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Hygrothermal Simulation of Multilayer Foamcrete Wall Panel with Pozzolans

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Abstract

Innovative building materials have been used in building envelops to reduce the heating and cooling loads of the building. Foamcrete consist of an air-void network that not only makes it lightweight but also improves the thermal properties of cement composites. This numerical study aims to assess the hygrothermal performance and risk of fungal growth in multilayer lightweight concrete panel with foamcrete and pozzolanic admixtures. A model of 226 mm thick wall assembly consisting of plaster layers on both surface with foamcrete filled in between the layers of normal concrete was created in WUFI Pro software. Also, a layer of weather resistive barrier was provided on the exterior surface to prevent rainwater. The foamcrete layer used consists of fly ash, metakaolin, and silica fume replaced by cement up to 20% by weight, for the cast density of 400 kg/m^3. During the hygrothermal analysis, Harbin city of China, which has extreme cold climatic conditions, was selected for all five different mixtures. The results showed that wall with formcrete blended with fly ash reduces the heat loss up to 38% in comparison with normal concrete which is highest among all the pozzolans. Furthermore, all walls based on insulation foamcrete mixed with pozzolans showed the mold index within the acceptable range, i.e., 2. Addition of pozzolanic admixtures in foamcrete layer showed improvement in the relative humidity and temperature at the interior surface of walls. The indoor temperature increased from 0.43 °C to 13 °C while the range of relative humidity reduces from 57 - 95% for reference wall to 42 - 68% for insulated wall. This material allows stabilisation of relative humidity levels in the ambient air by naturally regulating the hygrometry, to ensure better ambience. Similarly, the water resistivity of the wall also improved in the presence of foamcrete layers. Thus, this material can be used massively in the construction field to meet the requirements of the current standards which aim to reduce the energy and environmental impacts of dwelling and office building.

Keywords

Mold risk, Hygrothermal performance, Heat loss, Foamcrete, Pozzolans

Introduction

Over the past few years, there has been a growing interest in cement-based foam due to its various benefits such as easy production, low density, insulation capabilities, and potential use with industrial by-products [1, 2]. These foams typically consist of Portland cement, water, and foam, which is added to the mix through either surfactants or preformed foam. Depending on the desired application, the density of these composites can range from 300 to 1600 kