption of space moisture. It is highly influential in the moisture transfer of a building envelope. This results in a decrease in indoor relative humidity but at the same time, there is a risk of damaging the envelope. Lime plaster has a self-healing quality which prevents the formation of inner cracks. Moreover, because of its durability, it has a longer life span. This explains the fact that old historical structures for thousands of years old are still functioning and standing strong. Hence, it is essentially used in conservation projects and vastly adds up to the qualities of the old building. In old structures, an important function is the breathability of the ceiling and walls. The presence of organic mixes and moisture buffering quality of lime plaster makes it more prone to phenomena like mould growth on the surface of the walls. Mould growth further degrades the indoor air quality and the occupant health is compromised. To avoid mould related problems, it is necessary to understand the behaviour of lime plaster with respect to the indoor relative humidity and surface moisture content.

A lot of information is available on the advantages of having lime plaster as a passive sustainable technique. However, the literature lacks studies about the post-occupancy behaviour of lime plastered buildings in terms of their indoor environment and mould growth characteristics. This information can support conservation projects to maintain their longevity and improve their indoor air quality. This work attempts to evaluate the state of traditional lime plastered buildings in Ahmedabad and correlates the findings in terms of the building characteristics like coatings on the wall, ventilation, the level of water activity inside the space, function of the space, etc. Simulations are also carried out to understand the hygrothermal performance of lime plaster. Finally, experiments are also carried out to study the onset of mould growth in lime plaster samples.

The hygrothermal performance of lime plaster is observed through field measurements and simulations. Point in time surveys of the outdoor and indoor air temperature, relative humidity, globe temperature, surface temperature, moisture content of walls, and air velocity are noted for each space. It is observed that lime plaster can effectively modulate indoor relative humidity. Due to lack of ventilation and sunlight, the moisture trapped inside the space leads to mould growth. Mould growth inside lime plaster is observed if the moisture transfer is obstructed by any surface coating, object, or lack of ventilation. If lime plaster is allowed to breathe, favourable conditions for mould growth can be avoided.

The moisture buffering capacity of lime plaster is beneficial to regulate indoor relative humidity. However, one of the most important aspects is to prevent moisture from getting trapped in building fabric. With appropriate ventilation and allowing the lime plastered surface to breathe, lime plaster is one of the most sustainable building materials that can be used even today.

This ignites the probability to rejuvenate the appropriate use of lime plaster in the built environment. It overlays the importance of analyzing the hygrothermal properties of the surface material for predicting its accurate performance inside the space.

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# Moisture Buffering and Mould Growth Characteristics of Naturally Ventilated Lime Plastered Houses.

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**Abstract**

Lime plaster is well known for its moisture buffering capabilities but is also susceptible to mould growth. This work focuses on the hygrothermal performance of lime plaster in naturally ventilated residential spaces. Surveys are carried out for 45 traditional buildings of Ahmedabad in India with measurements of ambient variables, such as temperature, relative humidity, wall moisture content, etc. Mould growth patterns of these spaces are related to the measured variables and wall characteristics. Hygrothermal simulations of some spaces are also carried out to observe the moisture buffering of lime plaster. Experimental observations are contrasted with simulation results to see if numerical predictions are realistic.

*Keywords: Lime plaster; Hygrothermal simulations; mould growth; surface relative humidity conditions.*

## Nomenclature

$T_a$ – Ambient Temperature inside a space.

$T_o$ – Outside Dry Bulb Temperature.

$GT_o$ – Outside Globe Temperature.

$GT_i$ - Inside Globe Temperature.

$\mu$ - Moisture Content of the walls.

$RH_o$ – Outside Relative Humidity.

RHi – Inside Relative Humidity.

$Ts_O$ – Outside Surface Temperature.

$Ts_i$ - Inside Surface Temperature.

$RH_s$ – Inside Surface Relative Humidity

$v_a$ – air velocity at the level of the globe thermometer.

MRTo – Outside Mean Radiant Temperature.

MRTi – Inside Mean Radiant Temperature.

EMPD – Effective Moisture Penetration Depth

HAMT – Heat and Moisture Transport

MBV – Moisture Buffering Value

# 1 Introduction

The versatile nature of lime as a construction and finishing material has makes it to be the most commonly used binder in construction since the twentieth century. In buildings, lime has extensive applicability from concrete to bedding and pointing mortars to paint (limewash). The properties of lime mortar and plaster varies according to the nature of the lime binder used to prepare along with the effect of additives in the mixture (1).

Lime is obtained by heating limestone ($CaCO_3$) and calcinating it. It is preferred that the amount of $MgCO_3$ is less than 5% (2). The lime cycle which is a three-stage process for making lime mortar is given by (Boynton, 1980). Stage one is calcination where calcium carbonate on heating gives calcium oxide and carbon dioxide.

Calcination: $CaCO_3 + \text{heat} \rightarrow CaO + CO_2$

At the second stage of hydration, this calcium oxide reacts exothermically with water to give calcium hydroxide which is also known as slaked lime. This process is known as slaking and quicklime is obtained as the product.

Hydration: $CaO + H_2O \rightarrow Ca\,(OH)_2 + \text{Heat}$

In the third (carbonation) stage, the calcium hydroxide when in contact with air absorbs carbon dioxide to again give hard calcium carbonate and gives away the moisture.

Carbonation: $Ca\,(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

Lime mortar and lime plaster are self-healing and thus prevent the formation of inner cracks. The carbohydrates in the organic additives used in the reduction stage, continuously supply $CO_2$ in the inner layer of the mortar. Moreover, because of its durability, it has a longer life span of 70 years as compared to the life span of cement~~.~~

## 1.1 Need of the Study

Since ancient times to obtain durable plaster, the sand is mixed in three parts with one part of slaked lime (3). The organic additives are used, their application technology, the process of making mortar, and the advantages of lime plaster (4).

There is literary evidence linking to the composition of lime mortars used in India . It can be stated that they included ingredients like curd, jaggery, Bel pulp (from the fruit Aegel marmelos), lentils, and oil of Margosa. These mixes were used for improvising different properties of the lime mortar. Thus, the presence of such organic mixes and moisture buffering quality of lime plaster makes it more prone to phenomena like mold growth on the surface of the walls. This furthermore degrades the indoor air quality and the occupant health is compromised. To keep this in check it is necessary to understand the behavior of lime plaster with respect to the indoor relative humidity and surface moisture content. It is also necessary to understand the causes and conditions of the mold growth in a lime plaster.

It is possible to substantiate if the performance of lime plaster leads to presence of mold or creates a favourable environment for mold growth. And if it does then what can be the controllable parameters to optimize the performance of the lime plaster. The impact of using lime plaster on the indoor environment in naturally ventilated spaces can be understood.

There have been few simulation-based researches on lime plaster buffering impact on the energy consumption of the building. Also, a lot of information is available on the advantages of having lime plaster as a passive sustainable technique. However, the literature lacks information about the post occupant behavior of lime plastered buildings in terms of their indoor environment and mold growth characteristics. Knowing this information can support conservation projects to maintain the longevity and improving the indoor air quality in such buildings.

A hypothesis can be rested that lime plaster has moisture buffering characteristics which should moderate the Mean Radiant Temperature (MRT) of a space making it thermally comfortable in naturally ventilated buildings. Therefore, the surface temperature of the inside envelope should be lower than the indoor air temperature. Also, the relative humidity of the space should be moderated inside the space with respect to the outside.

Through EMPD simulations the onset of mold growth inside a space can be predicted if hygrothermal properties of the rendering material are known.

# 2 Literature Review

## 2.1 Moisture Buffering of lime plaster

The indoor air relative humidity in a building plays a significant role in its energy consumption, its performance and its indoor air quality (6). This fluctuation in relative humidity is mainly cause of the moisture buffering quality of the surface wall finishes which modulates the indoor humidity by absorbing and releasing the moisture. Using the analytical methods, it is derived that the humidity present in ambient air and room air can modify up to 2–3 ℃ of room temperature with respect to the amount and direction of temperature and moisture gradients(7), (8) and (9). There is a high potential in the reduction of energy consumption of buildings directly and indirectly through moisture transfer (10). The use of hygroscopic materials in the envelope and a well-controlled HVAC system is the indirect savings and has the potential of saving from 5% to 20%. Due to moisture buffering up to 20% of reduction in heating energy is possible in cold, temperate and composite climate of India. Whereas, only 2% increase in cooling load is observed in all climatic conditions of India and in all types of wall construction (11). Thus, it proves that hygroscopic materials improve the performance of a building which reduces its energy consumption.

The vapor transfer and its storage have a significant impact on heat transfer, indoor comfort, and durability of the wall assemblies. The durability of the wall assembly and the vapor barrier can be improved by using a repour open wall assembly instead of vapor-tight assembly. For long term phenomena the moisture production had almost no impact. So, to avoid envelope damage, repour open wall assembly is a better option over vapor-tight assembly (12).

The plaster materials having lime as a binder have more polar surfaces and they contain micro and mesopores (13). In sulphate phase of the lime plaster mortar formation, high porosity was observed (14). This qualifies lime plaster as a good material for moisture buffering.

In the winter season, the absorbent walls are capable to pump water vapor to surge the indoor relative humidity in warmed buildings. (15) experimented to understand the effectiveness of porous, water-absorbent walls performing as moisture buffers for occupied rooms at 0.5 ACH. Absorbent materials can be used as a buffer for a brief period and can substitute for mechanical ventilation. The heat of evaporation is substituted as the heat of absorption on the surface. For over a longer period, the performance of the absorbent buffers is not as effective as ventilation. So, along with buffering proper ventilation must be also maintained for the effective performance of the pace.

## 2.2 Lime plaster and mold risk.

The rain exposure impact on hygrothermal performance is minor. But the impact is significant on mold index for a lime plaster assembly as compared to mineral-cement based plaster (16). Materials like lime plaster have higher capillary action and its moisture content is vastly dependent on their exposure to driving rain (17). The presence of moisture in or on the surface of walls invites a favorable atmosphere for mold growth (18). Several other factors like the nutrient, Relative Humidity, temperature, and so on influence the fungal growth in buildings. Some possible ways to evaluate the fungal contamination on the indoor environment include the determination of levels of fungal components like ergosterol, bet aglucon, mycotoxins, and microbial volatile organic compounds (MVOC).

Building materials are affected by the moisture in a building structure. This leads to microbial and chemical processes to take place. Odorous and irritant substances or allergens are emitted. Furthermore, this increases the risk of house dust and mite infestation. A study is carried out by (21) on 21 different types of building material to understand the influence on Temperature and Relative Humidity on the metabolism and growth of eight different micro-fungi. The results show that when under constant conditions, at RH up to 95% and water activity at 0:95 Penicillium, Aspergillus, and Eurotium overgrew other indoor fungi. However, Eurotium fungi produce very small amounts of secondary metabolites. Water activity of 0.78 – 0.80 is the minimum required for fungal growth most inclined materials. Although more, at 10°C it is 80 – 90 % RH and 90% RH at 5°C. The fungal growth inside a space is highly influenced by the relative humidity (RH) inside the dwelling. These RH levels inside are further an effect of the moisture buffering capacity of the wall assemblies, ceiling coverings, furniture, and textiles used inside the building.

Relative humidity also affects the concentration of noxious gases in the air as it alters the rate of off-gassing in the building materials. The presence of moisture is a cause of deteriorations inside buildings (22) while affecting the latent and sensible conduction loads (23).

Relative humidity coupled with high temperature, has an adverse and direct as well as indirect effect on human health leading to allergic incidences and respiratory diseases. (24).

There are several health issues like asthma and respiratory disorders associated with the dampness of the buildings. (25) identified four sources of dampness and moisture in the building: leakage of rain and snow into the building construction or moisture from the ground; moisture from occupants and their indoor activities; water leakage.

The moisture starts accumulating if the rate at which moisture enters an assembly exceeds its rate of moisture removal (26). Moreover, the problem of even small water leak has a significant impact if the hygric buffer capacity of the material is low while for higher hygric buffer capacity materials it’s not.

### 2.3 The solution to mold growth.

Variations in the location of humidity sources and room ventilation rates give rise to pockets of high relative humidity. Therefore, the average relative humidity throughout the building should be maintained between 40 to 60 %. Above 90% RH and 15°C temperature, all types of building materials are prone to mold growth (27). While for over a year no fungal growth is noticed for a lower RH of 80%. Hence wall surface materials are needed to be kept free of mold or fungal attacks to maintain the indoor air quality of a space.

One of the techniques for limiting mold growth in most of the large buildings in the US is building pressurization. Research paper (30) suggests that for spaces modeled in a hot and humid climate, the effective solution is positive pressurization and keeping a higher setpoint of indoor temperature.

The use of incompatible materials like cement plaster or chemical paint on walls causes deterioration of the building envelope in heritage structures (31). It traps the moisture inside and soon the walls crumble and fall off (32).

Prof. M. D. Apte (33) suggests that developing India should utilize freshly ground lime against cement. On increasing the amount of pozzolana in a lime plaster mixture, the values of the water vapor diffusion coefficient went down (34). Thus, renders for historical buildings should have strong buffering towards water absorption to achieve thermal comfort and reduce the risk of damage (35).

Roger Hunt (36) mentions that lime avoids problems of decay and dampness by allowing the building envelope to breathe and unlike several modern nonporous materials. Lime mortar has good permeability which is beneficial as a building material. The moisture buffering quality of lime and its permeability results in adsorption and desorption of space moisture. It is highly influential in the moisture transfer of a building envelope. Lime plaster is less rigid and brittle than cement plaster. They have a reduced tendency to crack which makes lime ideal for flexible substrates. It is said to be 'self-healing' as larger cracks can be easily healed with limewash. Another good quality is that it is vapor-permeable i.e. useful in 'breathing wall' construction. (37). Along with increasing its strength eventually, lime plaster is easy to remediation for cracks and defects. It involves nontoxic chemicals for manufacturing, production can be downscaled as per need, it is recyclable in use, has a porous surface after curing, highly reflective if in natural white color. When used as an internal render, it improves the indoor air quality by absorbing low amounts of Carbon dioxide and regulating the indoor relative humidity for a prolonged period.

A study conducted in two lime plaster buildings in Auroville addressed the post-occupancy thermal performance of lime plaster. It proved that using lime plaster as a building material optimizes the thermal performance of the buildings in warm and humid climates. There was a difference of 10.7% noticed between the façade temperatures and cooler interior surfaces than the exterior by 16.8% for the case study of Language Lab (38).

### 2.4 Scope of current work.

Several advantages of lime plaster, like lower RH levels and lower indoor temperature, are reflected in the literature review. However, due to its moisture absorbing capacity and use of additives such as sand, powdered limestone, perlite, and others, it is hugely prone to issues of mold growth. Mold growth if not addressed for a long time further leads to health problems for occupants inside the space.

Therefore, in this study, an attempt has been made to evaluate the moisture buffering and mold growth characteristics of naturally ventilated lime plastered spaces. The study is conducted in Ahmedabad and the results are correlated in terms of the building characteristics like coatings on the wall, ventilation, the level of water activity inside the space, function of the space, etc.

Simulations are also carried out to understand the hygrothermal performance of lime plaster.

Finally, experiments are also carried out to study the onset of mold growth in lime plaster samples

# 3 Methodology

The research methodology used in this study is in three sections:

1. Simulating the studied spaces with an Effective Moisture Penetration Depth (EMPD) Model using Energy Plus (39).
2. Survey of Naturally Ventilated Residential Spaces
3. Study the onset of mold growth in lime plaster samples

The cumulative inference from the above three sections is used to co-relate the overall hydrothermal performance of lime plastered spaces and the onset of mould growth. Furthermore, the factors leading to mould growth are identified. The capability of the EMPD model to predict hygrothermal performance is verified by carrying out annual simulations and contrasting the simulation results with those observed onsite.

## 3.1 Simulating the studied spaces with the EMPD model.

It is important to know the moisture conditions of buildings, especially during the cooling period to know the accurate building performance. The materials binding, a room stores, and releases moisture. Hence, should be considered along with moisture in the air inside the room. The EMPD model simulates the surface moisture adsorption and desorption in a simplified way. It assumes a thin layer of air near the wall surface which is dynamic and exchanges moisture in the air in cyclic pulses of air moisture. EMPD has a reasonable approximation of reality for short periods when there is no net moisture storage (39).

Properties of the base material required for the EMPD model are available in Energy Plus (40) data. However, there is limited literature available on hygric properties of lime plaster due to its non-standardized compositions. This is restricted the simulations to be conducted using the EMPD model which requires lesser hygric properties instead of a detailed hygrothermal model in Energy Plus.

It is a challenge to derive a universal curve for Lime plaster mixes as they are always site-specific and vary from region to region. Hence, a simplified version of the EMPD model in the Energy Plus (40) engine is used. Moisture content values required in the input are referred from (41) catalog of building materials. To derive the sorption coefficients through these moisture content values, a close-fitting curve shown in Figure 1 is plotted. The values of this curve are then fed into the EMPD model and simulated.

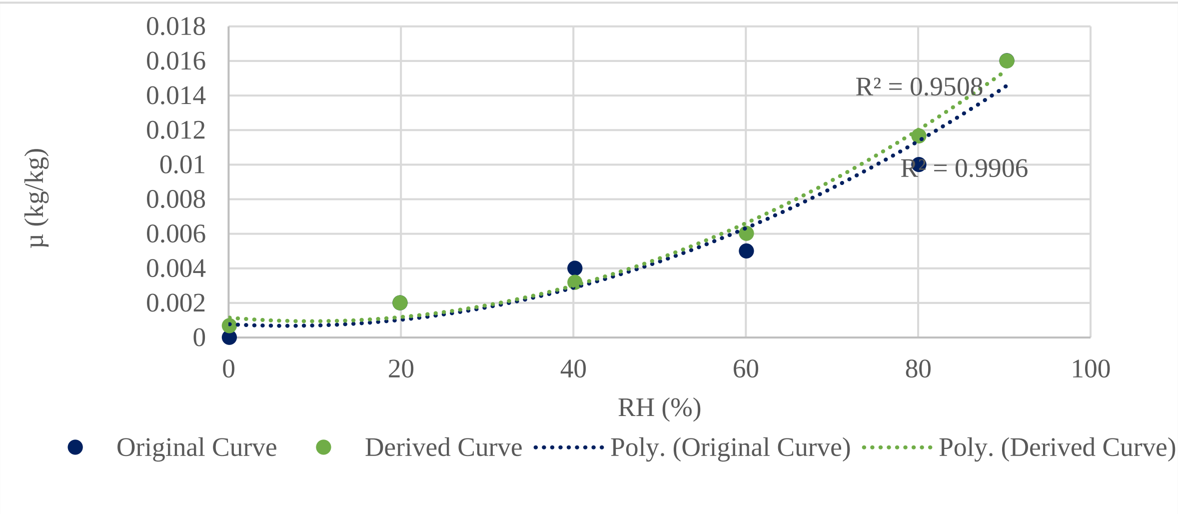



Figure 1 Best fitted sorption curve for lime plaster.

A BESTEST model (42) is used which is also validated by several other authors (43), (44)(45)(46) for hygrothermal simulation. Figure 2 represents the single-zone space of 8m x 6m x 2.7m of brick walls with lime rendering.  There is a moisture source of 500 grams per hour inside is provided from 9 a.m. to 5 p.m. and 0.5 per hour of air exchange per hour.

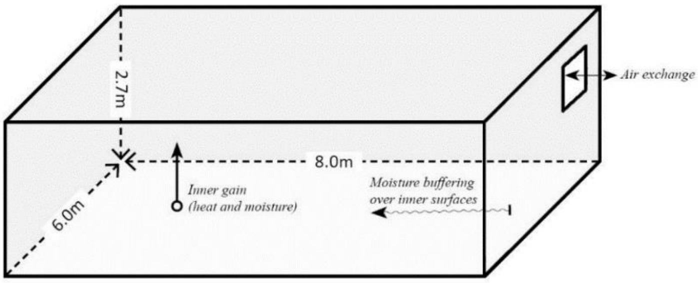



Figure 2 BESTEST model used *Source:* (45)

To ensure the working of hygrothermal simulation in EMPD, the above shoe box model is simulated as thermal only and later using the EMPD algorithm. The EMPD model is then simulated for building materials like lime plaster, gypsum plasterboard, and plywood. The hygrothermal behavior of lime plaster is observed in the EMPD simulation results.

After validation of the EMPD inputs, a sample study space from the survey is modeled. The change in MRT, relative humidity, and surface temperatures through simulation is derived. This further helped to predict the trend of the hygrothermal behavior of lime plaster in that space throughout the year.

## 3.2 Survey of residential spaces

### 3.2.1 Characteristics of survey cases

### 3.2.2 Pol houses

The heritage city of Ahmedabad majorly includes thousands of pols, a dense cluster of residences belonging to the same caste, religion, and occupation. The houses of such a neighborhood for more than 300 years are popularly known as Pol houses. (Figure 3 Pol Houses)

Figure 3 Pol Houses

The passive strategies in the design of Pols are prominent. Strategies like mutual shading, thick walls, long shared walls, some have a central courtyard, multi-story structure, narrow lanes and dense clusters, etc the house protects the inside spaces from heat gain. The otla (plinth) outside the house is usually used to dry clothes in some houses. Attached to the otla (plinth) is a small dedicated space for washing utensils and toilets in every house. The construction of the house is of timber, brick, and lime plaster.

#### *3.2.2.1 Girikunj Residence:*

Girikunj Residence is a residential bungalow of Ar. Nimish Patel and Parul Zaveri (47), which is designed using passive design strategies, traditional materials, methods, and technology. Glass exhaust shafts on the periphery collect the hot air from the small grill outlets in the spaces when the windows are closed. Air vents attached to it give away this air to the outside. Lime is used in plastering; wall wash and mortar. It consists of additives like Gur (jaggery), gugal (Indian bdellium), and methi (fenugreek) for improving binding and waterproofing. (Refer Figure 4 (a))

#### *3.2.2.2 RSR Residence:*

The RSR Residence is a bungalow designed by Abhikram Architects (47), which is constructed using lime mortar and plaster. The type of lime plaster used is Marmarino lime plaster which gives a marble-like finish. Hence, no coating of paint is used on any of the walls. Mechanical ventilation is provided with the help of air vents throughout the space. (Refer Figure 4 (b))

The surveys are carried out in the afternoon from 02:00 pm to 04:00 pm when the temperatures are relatively high outside on every alternate day from the 25th of December 2019. A layout of the space is created considering the wall thickness, opening area, and adjacent spaces. The use and activities of the space are also noted.

Figure 4 (a) Girikunj Residence (*Source: Abhikram Architects*) ; (b) RSR Residence

Point in time measurements (Figure 5) of the air temperature, relative humidity, globe temperature, and air velocity are noted for each space. Similarly, inside air temperature, Relative Humidity, Black Globe Temperature, and wind velocity at the center of the space are measured. For measuring the inside surface temperatures of all the walls, the emissivity of the FLIR thermal Gun is set to 0.95. The surface temperature of the ceiling and floor was also noted.
The above figure shows various measurements taken during the survey. It includes the following:

(a) Outdoor Air, RH, and Globe temperature using Heat Stress meter,
(b) Indoor Air, RH, and Globe temperature using Heat Stress meter
(c) Moisture Meter reading of exposed lime plaster,
(d) Air velocity reading using Vane Anemometer and

(e) Surface temperature readings or external and indoor walls using Thermal Gun.


(a) (b) (c) (d) (e)

Figure 5 Site Measurements carried out using several instruments.

Table 3-1 gives the details of the parameters and the location measured on-site by the respective instruments. For details and specifications of the instruments refer to Appendix A

Table 3-1 List of instruments for their measured parameters

| **Instrument used** | **Parameter measured** | **Measurement location** |
|---|---|---|
| Heat Stress WBGT Meter (Extech HT30) | Outside air temperature, Relative Humidity, Black Globe Temperature | Outside the survey space at a height of 1100 mm from the ground |
| Heat Stress WBGT Meter (Extech HT30) | Inside air temperature, relative humidity, Black Globe Temperature | At the center of the survey space at a height of 1100 mm from the FFL. |
| Vane Anemometer (PEAKMETER MS6252A). | Air velocity | 1. Near the globe thermometer, perpendicular to three planer axis.<br>2. Perpendicular to the vertical plane of the openings inside a space. |
| Thermal Gun (FLIR TG165) | Surface temperature. | Inside and outside exposed surfaces of all the walls surrounding the space (including the ceiling and floor). |
| Testo 606-2 Moisture Meter (38767439/711) | Moisture Content and surface relative humidity. | Moisture content inside lime plaster and surface relative humidity near it. |

Forty-five spaces are surveyed in such houses which had lime plaster as the rendering material with characteristics mentioned in Table 3-3-2

Table 3-3-2 Characteristics of studied spaces

| SPACE NAME | WALL DETAILS | MOULD GROWTH OBSERVED | FUNCTION | COATING OVER PLASTER | Volume |
|---|---|---|---|---|---|
| KL_A | North and West Wall Exposed | No Visible Mould Growth | Living Area | Lime Wash | 34.52 |
| KL_B | South and West Wall Exposed | Outside exposed wall | Kitchen | Lime Wash | 36.62 |
| PS_A | North Wall Exposed | No Visible Mould Growth | Living Area | Lime Wash | 69.01 |
| PS_B | Open to sky | On 1 Common Wall | Kitchen | Lime Wash | 120.06 |
| PS_C | No Exposed Wall | On all Walls | Store Room | Lime Wash | 21.09 |
| BT_A | North Wall Exposed | No Visible Mould Growth | Bedroom | Lime Wash | |
| PT_A | South and West Wall Exposed | Inside and Outside all Walls | Common area | Lime Wash | 33.68 |
| PT_B | North Wall Exposed | On all Walls | Bedroom | Lime Wash | 23.32 |
| PR_A | East Wall Exposed | On all Walls | Store Room | Lime Wash | 72.90 |
| PR_B | No Exposed Wall | On all Walls | Store Room | Lime Wash | 25.80 |
| MN_A | South Wall Exposed | On Common Walls | Living Area | Lime Wash | |
| MN_B | North Wall Exposed | No Visible Mould Growth | Kitchen | Lime Wash | |
| MZ_A | East Wall Exposed but shaded | No Visible Mould Growth | Small scale industry activity | Distemper | 28.92 |
| MZ_B | No Exposed Wall | On Both the Walls | Passage | No Coating | 7.51 |
| BH_A | West Wall Exposed | On East Wall | Living Area | Plastic Paint | 41.10 |
| BH_B | North and West Wall Exposed | On East Wall | Kitchen | Plastic Paint | 31.50 |
| RM_A | East Wall Exposed | No Visible Mould Growth | Living Area | Distemper | 39.30 |
| RM_B | North Wall Exposed | No Visible Mould Growth | Bedroom | Distemper | 32.10 |
| JG_A | North and East Wall Exposed | On all Walls | Common area | Plastic Paint | 72.00 |
| JG_B | No Exposed Wall | On all Walls | Store Room | Plastic Paint | 45.00 |
| CH_A | North Wall Exposed | No Visible Mould Growth | Kitchen | Lime Wash | 26.19 |
| CH_B | No Exposed Wall | No Visible Mould Growth | Bedroom | Lime Wash | 52.96 |
| CH_C | No Exposed Wall | No Visible Mould Growth | Store Room | Lime Wash | 6.28 |
| GRD2_A | East Wall Exposed | No Visible Mould Growth | Dining Area | Lime Wash | 37.92 |
| GED2_E | West Wall Exposed | No Visible Mould Growth | Store Room | Lime Wash | 18.79 |
| GRD2_C | East Wall Exposed | No Visible Mould Growth | Store Room | Lime Wash | 22.75 |
| PZ_A | South and West Wall Exposed | No Visible Mould Growth | Living Area | Lime Wash | 210.77 |
| PZ_B | South and West Wall Exposed | No Visible Mould Growth | Bedroom | Lime Wash | 44.21 |
| PZ_C | South and West Wall Exposed | On Common Walls | Basement Store Room | Lime Wash | 45.26 |
| PZ_D | South and West Wall Exposed | No Visible Mould Growth | Basement Store Room | Lime Wash | 110.52 |
| PZ_E | South and West Wall Exposed | On 2 Common Walls | Basement Store Room | Lime Wash | 94.33 |
| PZ_F | South and West Wall Exposed | No Visible Mould Growth | Common area | Lime Wash | 107.28 |
| PZ_G | South and West Wall Exposed | No Visible Mould Growth | Bedroom | Lime Wash | 49.50 |
| PZ_H | South and West Wall Exposed | No Visible Mould Growth | Bedroom | Lime Wash | 113.83 |
| PZ_I | South and West Wall Exposed | On Exposed Walls | Terrace Common area | Lime Wash | |
| RJ_A | South and West Wall Exposed | No Visible Mould Growth | Living Area | No Coating | 196.00 |
| RJ_B | South and West Wall Exposed | No Visible Mould Growth | Dining Area | No Coating | 126.60 |
| RJ_D | South and West Wall Exposed | No Visible Mould Growth | Living Area | No Coating | 189.00 |
| RJ_E | South and West Wall Exposed | No Visible Mould Growth | Bedroom | No Coating | 69.60 |
| RJ_F | South and West Wall Exposed | No Visible Mould Growth | Store Room | No Coating | 33.60 |
| RJ_G | South and West Wall Exposed | No Visible Mould Growth | Store Room | No Coating | 105.00 |
| RJ_H | South and West Wall Exposed | No Visible Mould Growth | Store Room | No Coating | 47.20 |
| RJ_I | South and West Wall Exposed | No Visible Mould Growth | Living Area | No Coating | 183.41 |
| RJ_I | South and West Wall Exposed | No Visible Mould Growth | Entrance Lobby | No Coating | 17.92 |
| RJ_K | South and West Wall Exposed | Inside and Outside Exposed Walls | Living Area | No Coating | 73.41 |

### 3.3 Studying the onset of mold growth in lime plaster samples

To understand the onset of mold growth on lime plaster, an experiment similar to (48) is carried out. Different relative humidity levels are maintained in containers for a longer span by different salt solutions.

For this experiment, four different plastic containers are filled with different salt solutions. Table 3-3-3 shows the different salts and the quantity of salt and water to maintain RH levels inside the container. Preliminary trials were carried out by trial and error to fix the quantity of salt and water to obtain the RH values. Logger data of RH level maintained is given in Appendix F.

Table 3-3-3 Relative humidity achieved for different Salt Compositions.

| Name of Salt | Composition of Salts | RH Gained | Quantity (gm) | Water Quantity (gm) |
|---|---|---|---|---|
| Sodium Chloride | NaCl | 75% | 53.33 | 27.283 |
| Ammonium sulfate | $(NH_4)_2SO_4$ | 80% | 53.33 | 30 |
| Potassium Chloride | KCl | 86% | 30 | 10 |
| Potassium sulphate | K2SO4 | 99% | 53.33 | 18.19 |

Figure 7 Lime plaster samples for the experiment


Figure 6 Four jars containing different salt solutions.

The sample of lime plaster used is prepared in March 2019. It contains one-part lime putty, one and a half parts Surkhi and two parts of sand in the mixture. Along with these, additives jaggery water, googol water, and plaster mix are used.

Using Hobo loggers, the data was logged for four weeks to check the relative humidity levels inside. Once the desired RH levels are achieved, lime plasters samples of equal size, weight, and known composition are introduced. These samples are left unattended until the visible mold is observed on the surface of it. The instruments used for conducting the experiments are the following:

- Hobo Temperature and RH loggers.
- Transparent Plastic Containers.
- Salt solutions
- Lime plaster Samples (40mm X 40 mm X 10 mm).

The specifications of the instruments can be found in Appendix A

# 4 Results

## 4.1 Simulation results of BESTEST Model

The contrast in the Relative Humidity (RH) results of a thermal only and EMPD model can be effectively observed in Figure 8. It can be seen that the relative humidity (RH) levels in the case of the Thermal only model (CT) model reach 100% at times. While for the hygrothermal model of lime plaster, the RH levels are maintained between 39% to 95%. This shows that the EMPD model (40) of lime plaster is successfully showing the moisture buffering inside the space.

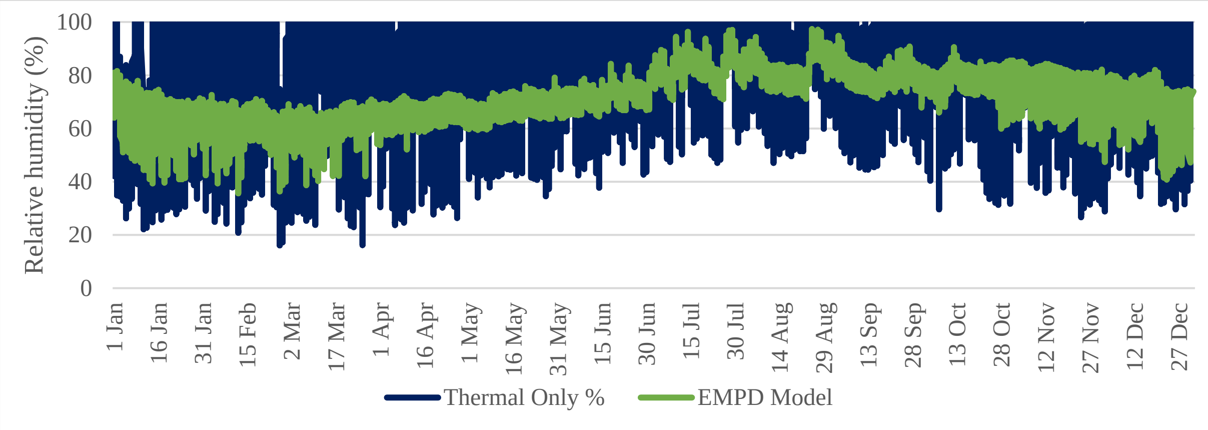



Figure 8 Relative Humidity BESTEST Model of Thermal Only and EMPD.

Further simulations in the same EMPD are carried out for different rendering cases like without lime plaster, with lime plaster, gypsum plasterboard, and plywood. The box plot Figure 9 visibly shows that lime plaster has the least variation of RH levels with the least amplitude. In the case without plaster, Gypsum plasterboard, and plywood the maximum RH is 99%. While the maximum of lime plaster is about 97 %. This amounts to a reduction of 2% when compared to other cases. Lime plaster and plasterboard are always more than 30% for the given conditions. Also, 50% of the time for lime plaster the range is between 62% to 72%. It can be inferred that; the relative humidity values are lower during moisture increase and higher during moisture reduction for lime plaster.

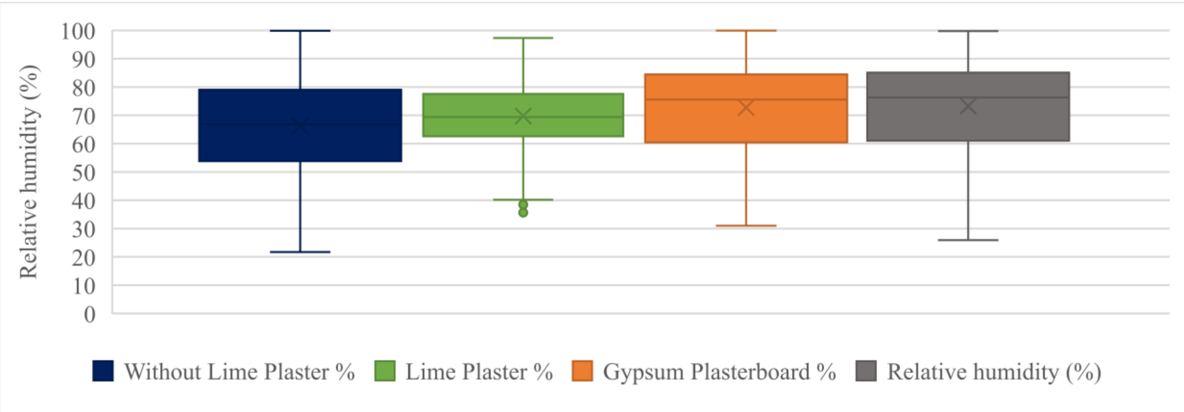



Figure 9 Indoor Relative Humidity for different cases.

This confirms the better performance of lime Plaster over the rest of the cases. Moreover, to now observe its hygrothermal performance of it under actual circumstances, two sample spaces from the survey are modeled. Its performance in terms of MRT and RH inside is observed throughout the year.

#### 4.1.1 Simulation Results of Survey Sample Space

Two spaces PT_B and PS_A where mold growth is observed during the survey are selected for modeling. Physical parameters similar to the actual case are created except for the lime composition as it is unknown for the actual case. In both cases, there is no external source of the moisture other than occupancy.

Figure 10 shows the temperature variations observed from outside to inside throughout the year for model PT_B. The outside DBT has varying bandwidth with a maximum diurnal variation of 20°C to a minimum variation of 7°C. Whereas there is a variation of around 5°C for indoor air temperature. Similarly, the bandwidth of the MRT inside the space is around 2°C. Hardly any fluctuations are observed in this band while the temperature is maintained between 20 to 30°C for this space.

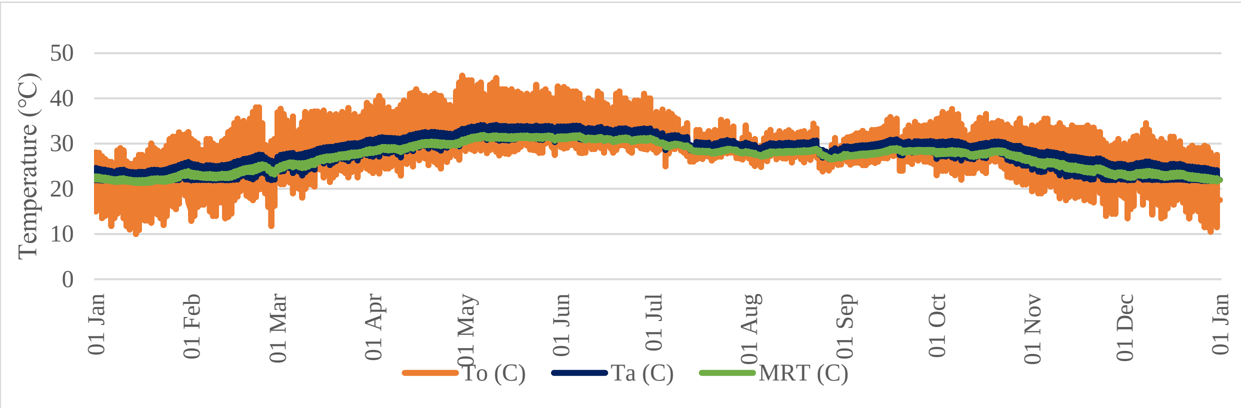



Figure 10 Simulations results showing a range of outdoor, indoor, and mean radiant temperature in PT_B.

The outside relative humidity is compared with the inside RH levels and the surface RH level in Figure 11. There is a difference of 11.5% from the maximum of outside to inside. Whereas an 11% difference is observed between the minimum levels of outside RH and Inside RH. Also, the difference between the first quartile and third quartile is 33% for outside RH and 24% for the Inside RH. It can be predominantly seen that the surface RH levels are higher than the inside RH levels. The maximum of RHs values is high by 3% and the minimum of RHs is high by 7% more than the maximum and minimum of RHi. ASHRAE suggests that to prevent mold growth it is necessary to keep the spaces below 60% RH (49). However, 25% of the surface RH values are more than 70% leading to mold risk.

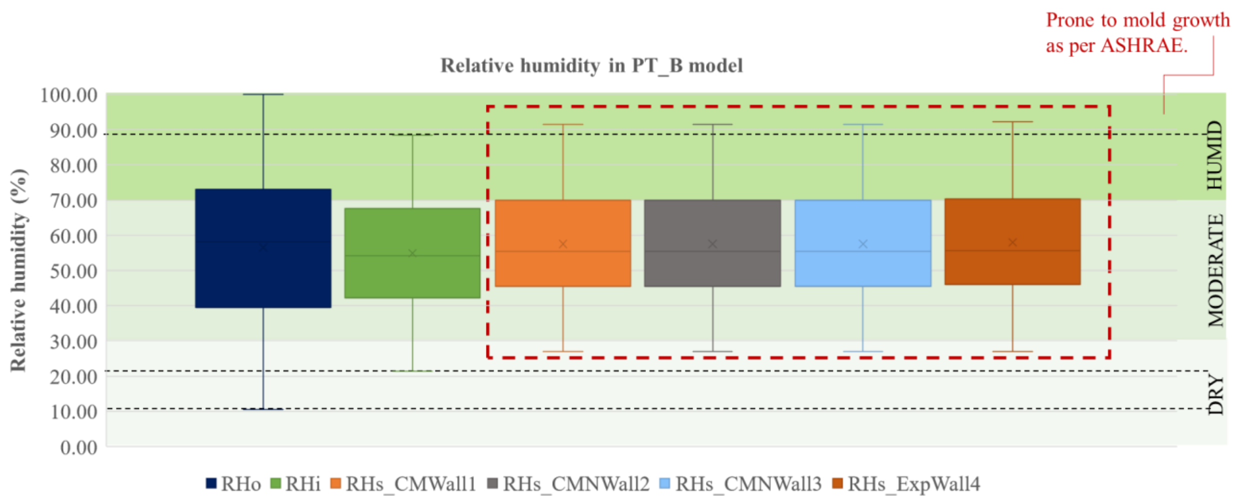



Figure 11 Relative Humidity levels of space and on the surface of the walls in PT_B.

Figure 12 further indicates the time when RH levels are high and low. During the monsoon months from July, the inside RH is always above 60%. While the surface RH of the walls is always above 68%. These are the months when the wall surfaces are highly prone to mold growth.

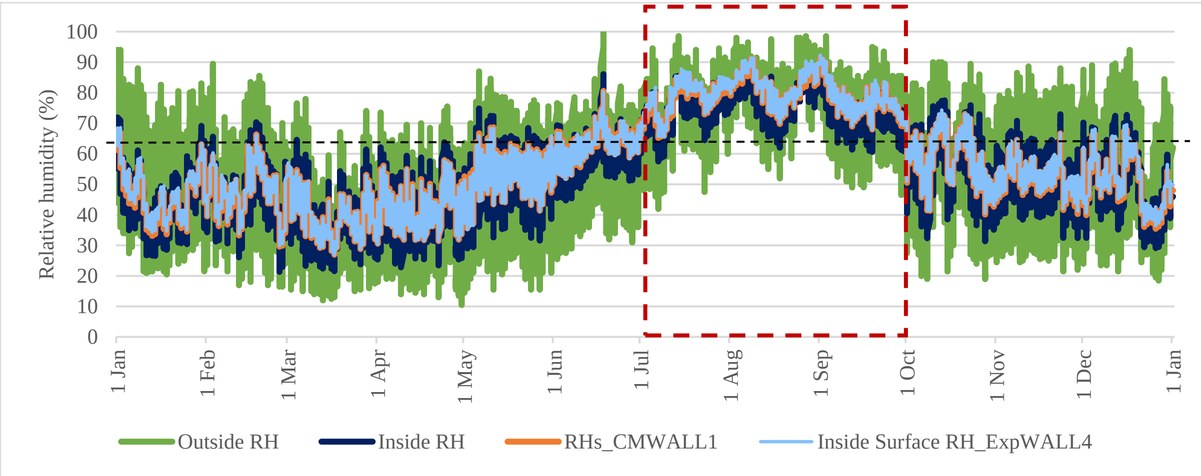



Figure 12 Varying RH levels with time throughout the year in PT_B.

The percentage when the RH levels are prone to mold growth can be observed in Figure 13. Out of 8760 hours, 32 to 54 hours are above 90% RH near the walls. Whereas, 60% of the hours are between 60%RH to 90% RH resulting in a risk of mold growth. Even though, the simulation results show an equal percentage of RH near the walls, the percentage of mold growth observed on-site over each wall is different. This can be because of the varying placement of furniture, openings, and air velocity inside.

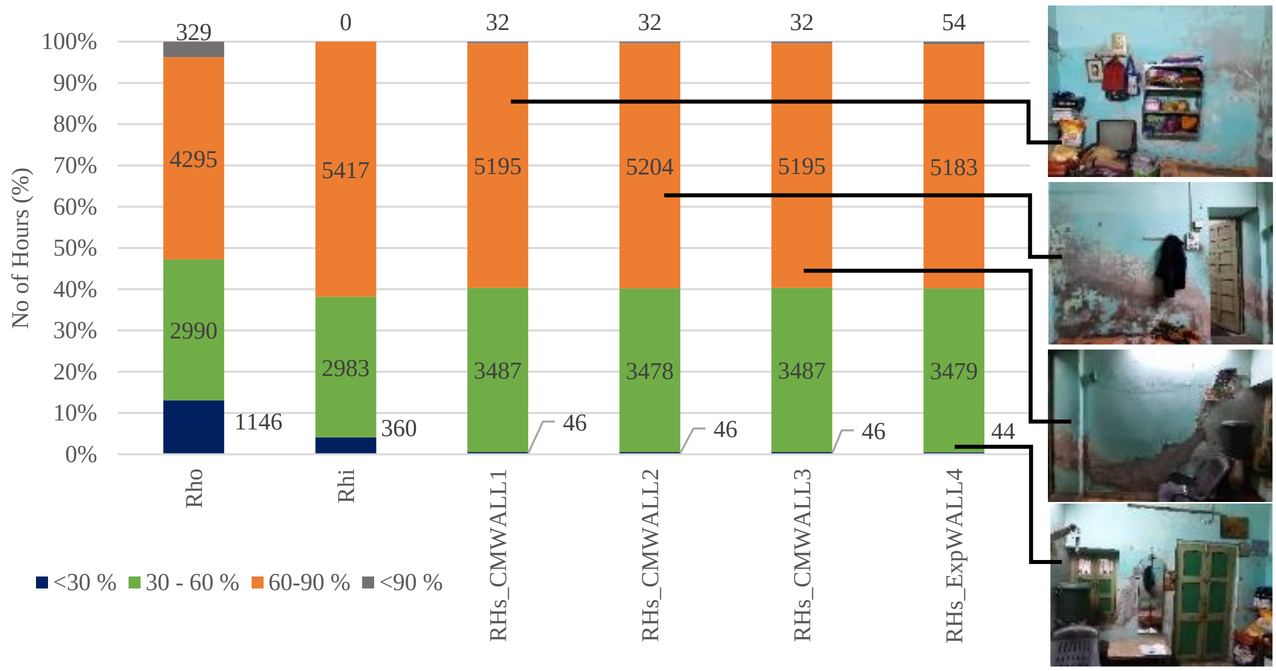



Figure 13 PT_B RH levels observed throughout the year with respect to the number of hours.

The space PS_A has an occupancy of 3 and had mold on all the walls as observed in PT_B. However, the percentage of mold observed in this space is less as compared to PT_B. This can be referred to through surface RH values in the similar simulation graphs plotted for this case. The box plot in Figure 14 has maximum surface RH values always below 90%. A difference of 17% is observed between the maximum value of outside to inside RH levels.

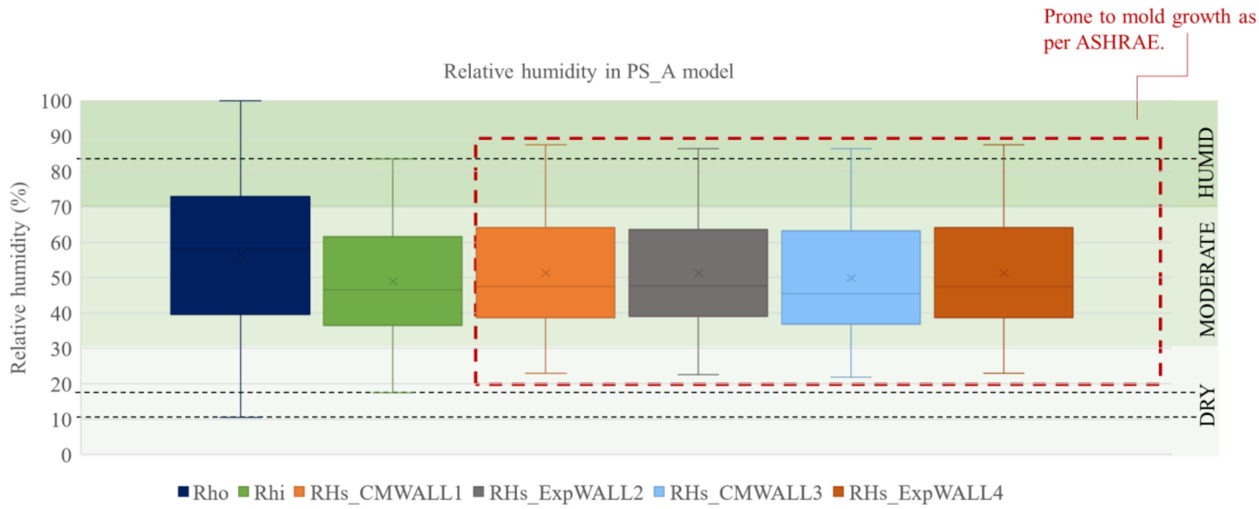



Figure 14 Relative Humidity levels of space and on the surface of the walls in PS_A.

The detailed high and low values throughout the year are given in Figure 15. The surface RH near the walls of the space is in the range of 60% to 80% for the monsoon months. For three consecutive months at a stretch, the surface relative humidity is more than 70% which makes it more susceptible to mold growth at those times (27).

The duration of the range of RH levels is observed in Figure 16. The inside space is humid and is above 60% for more than 6000 hours (i.e. more than 70% of 8760 hours). This can be due to consistent occupancy in the space throughout the year. In the absence of a moisture source, the humidity near the walls does not cross 90%. Thus, there are no chances of condensation happening near the walls.

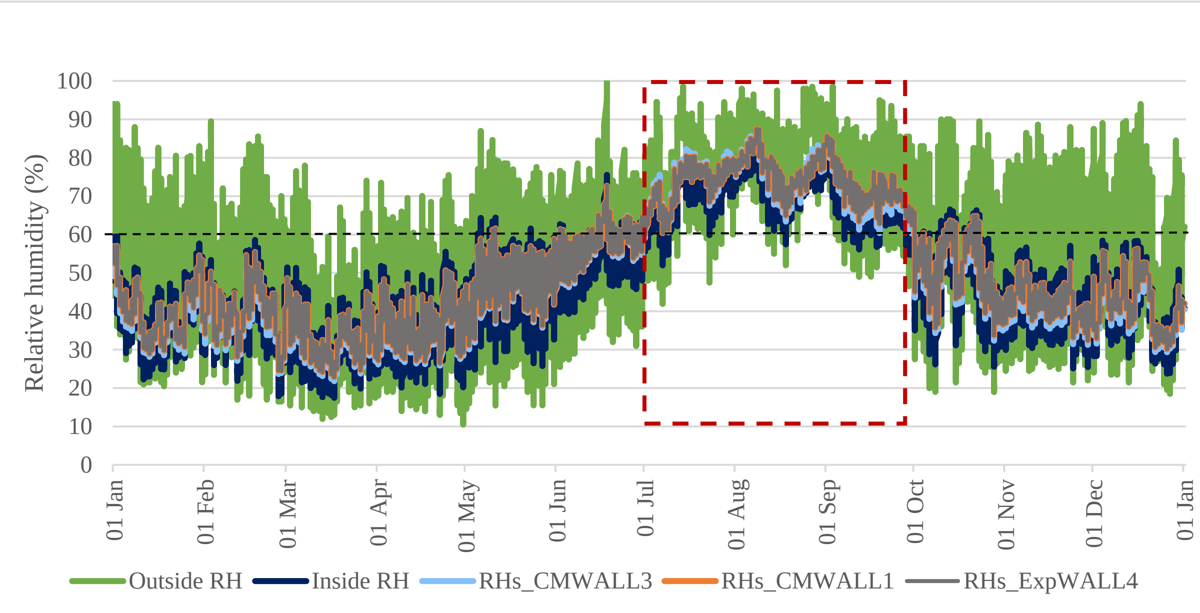



Figure 15 Varying RH levels with time throughout the year in PS_A

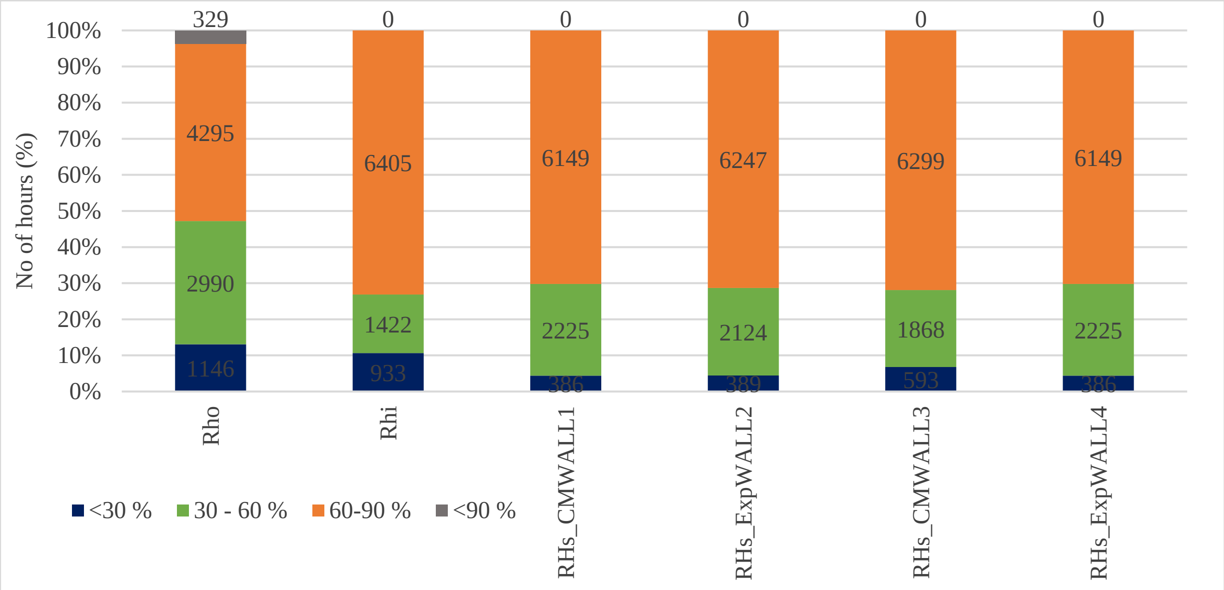



Figure 16 PS_A RH levels observed throughout the year with respect to the number of hours.

Through simulations the moisture buffering and MRT inside the space is observed. Lime plastered spaces maintain MRT between 20℃ to 30℃ and 9% to 11% of the difference from the outside RH level. Overall, simulations can also help to predict how long the walls are exposed to high RH levels (>70 %) and when they are exposed to mold growth risk. The indoor RH is modulated and MRT is lower in these spaces.

### 4.2 Survey Results:

The observations of the survey results are discussed in this section for the Pol houses and residences.

#### 4.2.1 Pol Houses

The surveyed pol houses are categorized according to the coatings used over lime plaster. According to Figure 17, for the studied period from December to March the outside RH levels are between 10% to 55%. However, the minimum value is higher inside by 2.1% in lime-wash houses and 1% in Non-porous paint. For outside RH below 15%, the inside RH is high. The reason can be moisture buffering of the material, occupancy, and inside moisture generation rate.

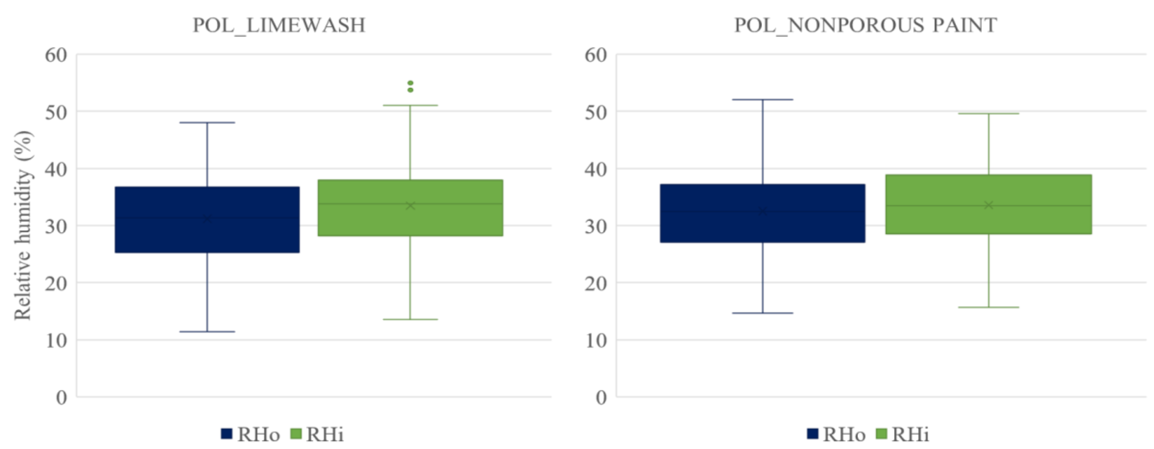



Figure 17 RH levels of studied POL houses.

The inside and outside temperatures in both cases are plotted in Figure 18. In spaces having limewash, the air temperature is lower by 1℃. For the non-porous finish, the inside ambient temperature is lower by 1.4℃ from the outside high. The outliers observed are the readings when the space is exposed to solar radiation. Otherwise, the rest of the spaces are always under shade.

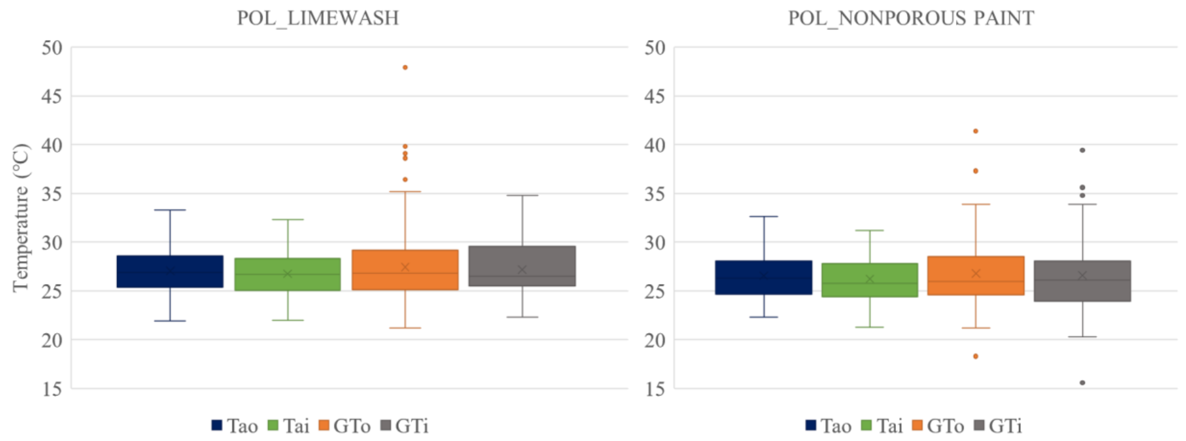



Figure 18 Temperature levels of studied POL houses.

To further examine the simulation observations for sample space PT_B, the onsite readings are analyzed. In Figure 19, the outside relative humidity is compared with the inside space RH levels and the surface RH levels from January to March.

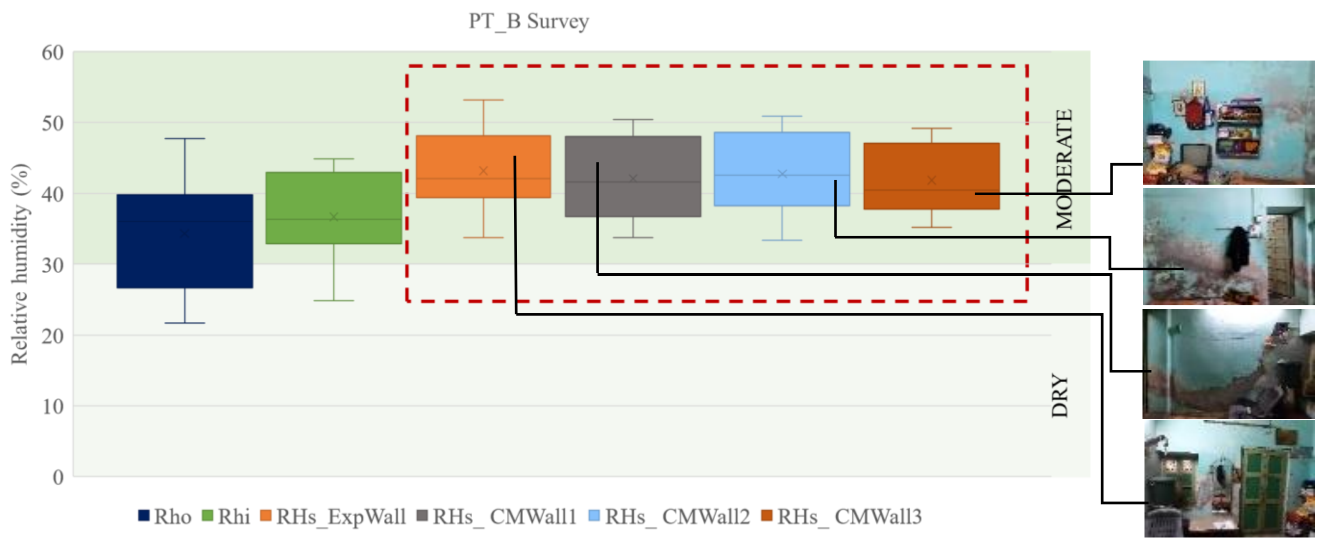



Figure 19 Onsite RH levels inside PT_B

Similar to the simulation results (refer to Figure 11), surface RH levels are higher than the inside RH levels where moisture buffering is observed. 50% of the readings are higher inside than the outside indicating it to be humid inside. The minimum values of surface RH levels are 9.8% to 12.4% higher than the minimum of inside space (RHi). And the maximum surface RH is 4.3% to 8.3% higher than the maximum of inside space. So, if the above pattern is followed throughout the year, whenever the space RH goes above 60%, the surface of the wall will have around 65 to 70 % RH. In the monsoon period when the outside RH levels are in the range of 80-95%, the RH near the walls can be predicted to reach 95 to 97%. At this RH level, if the moisture is not removed from the surface, it gets prone to mold growth.

#### 4.2.2 Girikunj Residence

For Girikunj Residence, the spaces also included a basement and topmost rooms exposed to the sun. The study span is for March. Figure 20 shows the relative humidity and temperature readings in this span. The outside RH of Girikunj is between 14.6% to 40% for March. For the given dataset, the inside space is having indoor relative humidity between 18.2% to 37.4%. A difference of 3% to 4% is observed between the high and low values from outside to inside. Whereas the ambient temperature and globe temperature are lower by 3℃ and 2℃ from outside high temperature. The mean is also lower by 2.2℃ and 5.4℃ for ambient and globe temperature respectively. No water activity or occupancy (excluding the surveyor) is observed inside any of these spaces. The mean value of the globe temperature inside is significantly less by 6% from the outside.

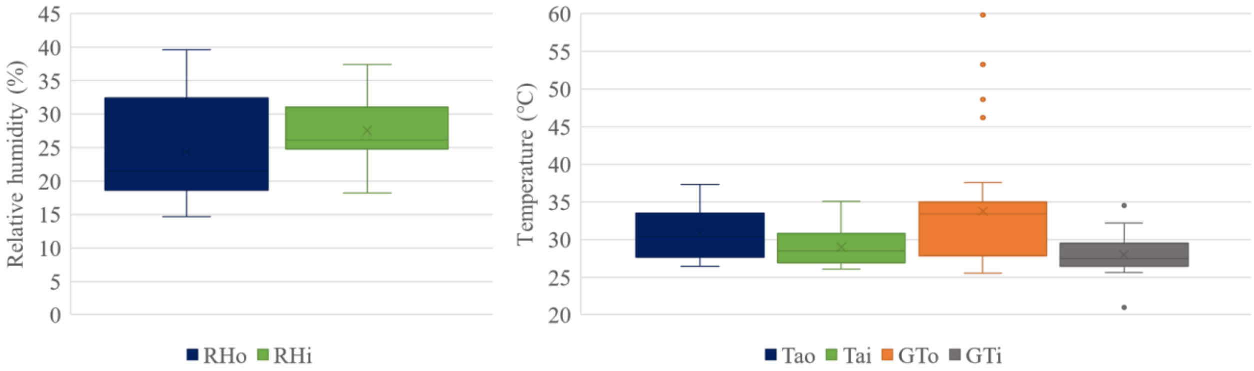



Figure 20 RH and Temperature levels of Girikunj Residence

This can be additionally understood in Figure 21 where a basement space (PZ_D), a ground floor space (PZ_B), and a topmost terrace space (PZ_I) are plotted in one graph.

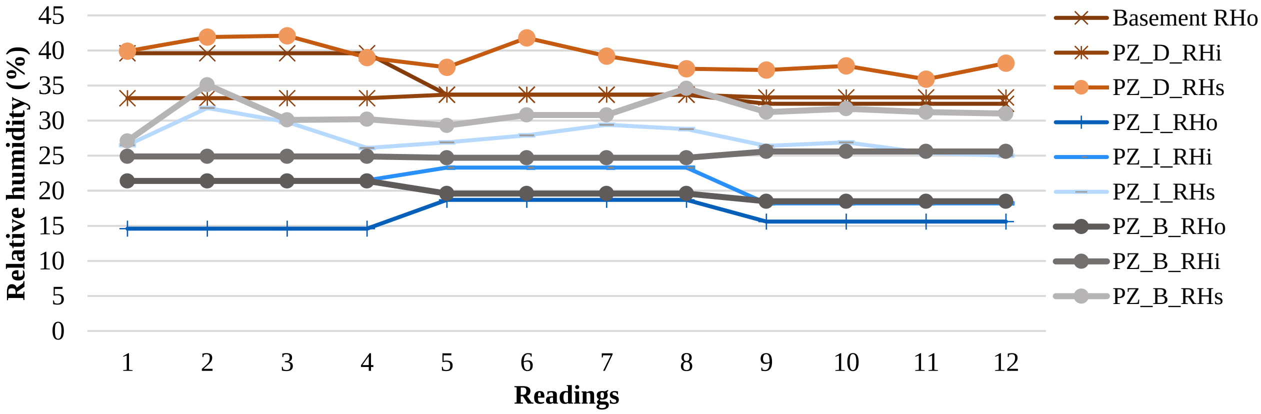



Figure 21 RH levels inside different rooms in Girikunj Residence

The outside RH levels of terrace space have RH levels between 15 to 20% while inside RH levels are higher inside by a minimum of 2.6% to a maximum of 7.0% from the outside. Also, the surface RH levels are high from the inside RH levels by 5% to 8.3%. Mold is observed on these surfaces even though the RH levels are low than the rest of the spaces. The reason can be due to the presence of earthen pots used as insulation on the terrace or a source of seepage of moisture from outside to inside. Mold was also observed in basement spaces. As seen on the graph the basement is relatively damp. The surface RH in the basement is higher in the range of 35 to 40% than in the other spaces and so is the space's inside RH levels.

#### 4.2.3 RSR Residence

The topmost coating in RSR residence is that of Venetial lime plaster. It is smooth marble-like finish lime plaster that doesn't require any paint coating. Thirteen ground floor spaces are surveyed of this residence. The readings are only for March which is plotted in Figure 22.

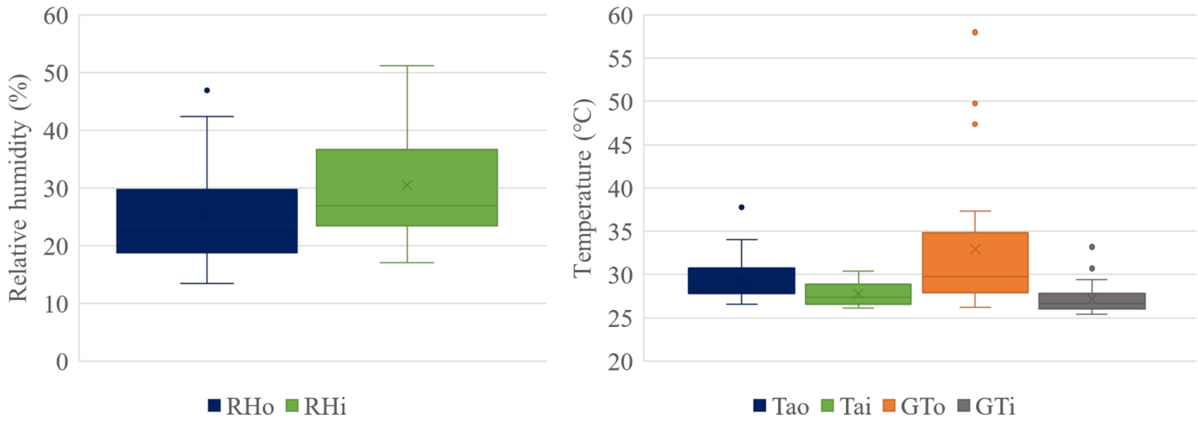



Figure 22 RH and Temperature levels of Girikunj Residence.

The following Figure 23 has the RH levels of two ground floor spaces are plotted where one is having mold growth (RJ_K) and the other is free of mold (RJ_J). Both spaces are adjacent to each other. In the RJ_K case, the inside RH is high by 8 to 14%. A maximum difference of 18% is observed between the surface RH and indoor RH. Whereas, the RH of the adjacent room RJ_J is high by 1% to 5%. The surface RH is high by 5% to 9%.

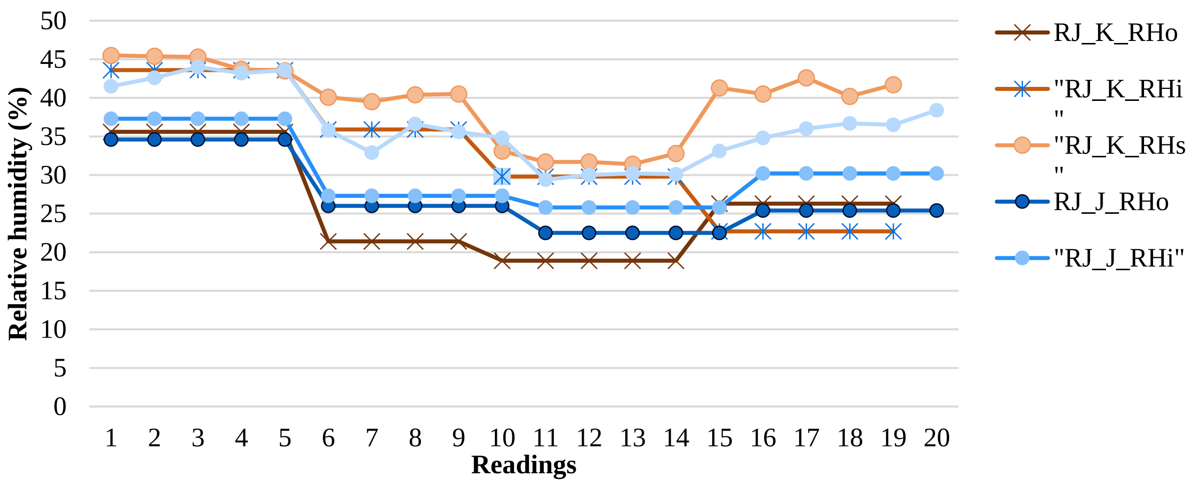



Figure 23 RH levels inside different rooms in RSR Residence

### 4.2.4 MRT observations

Figure 24 shows the trend followed in the MRT as the temperature outside rises in all the studied spaces. The MRT of the space is calculated using the formula mentioned in the Appendix. The difference between MRT observed outside with the inside is compared. It can be seen that as temperature rises in all the spaces except for those having nonporous coating over lime plaster, the difference is increasing. A positive increase shows that the inside MRT is lower than the outside MRT. A steeper slope is observed for the RSR residence where lime plaster is exposed. This is followed by Girikunj Residence and then limewash Pol houses.

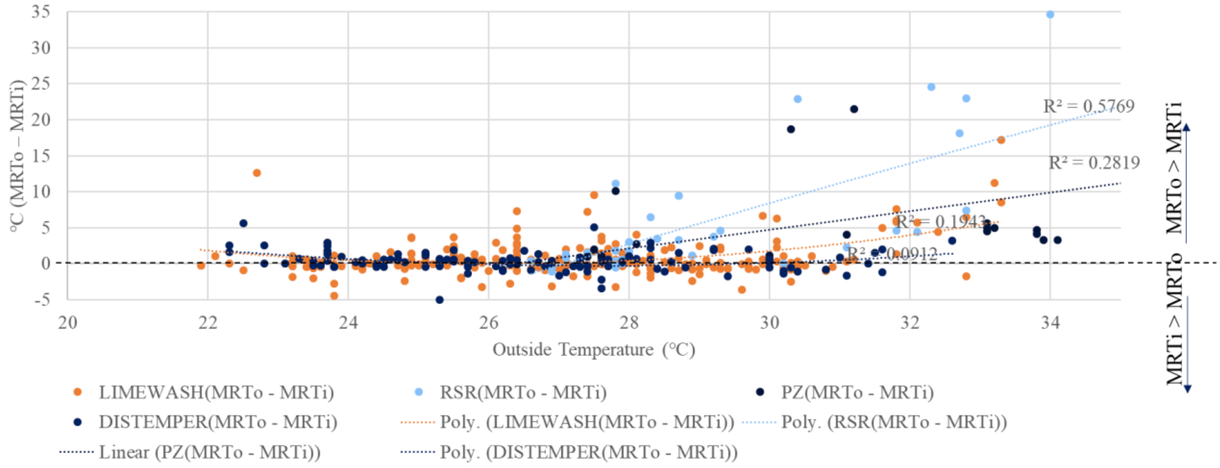



Figure 24 MRT performance for different categories of lime plaster survey cases.

The percentage of time when MRT inside space is higher than the outside in March is plotted in the graph below Figure 25. This graph indicates that 30% of the time it was hotter inside for non-porous paint spaces. For limewash coated spaces the percentage was 18.52%. RSR and Girikunj Residence have 8.57% and 7.41% respectively. Thus, RSR and Girikunj Residences are better performing and comfortable inside for more than 90% of the time. RSR remains cooler than all other studied spaces. Pol houses with Limewash coating are comfortable 81% of the time in March. This difference could be more in hotter months and needs to be studied further by year around measurements.

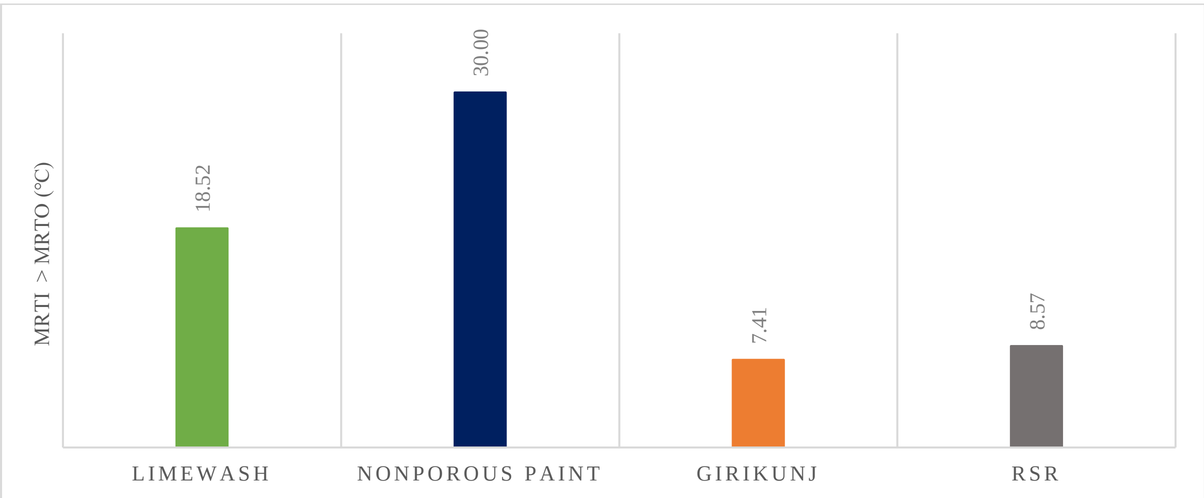



Figure 25 Percentage of readings Inside MRT > Outside MRT in Marchq

### 4.2.5 Mold Risk Observations

Through the survey results, it is witnessed that the hygrothermal behavior of space varies as per its characteristics. The spaces are identified and observed separately based on the topmost finish of the wall surface layer, air velocity inside the space, occupancy, storage, the sunlight received and the type of activity happening in that space. Figure 27 and Figure 26 describe the above factors that influence the mold.

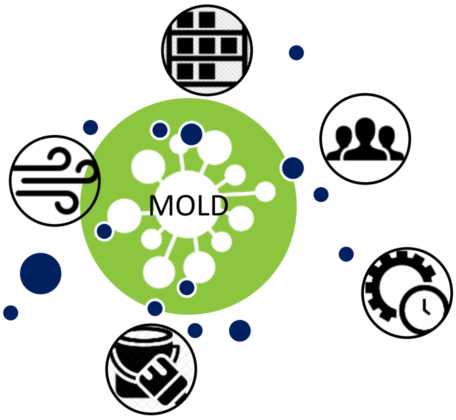



Figure 27 Factors affecting mould growth

Figure 26 Onsite photos of different case scenarios indicating the factors.

Further analysis of the moisture content recorded on the walls is shown in Figure 28. The walls of the spaces where mold growth is observed are marked in orange. Majorly all the walls of the studied spaces from December to March had low moisture content below 2%. These are drywalls and do not poses any damage due to mold growth. However, mold growth is still observed on these walls which indicates that during the monsoon season in the past the mold growth was initiated from within. This happens when the surface relative humidity of the walls goes above 60%. Other factors like damaged construction, presence of water pipelines, low ventilation, etc. are also the reasons. Further specifications can be found in Appendix B.

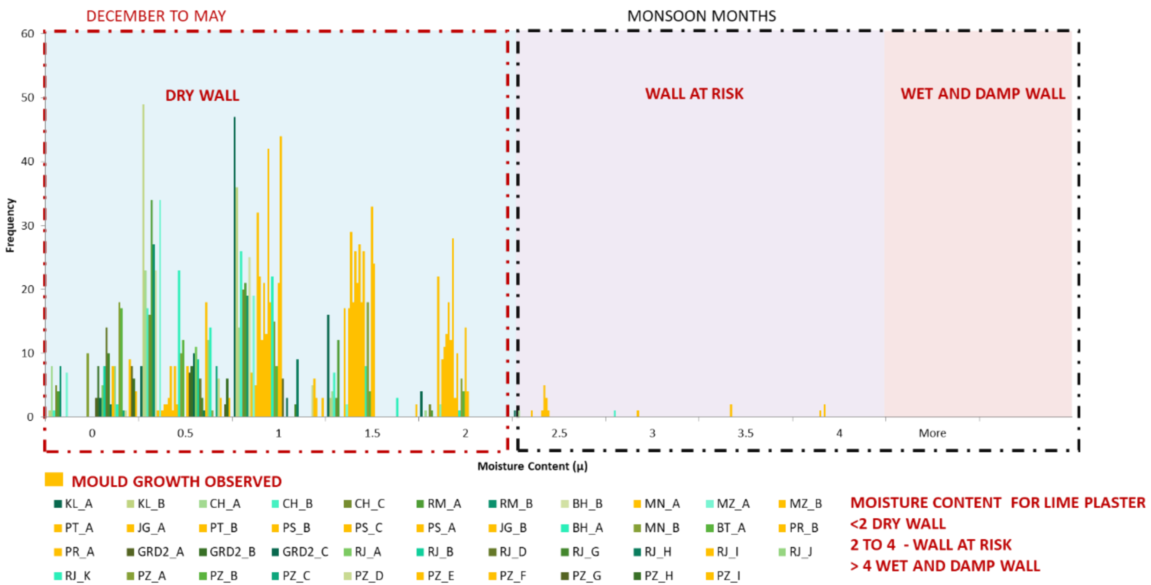


Figure 28 Moisture content of all walls studied from December to March.

Since the study span is during drier months there are hardly any walls having a moisture content of more than 2%. Nonetheless, mold is present on these walls which can further be analyzed by understanding the co-relation of moisture content with the surface relative humidity.

In Figure 29, all moisture content readings with their recorded indoor surface relative humidity on walls are plotted. The points marked in orange, ocher, red, and maroon represent the readings of walls having mold. The rest of the points are in the shade of blue. Referring to the characteristic curve of lime mortar in the moisture meter (50), the graph is divided into six sections. For humidity above 60% and moisture content above 2%, there are definite chances of mold. While for relative humidity below 30% and 1.5 moisture content the conditions are dry enough to restrict mold. No wall having mold recorded moisture content below 0.5.

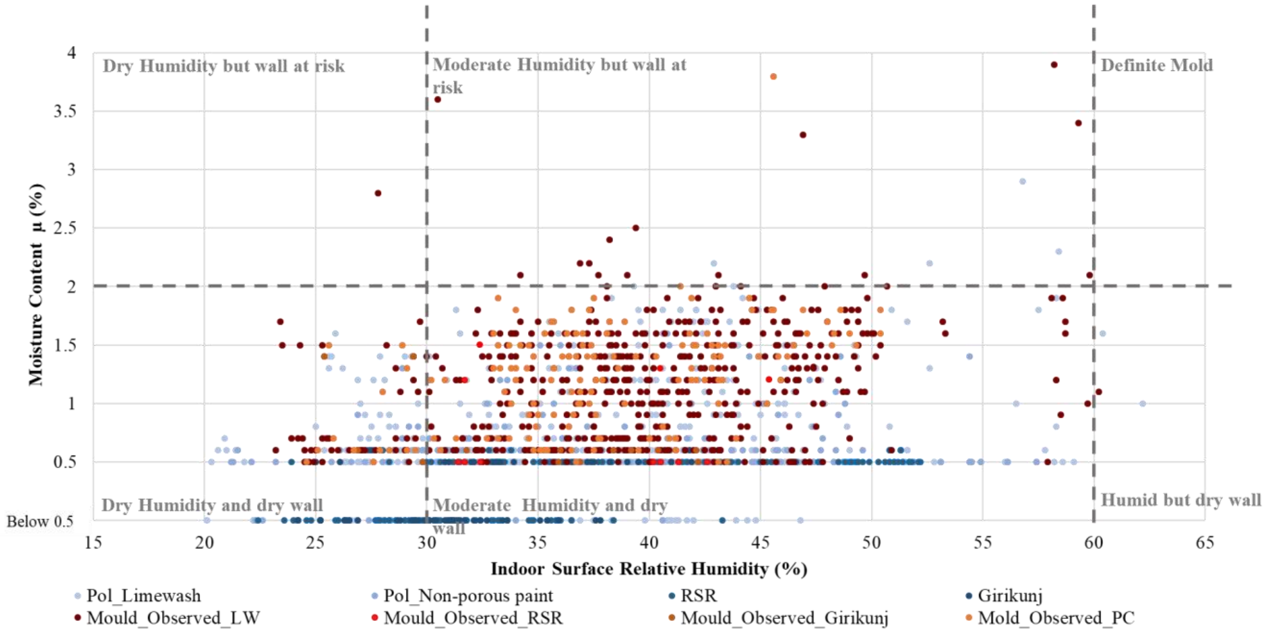



Figure 29 Moisture content Vs Surface relative humidity

Most of the readings are populated in the section of moderate humidity and drywall. These also include walls affected by mold in that range which is due to its predated presence on walls. This shows the poor performance of the building during monsoons or due to damage. Points lying below 60% and above 2% moisture content suggest the moisture being trapped in the walls leading to mold growth.

Points in bright red are of RSR residence, where the reason for the presence of mold was the existence of a water pipeline and high moisture source (pool) outside the space. Whereas, in Girikunj residence (marked in ocher) the mold was observed in the basement and space attached to the terrace. Due to rain leakage near the slab of the terrace, the walls might have been damaged. There are several blue scatter plots observed towards the right of the graph indicating well ventilated and undamaged walls.

Overall, a gradual shift towards the right is observed with the increase in indoor surface relative humidity. This indicates the increase in moisture content with the increase in the indoor surface relative humidity.

Figure 30 below shows the scenario of each space concerning the mentioned factors. It helps in identifying the strongest and common factors that affect mold growth. The spaces highlighted in black are indicative of mold growth. All the spaces are then further categorized and color-coded under the following observations:

- Plaster paint: Coating used over the plaster-like lime wash paint, distemper paint, plastic emulsion paint, or not coated. If the topmost coating is nonporous, the moisture is trapped inside and this results in mold growth.
- Ventilation: If the wall surfaces are not properly ventilated, the moisture inside the pores of the finishing layer gets stagnant giving rise to mold growth.
- Sunlight: Sunlight plays a role in killing bacteria and keeping highly humid surfaces dry.
- Water Activity: High water activity i.e activities like washing, cleaning, etc. results in higher moisture inside the space.
- Clutter near the wall (Storage): More stuffed the room is, more will be the more humidity pockets created inside the space.

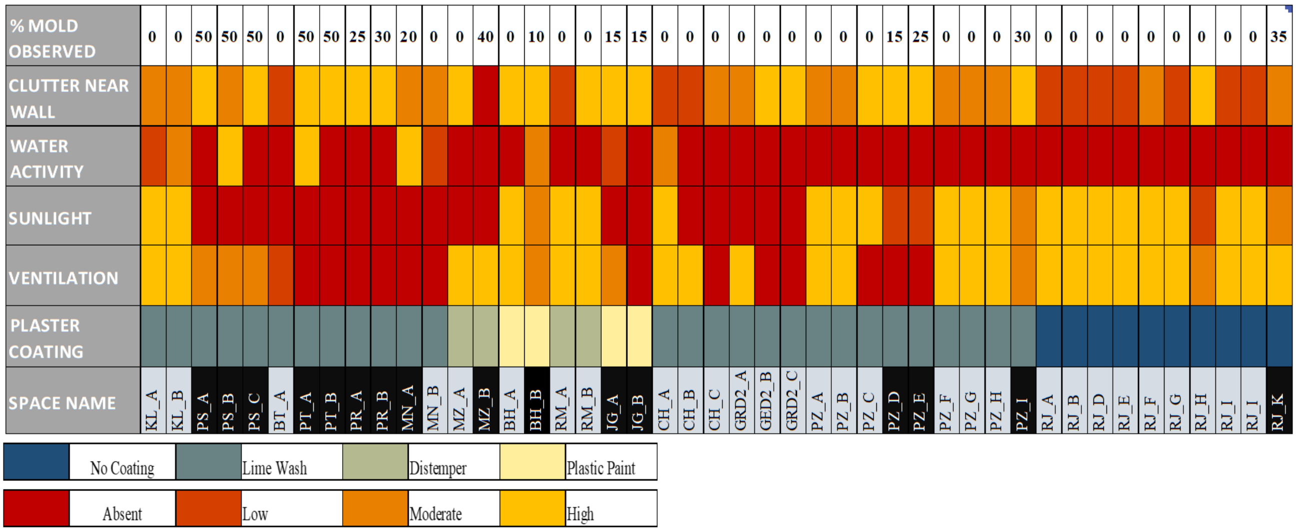



Figure 30 Inference map

The best and the worst combination for predicting the mold risk can be inferred from this. For example, the worst-case scenario is observed in spaces PT_B and PT_A. More than 50% of walls are densely covered with mold. PT_B has a good scope of ventilation but the openings are always closed. So, it can be stated as low ventilated, no sunlight, no water activity, moderate storage near walls, and lime wash coating on the wall. Even though there is no water activity, other factors are dominating it. In another case, PT_A has openings mostly closed, so no ventilation, no sunlight, high water activity, moderate storage near the walls, and lime wash. In both cases, it is observed that due to lack of ventilation and no sunlight the moisture is trapped inside the space thus leading to mold growth. The best combination is where lime plaster is not coated or coated with limewash, well ventilated with sunlit spaces.

It can be suggested that mold growth inside lime plaster is observed if the buffering of moisture is obstructed. If lime plaster is allowed to breathe, there won't be favorable situations created for mold growth.

Out of all the 45 spaces, 57% are spaces in Pol and 43% are of individual residences. In comparison to the pol houses, these individual residences have better strategies. In the hotter month of March, they show better hygrothermal performance and are more than 90% of the time comfortable. It is cooler inside than outside by 1 °C to 5 °C. The walls are drier and are recorded to be mostly below 0.5% of moisture content. Thus, as seen in Figure 31, only one space is affected due to mold out of 10 spaces. The exposed lime plaster can buffer moisture easily which helps in moderating the indoor Rh levels inside well. Due to passive strategies like air vents, maximum daylight the spaces are well ventilated and maintained. The major issue observed in lime plastered Pol houses was the lack of proper ventilation, sunlight, and maintenance.

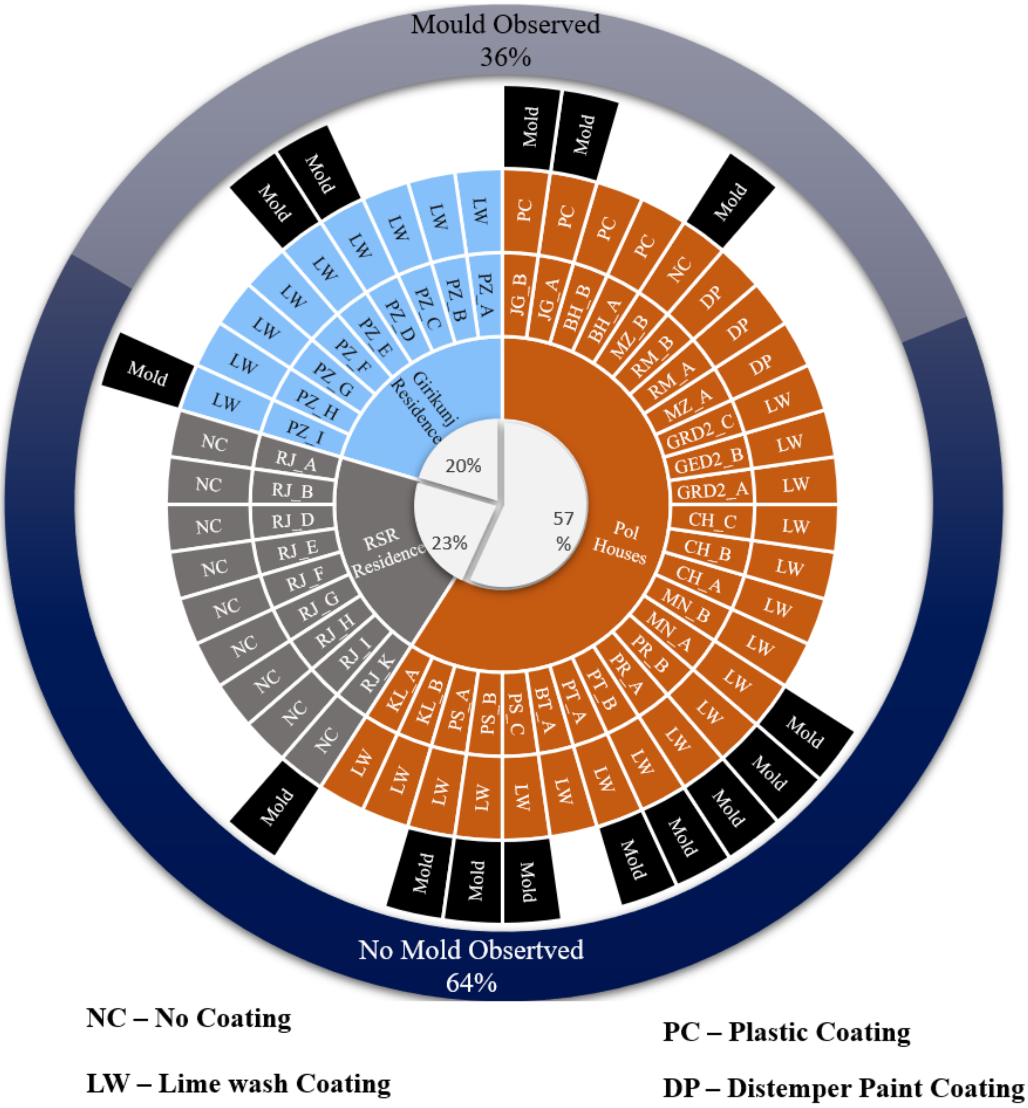
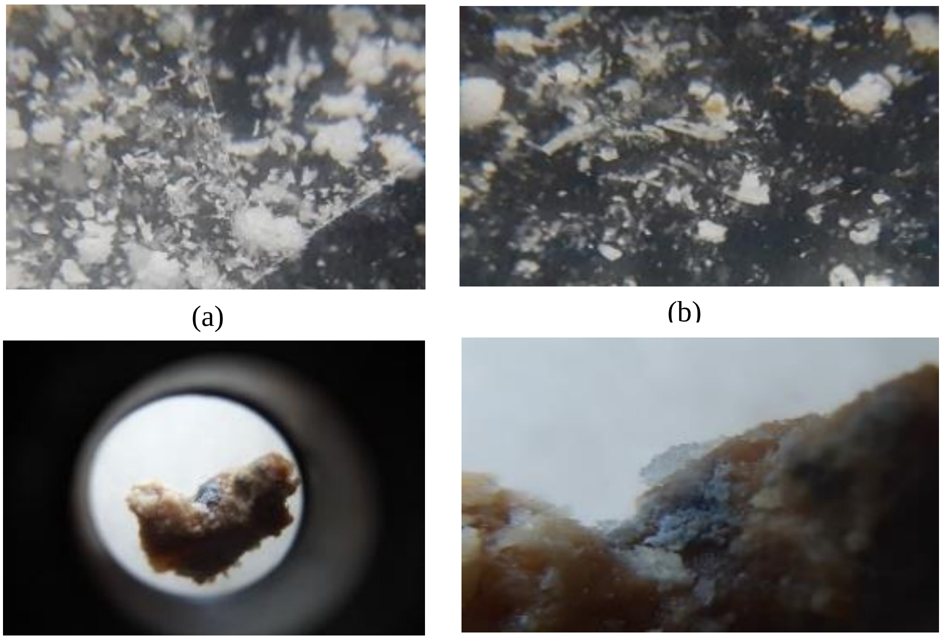



Figure 31 Overall summary of surveyed spaces.

### 4.2.6 Mold type observation under the microscope

Samples of mold are collected from the site to demonstrate the presence of mold instead of salination on the walls. Altogether the most common type of mold that is formed over lime plaster can be observed. Figure 32 shows the collected samples as observed under a 40x microscope.



(a) (b) (c) (d)

Figure 32 (a) and (b) mold sample collected from a lime plaster wall from different spaces. (c) and (d) mold sample collected from gap between wall and wooden door frame

As observed in (a) and (b), the tread-like filaments are the hyphae of the mold structure. The small granules are likely to be the spores. The images captioned as (c) and (d) above, are of the sample scrapped from a gap between a wooden door frame and the lime plaster wall. This type of mold is different from the one observed on the walls having lime plaster. In all the surveyed spaces mold was observed on the surface of walls except for the previous case. Furthermore, observation under a high-resolution compound microscope is required to identify the type of mold. Samples collected from the site are mentioned in Appendix H

## 4.3 Studying the onset of mold growth in a lime plaster sample.

Of the four jars, the one containing potassium sulphate had signs of mold growth earlier. All the samples of lime plaster introduced inside had an initial moisture content of 0.6 % and weighed 20gms.

In three cases (having RH 75%, 80%, and 86%) no visible mold growth was observed till the third week. However, at 96% RH mold growth can be visibly seen on the lime plaster sample after three weeks (Refer to Figure 33). If the surface relative humidity inside the space is more than 90%, a favorable environment is created for mold and fungi, provided there is enough buffering and ventilation happening.

Figure 33 Mold growth on sample under 96% RH

As this experimentation is in progress, the weight and moisture content are not checked afterward. But it can be assumed to have increased moisture content than it initially had.

# 5 Conclusion

The hygrothermal performance of lime plaster in naturally ventilated spaces is assessed and co-related with mold risk in this study. The EMPD simulations enable the prediction of the moisture buffering activity at wall surfaces. It also helps to predict the duration for which the walls are exposed to high RH levels. This can be used to identify the mold growth risk of different surfaces. However, more numerical analysis with hygrothermal properties of typical lime plaster used in India needs to be carried out for realistic predictions.

Through the point-in-time surveys, the significance of using appropriate wall finishes is understood. It can be established that the finishing coat applied over wall surfaces alters the properties and characteristics of the plaster underneath it.

If lime plaster is coated with nonporous coatings, it is not able to maintain an effective Mean Radiant Temperature (MRT) difference from outside to inside. As compared to spaces having nonporous coatings over lime plaster, spaces having a lime wash or exposed lime plaster could effectively maintain comfortable MRT inside during the study period.

The walls with high surface RH observed are susceptible to mold risk if this humidity of more than 60% is not removed for more than four weeks. The experiment for the onset of mold growth proves that for constant humidity above 95%, mold growth is visible after three weeks. By combining this observation with the simulations, the chances of mold growth in that space can be predicted.

In dry weather conditions, surface RH levels of the studied spaces are high than the outside. So, these levels are predicted to rise even more in monsoon and therefore prone to mold growth provided the space is well maintained and ventilated with proper sunlight. The most important parameter to avoid mold is the application of non-porous coating over the plaster. Thus, it is important to allow the wall to breathe and to have adequate ventilation.

The performance gap between a simulation and an actual case can also be narrowed down for better predictions if the simulations are carried out in collaboration with survey observations.

Lime Plaster as a building material is good for moisture buffering. It effectively maintains the RH levels inside a naturally ventilated space. As a passive technique for better thermal performance, it is advisable to use lime plaster for its beneficial characteristics. Taking the proper precautions, it is one of the most sustainable building materials that can be used in the building industry today as well. One important aspect to consider is preventing moisture from getting trapped in building fabrics.

## 5.1 Future Scope of work and recommendation and limitations

- Hygrothermal properties of typical lime plaster are to be derived. A fresh sample of lime plaster sample is being prepared for the same. But, due to time limitations and the long curing span of lime plaster required, it is still under process. Refer to Appendix G.
- The composition of lime plaster used in pol houses is not known and cannot be easily derived as it is older than 300 years. An EDX spectra analysis is required to be done for the chemical signatures, yielding a general stoichiometric formula to know the possible compounds within the sample.
- The study should be carried out over more than four months and should include the monsoon period when the RH is very high as well as the summer period.
- For experimenting onset of mold growth at different humidity, measuring RH inside while the experiment is in the process can help derive more conclusions. RH sensor circuit is in the process to be inserted inside the jars for logging the humidity inside. Refer to
Appendix E

- Furthermore, to improve the technical properties of lime plaster, optional additives as mentioned in (51)(37) (52) which are other than organic compounds should be used. This can prevent the degradation and damage to the plaster.
- Identify the type of mold observed in the survey spaces. Mold samples have been collected, but the identification through a microscope or other means is to be carried out. Refer to Appendix H.

# 6 Declarations and conflicts of interest

## 6.1 Conflicts of Interest

All authors declare no possible conflicts of interest.

## 6.2 Consent for publication statement

Ethics approval is not needed.

## 6.3 Consent for publication statement

Authors have secured informed consent to participate in the study and to publication before submitting it to the journal

## 6.4 Open data and materials availability

No further data was used in addition to referenced works.

## 6.5 Authorship contribution

Rashmin Damle has been the guiding faculty in this study and Vismaya Paralkar has done data compilation, assessments, and reporting.

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# Appendices

## Appendix A

**Instruments Specifications.**

Figure 34 shows the instruments used for carrying out the survey and experimentation.

Table 0-1 Instruments used for Survey

| Instrument | Measuring Range | Accuracy |
|---|---|---|
| **PEAKMETER MS6252A** | | |
| m/s(meter per second) | 0.40~30.0 | ±(2.0% reading+50) |
| ft/m (feet per minute) | 80~5900 | ±(2.0% reading+50) |
| km/h (kilometer per hour) | 1.4~108.0 | ±(2.0% reading+50) |
| mile/h(mile per hour) | 0.9~67.0 | ±(2.0% reading+50) |
| Knots(nautical miles per hour) | 0.8~58.0 | ±(2.0% reading+50) |
| CFM | 0 to 99990 | 0 to 9.999ft2 |
| CMM | 0 to 99990 | 0 to 9.999ft2 |
| CMS | 0 to 9999 | 0 – 9.999 m2 |
| | | |
| **FLIR: TG165** | | |
| Object Temperature Range | -25°C to 380°C (-13°F to 716°F) | ±1.5% or 1.5°C (2.7°F) |
| Thermal Sensitivity/NETD | <150 mK | |
| Detector Type | Focal plane array (FPA), uncooled microbolometer | |
| Field of view (FOV) | 50° x 38,6° | |
| IR Resolution | 80 × 60 pixels | |
| | | |
| **EXTECH Heat Stress meter** | | |
| Wet Bulb Globe Temperature (WBGT) | 32 to 122°F (0 to 50°C) | ±4°F/2°C |
| Black Globe Temperature (TG) | 32 to 176°F (0 to 80°C) | ±4°F/2°C |
| Air Temperature (TA) | 32 to 122°F (0 to 50°C) | ±1.8°F/1.0°C |
| Humidity | 0 to 100%RH | ±3%RH |
| Dimensions : | 10 x 1.9 x 1.1" (254 x 48.7 x 29.4mm) | |
| Ball Dim | 1.6" dia, 1.4" high (40mm diameter, 35mm high) | |
| **TESTO Moisture Meter: 606-2** | | |
| Temperature – NTC / Resolution | -10 to +50 °C | ±0.5 °C / 0.1 °C |
| Humidity - Capacitive | 0 to 100 %RH | ±2.5 %RH (5 to 95 %RH) |
| Resolution | 0.1 %RH | |
| Operating temperature | -10 to +50 °C | |
| Wood / Building material moisture | | |
| beech, spruce, larch, birch, cherry, walnut | 8.8 to 54.8 % by weight; | ±1 % |
| oak, pine, maple, ash-tree, douglas fir, meranti | 7.0 to 47.9 % by weight; | ±1 % |
| cement screed, concrete | 0.9 to 22.1 % by weight; | ±1 % |
| anhydrite screed | 0.0 to 11.0 % by weight; | ±1 % |
| cement mortar | 0.7 to 8.6 % by weight; | ±1 % |
| lime mortar, plaster | 0.6 to 9.9 % by weight; | ±1 % |
| bricks | 0.1 to 16.5 % by weight; | ±1 % |
| Measuring rate | 1s | |


Figure 34 Measurement Instruments

Table 0-2 Instruments used for Experimentation.

| Instrument | Measuring Range | Accuracy |
|---|---|---|
| **HOBO U10 Temperature and Humidity Logger (**Figure 35**)** | | |
| Temperature | -20° to 70°C (-4° to 158°F) | ± 0.53°C from 0° to 50°C (± 0.95°F from 32° to 122°F) |
| RH | 25% to 95% RH | ± 3.5% from 25% to 85% over the range of 15° to 45°C (59° to 113°F) ± 5% from 25% to 95% over the range of 5° to 55°C (41° to 131°F) |
| Operating range: | -20° to 70°C (-4° to 158°F); | |
| | 0 to 95% RH (non-condensing) | |
| Drift | 0.1°C/year(0.2°F/year) | |
| | RH: <1% per year typical | |
| Response time in airflow of 1 m/s (2.2 mph) | 10 minutes, typical to 90% | |
| | 6 minutes, typical to 90% | |


Figure 35 Instruments for Mold Growth experiment.

## Appendix B

To initiate the simulations, it is necessary to first get the basic input data required for the materials used in construction. Therefore, the sorption cure (refer Figure 36) is used in the basic BESTEST model geometry (refer Figure 37)

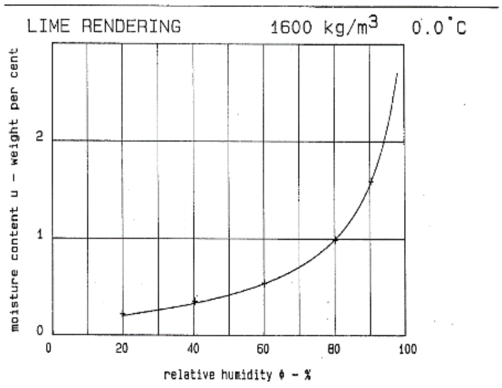



Figure 36 Sorption curve used for simulations.

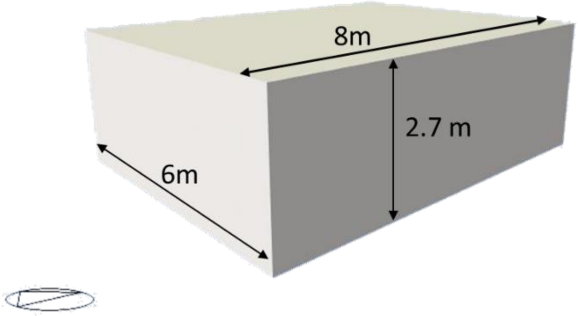



Figure 37 BESTEST Model Used for simulations.

The following formula is used for deriving the input data required in EMPD model

$\mu = a \cdot \phi b + c \cdot \phi d$

where,

a, b, c, d = Coefficients to define the relationship between the material's moisture content and the surface air relative humidity.

u = Moisture content defined as the mass fraction of water contained in a material, per mass of dry material [kg/kg]

ϕ = Surface air relative humidity [0 to 1],

**Error! Reference source not found.** shows the values derived using the solver method and back calculating the sorption coefficients. The values giving the least error are selected.

Table 0-3Derivation of sorption coefficients using solver in Excel.

| A | B | C | | | | | D | E | F | |
|---|---|---|---|---|---|---|---|---|---|---|
| Φ (%) | μ (%) | μ (kg/kg) | a | b | c | d | Calculated μ | D-C | E2 | Error |
| 0.1 | 0 | 0 | 0.000 | 3.197 | 0.001 | 0.195 | 0.001 | 0.001 | 0.000 | 4.89E-06 |
| 19.90 | 0.20 | 0.002 | | | | | 0.002 | 0.000 | 0.000 | |
| 40.2 | 0.4 | 0.004 | | | | | 0.003 | -0.001 | 0.000 | |
| 60.1 | 0.5 | 0.005 | | | | | 0.006 | 0.001 | 0.000 | |
| 80.1 | 1 | 0.01 | | | | | 0.012 | 0.002 | 0.000 | |
| 90.3 | 1.6 | 0.016 | | | | | 0.016 | 0.000 | 0.000 | |

The values derived from the above table are then inputted in the Energy Plus Software which is shown in **Error! Reference source not found.**.

Table 0-4 Input values of material for EMPD simulations.

| **Name** | **Units** | **Lime Plaster** |
|---|---|---|
| Water Vapor Diffusion Resistance Factor | Dimensionless | 7.3 |
| Moisture Equation Coefficient a | Dimensionless | 0.000 |
| Moisture Equation Coefficient b | Dimensionless | 3.1965 |
| Moisture Equation Coefficient c | Dimensionless | 0.00106 |
| Moisture Equation Coefficient d | Dimensionless | 0.19515 |

| | | |
|---|---|---|
| Surface Layer Penetration Depth | m | auto-calculate |
| Deep Layer Penetration Depth | m | auto-calculate |
| Coating Layer Thickness | m | 0 |
| Coating Layer Water Vapor Diffusion Resistance Factor | Dimensionless | 0 |

Table 0-5 Input parameters of models for simulation

| Description | BESTEST model | PT_B model | PS_A model |
|---|---|---|---|
| Location | Ahmedabad | Ahmedabad | Ahmedabad |
| Simulation Type | EMPD | EMPD | EMPD |
| Dimensions | 8m x 6m x 2.7 m | 2.6m x 3.5m x 3.0 m | 8m x 6m x 2.7 m |
| Volume | 129.6 | 23.32 cu.m | 69.01 cu.m |
| Occupancy | 0 | 1 | 3 |
| Moisture Source | 500 gms | NA | NA |
| ACH | 0.5 | 0.5 | 0.09 |

The layout and images survey model used for simulation is given in and Figure 38.

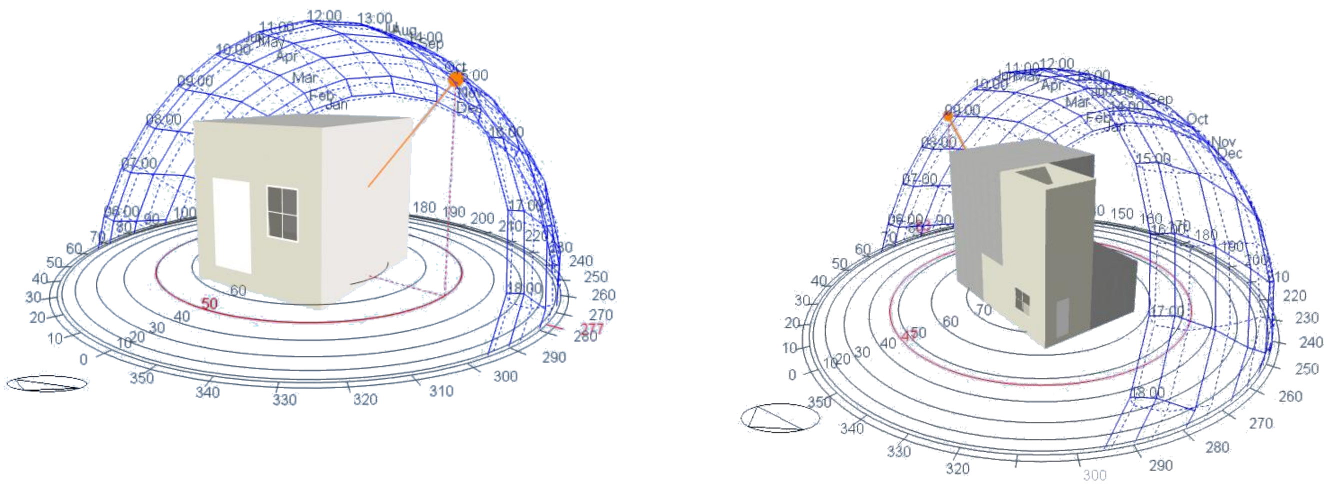


Figure 38 Simulation model of survey space PT_B

The layout and images survey model PS_A used for simulation is given Figure 39

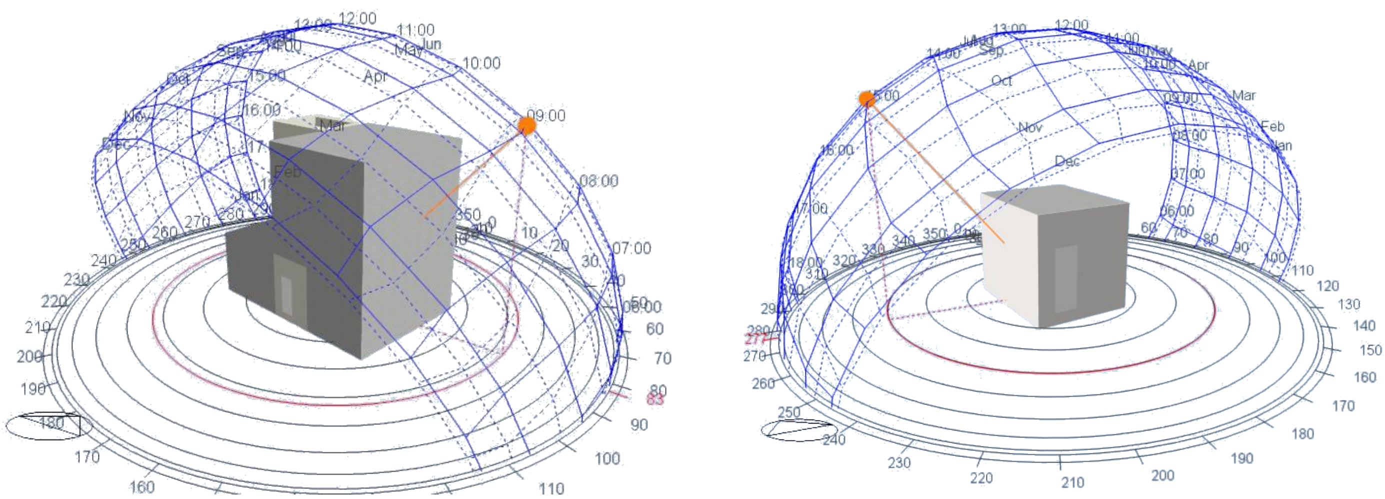


Figure 39 Simulation model of survey space PS_A

# Appendix C

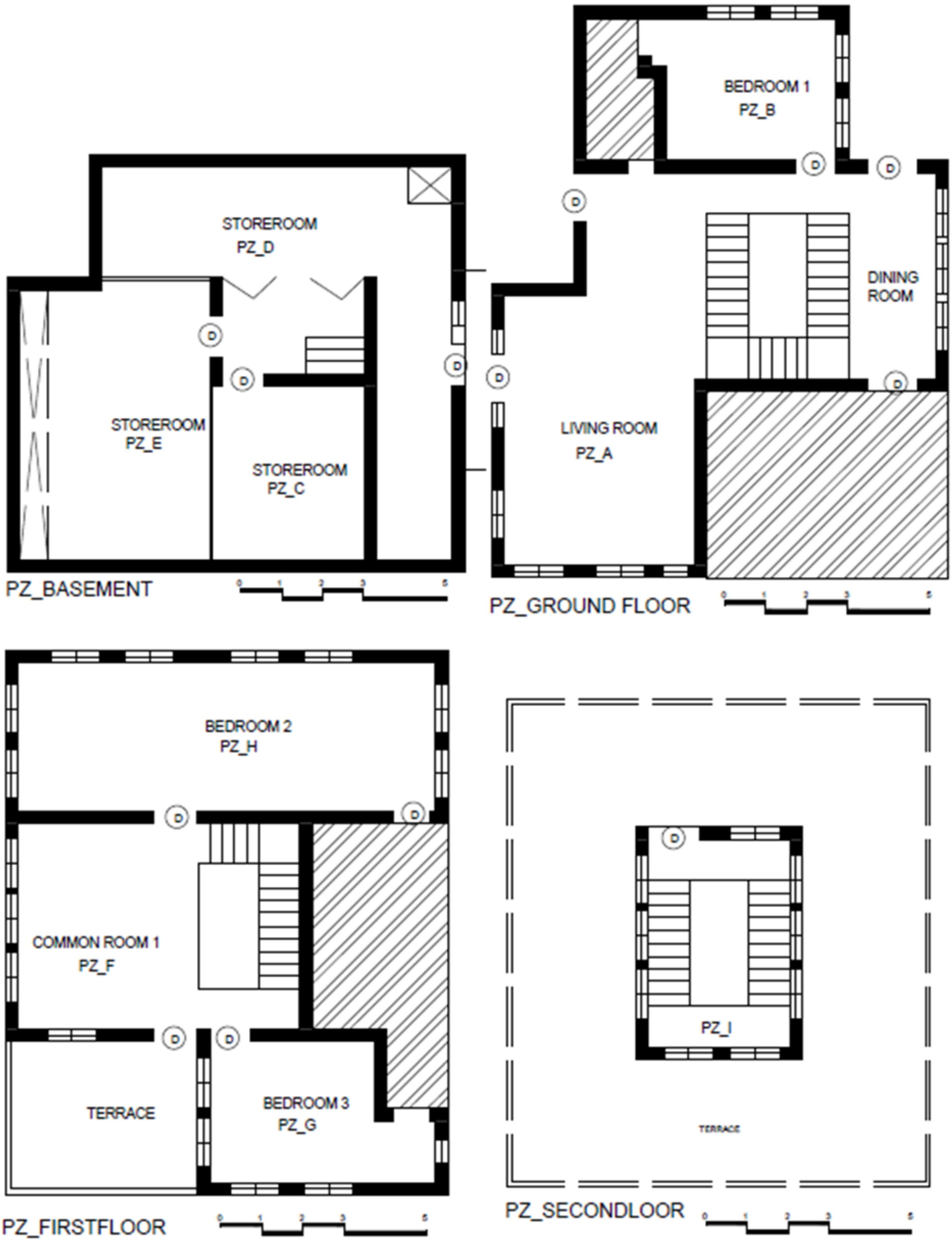



Figure 40 Girikunj Residence layout.

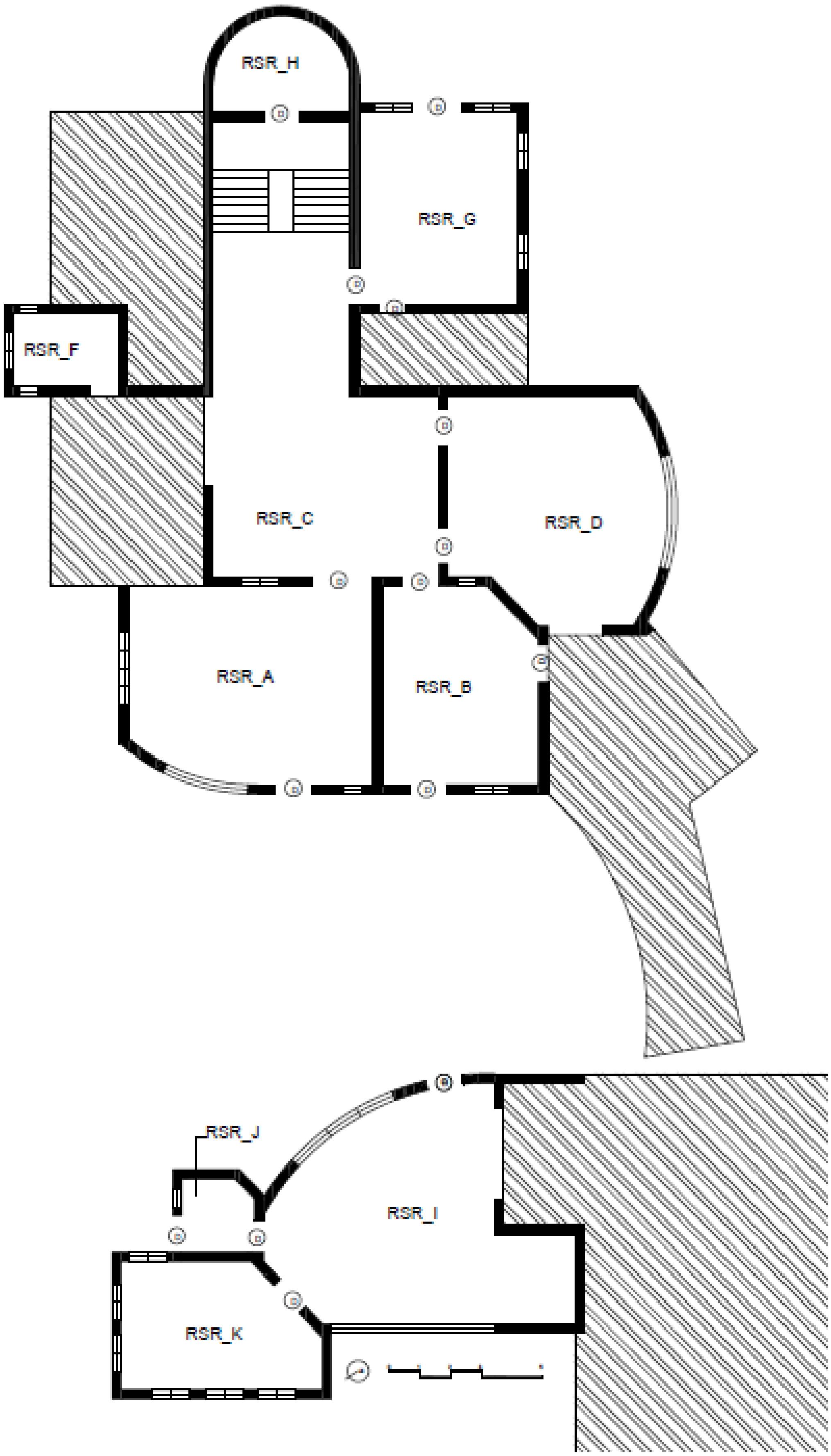



Figure 41 Layout of RSR studied spaces

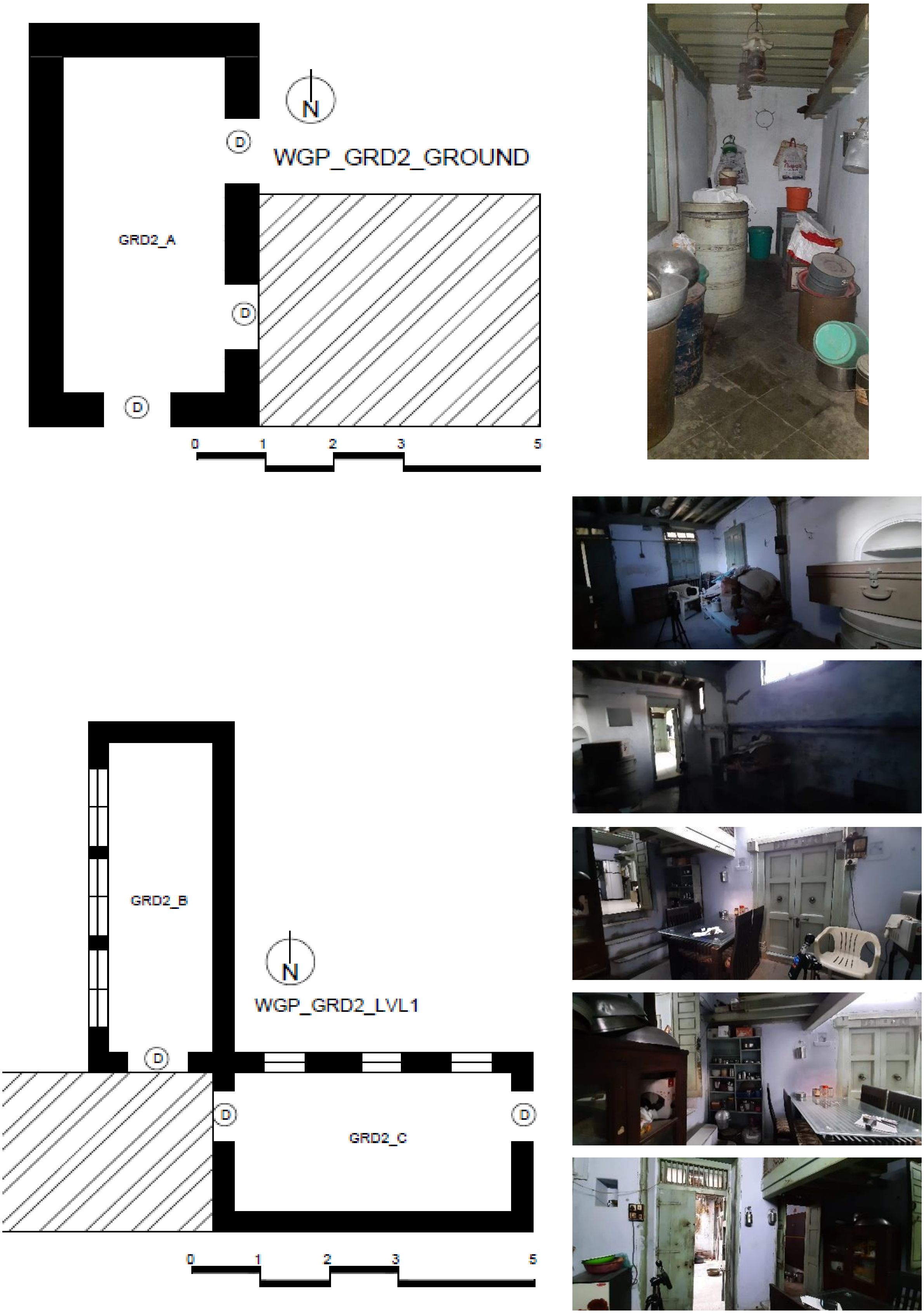



Figure 43 Grade II Structure layout and images


Figure 44 Pol house PT layout and images


Figure 45 Pol houses BH and KL layout and images.

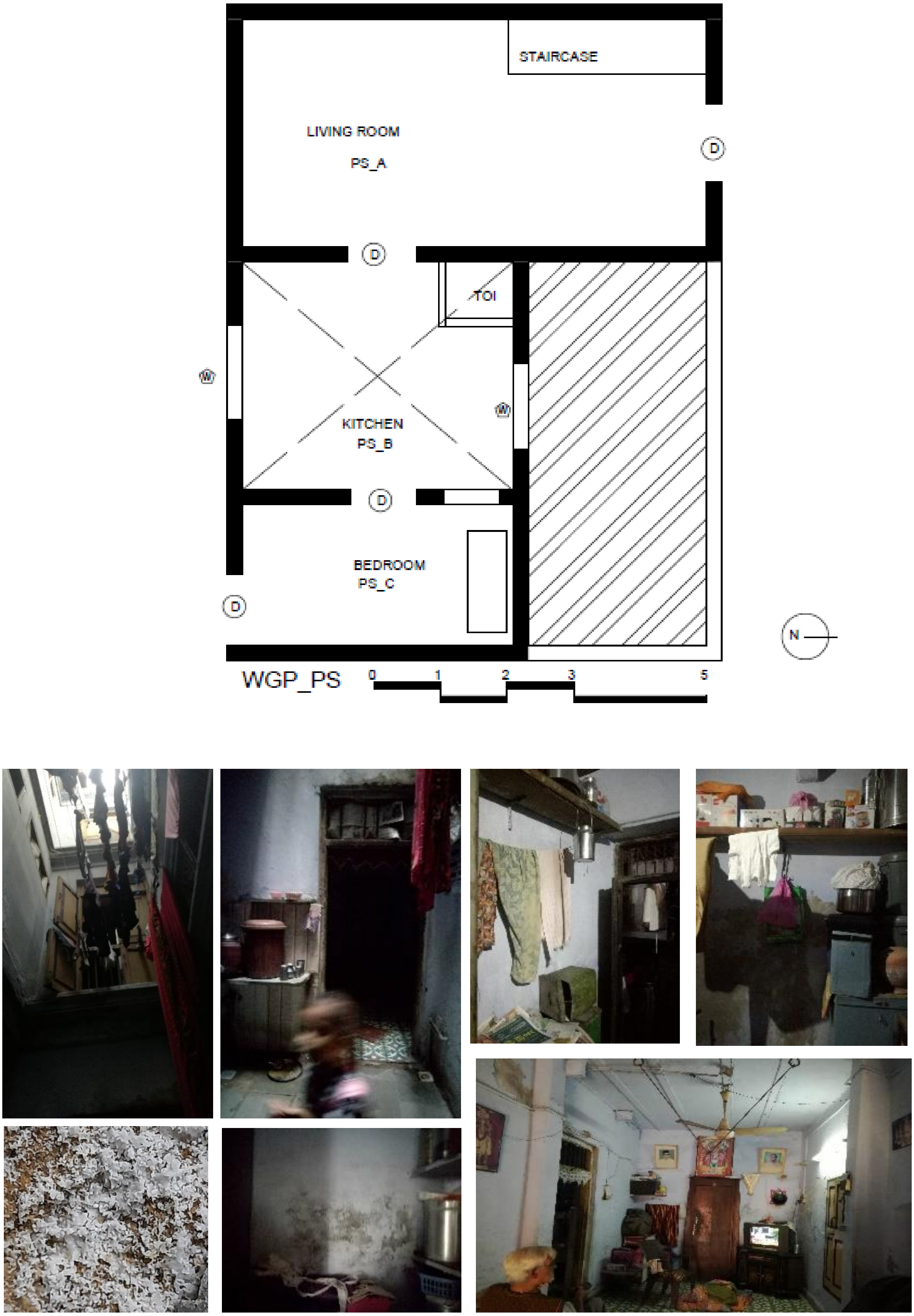



Figure 46 Pol house PS layout and images.

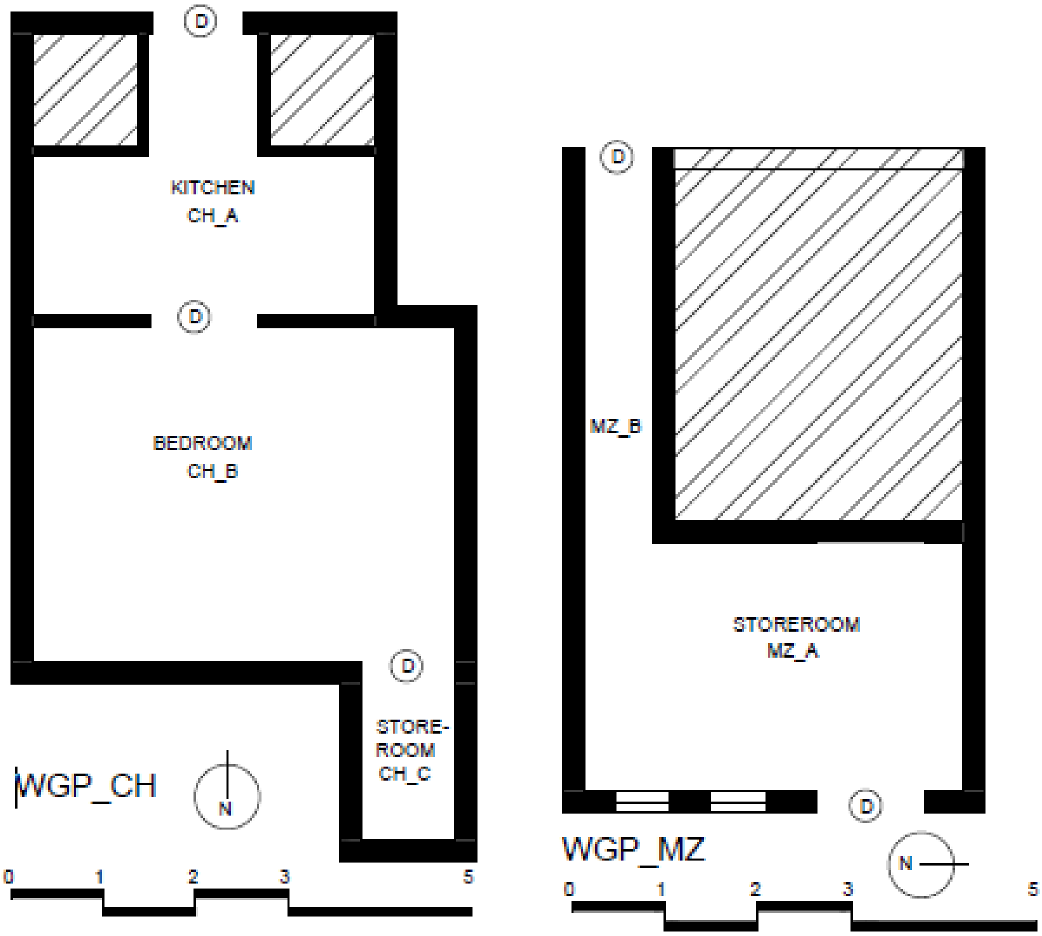
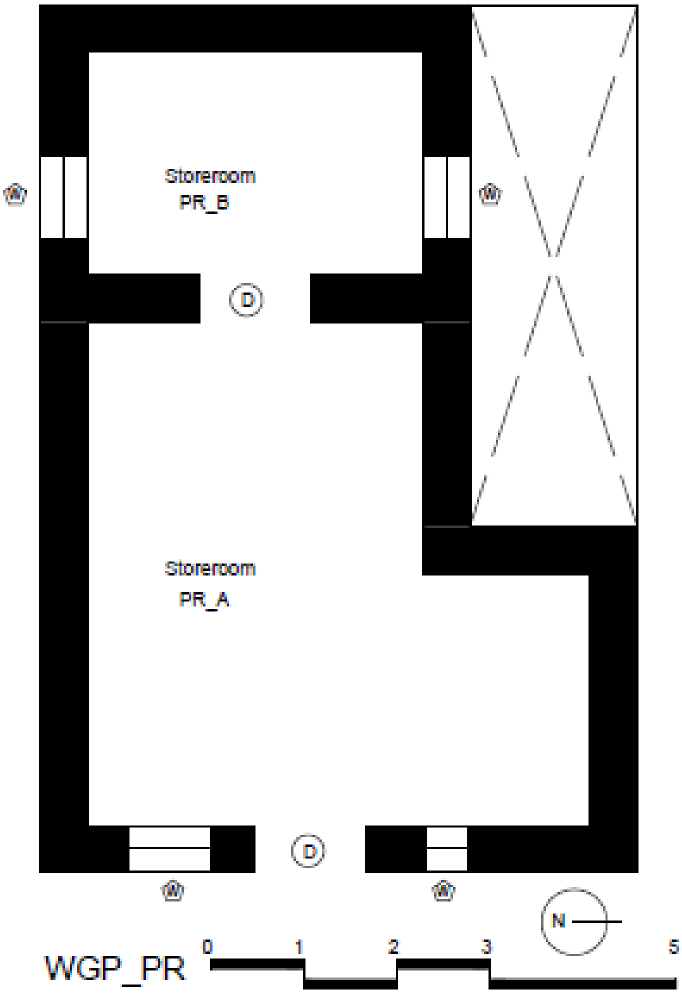



Figure 47 Pol house CH and MZ layout and images.


Figure 48 Pol house JG layout and images



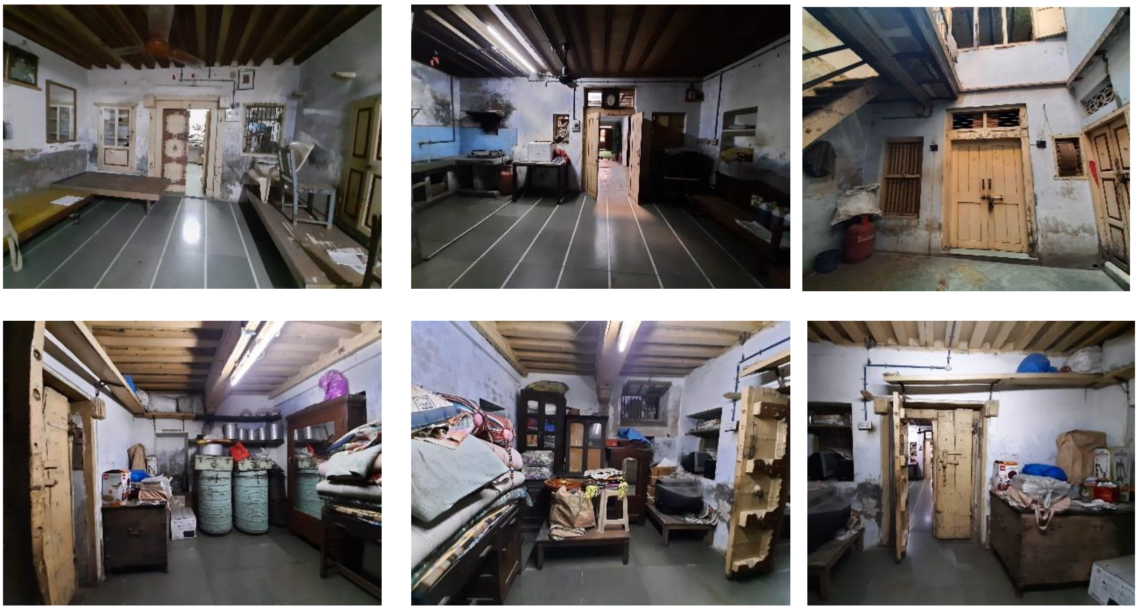



Figure 49 Pol house PR layout and images

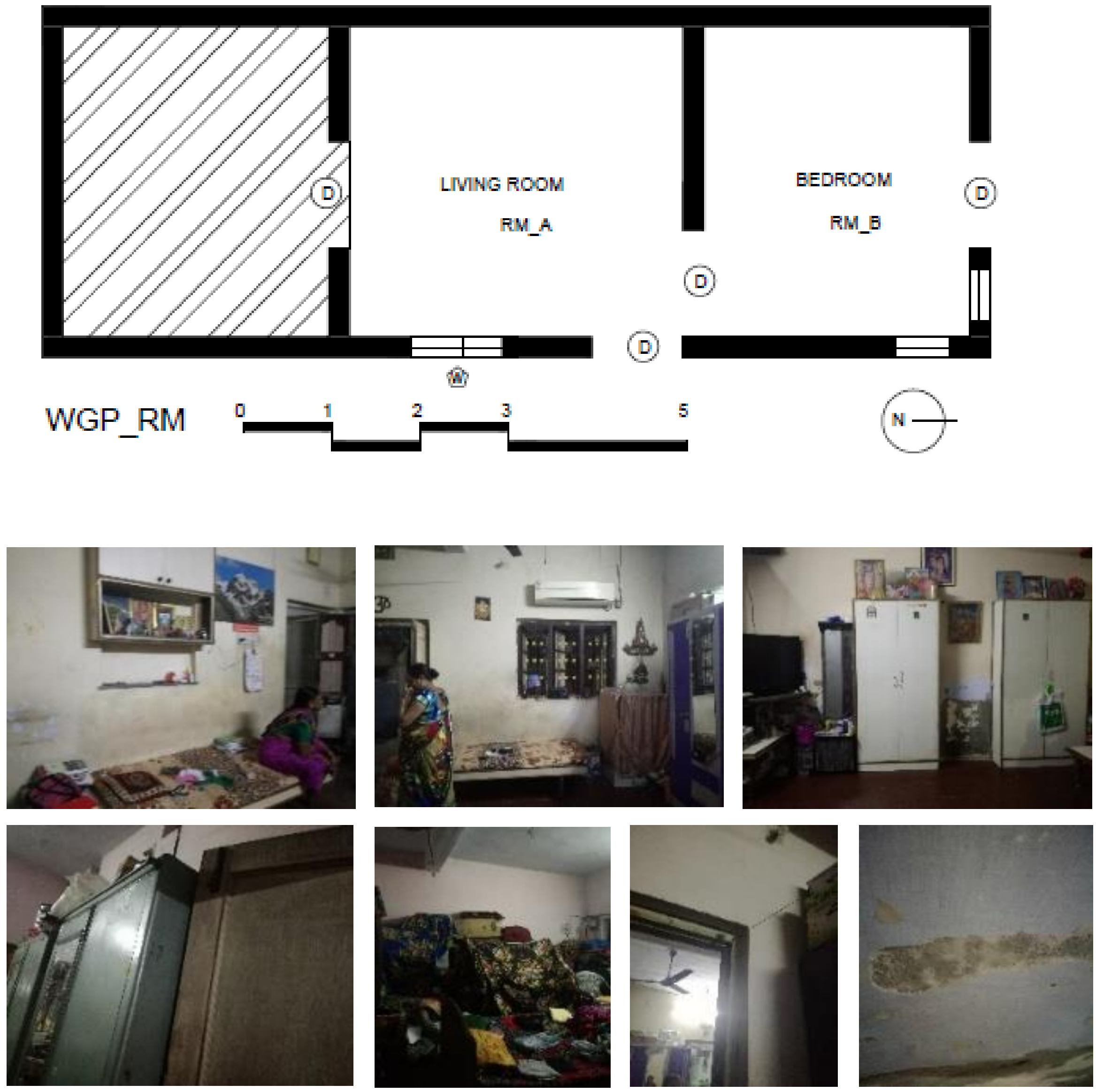



Figure 50 Pol house RM layout and images

## Appendix D

For calculating the MRT the following formula was referred from (53)

$$\text{Tmrt} = \left( \left( (Tg + 273.15)^4 \right) + \left( \left( \frac{hcg}{\varepsilon * D^{0.4}} \right) (Tg - Ta) \right)^{\left(\frac{1}{2}\right)} \right) - 273.15$$

Where $h_{cg}$ is the globe's mean convection coefficient.
Black Globe = $1.1 * 10^8 * va^{0.6}$

*va* – wind velocity

ε - emissivity of sphere (0.95)

Tg – globe temperature (°C)

Ta – air temperature. (°C)

D – Diameter of the sphere (mm)

## Appendix E

RH sensor circuit assembled for the onset of mold growth experiment.

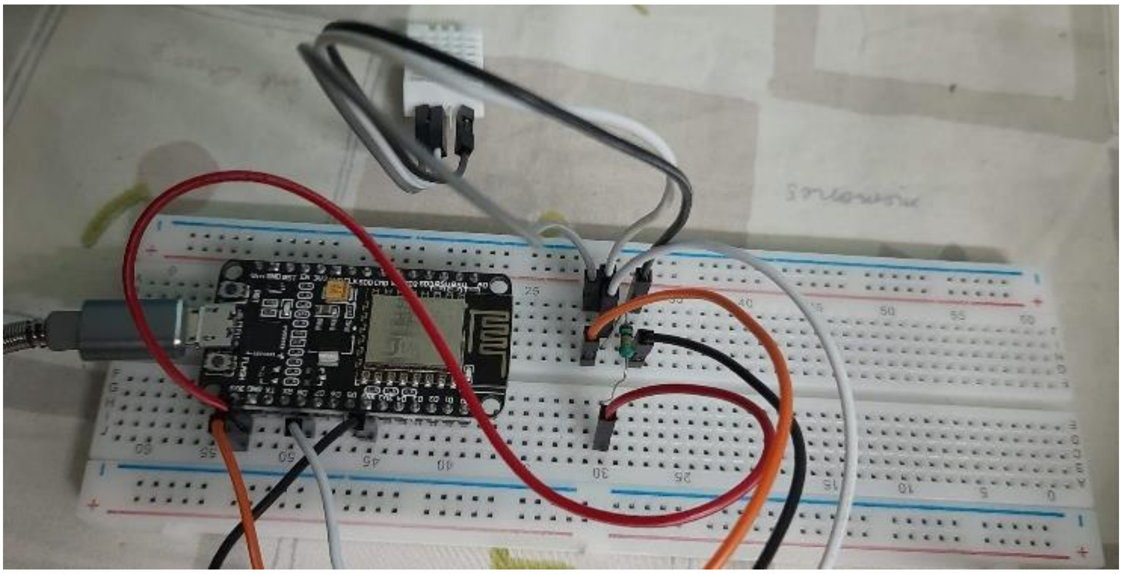


Figure 51 RH sensor circuit for logging RH levels

## Appendix F

Logger data of the salt solutions showing maintained RH levels.

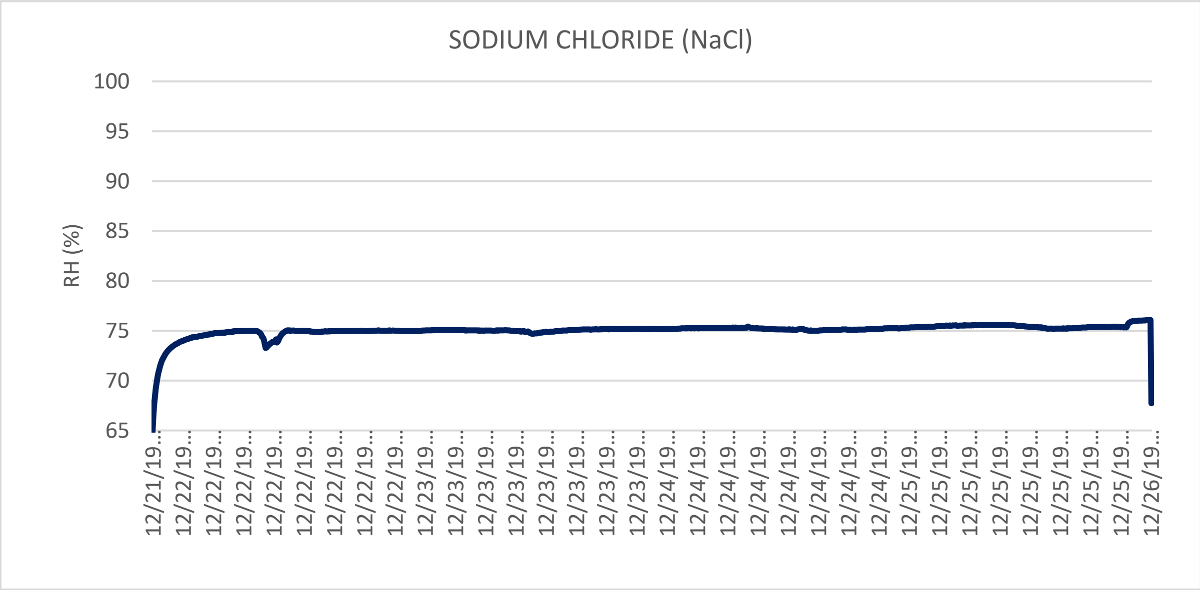



Figure 52  75% RH maintained by NaCl

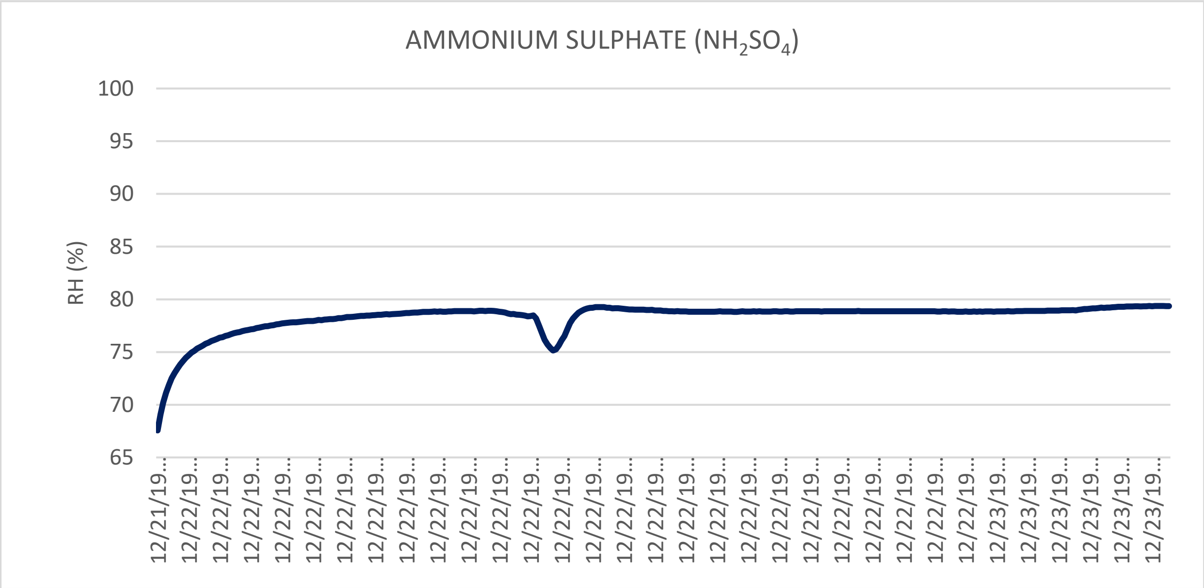



Figure 53 80% RH maintained by $NH_2SO_4$

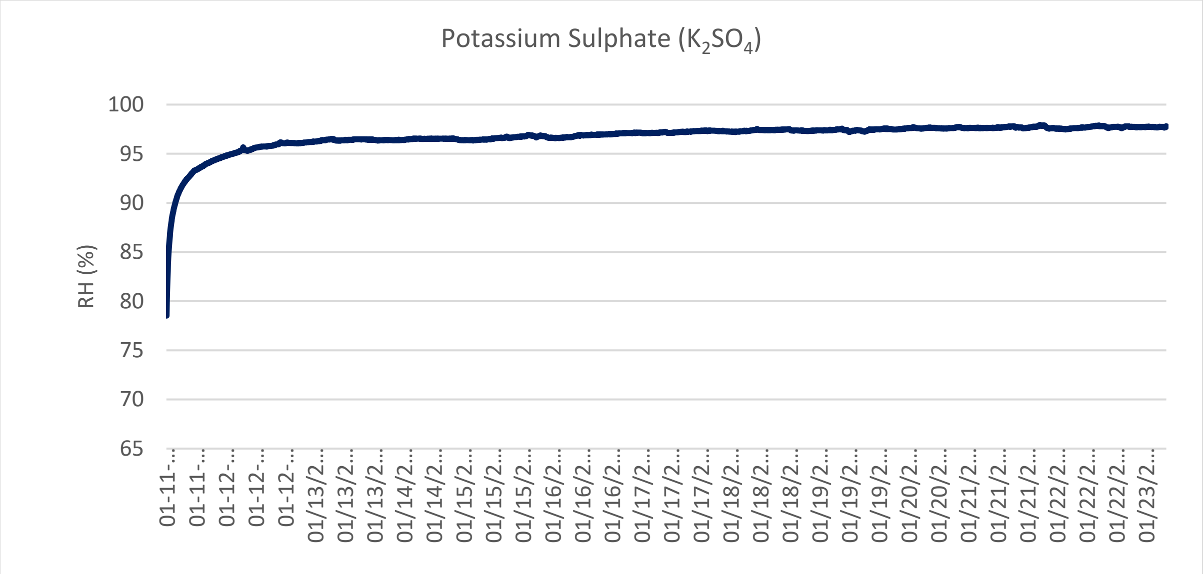



Figure 54 96% RH maintained by $K_2SO_4$

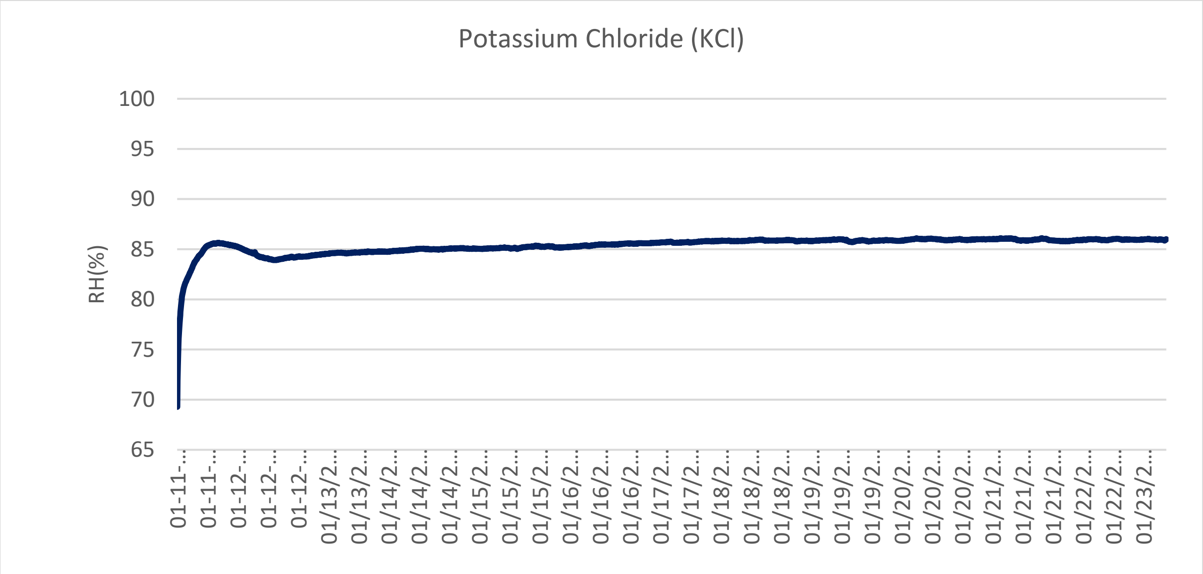



Figure 55  86% RH maintained by KCl

## Appendix G

To derive the hygrothermal properties of eight lime plaster samples are in making. First, lime is slaked and kept for more than 24 hours. This is then mixed in three parts of Surkhi with one part of lime and additives are added. After keeping the mixture for two to three days, it is poured in a battery mold of 90mm x 90 mm each. The first layer of ten millimeters is prepared and left for more than ten days to cure. The next 10mm of layer is then poured over it. The mixture contained, one part lime, one and half part sand with meethi, googol and jaggery.

Figure 58 Slaked lime

Figure 56 Lime putty after mixing surkhi and additives.

Figure 57 Lime Plaster samples in a battery mold for curing.

## Appendix H

Mold samples collected from site.

Figure 59 Mold samples collected onsite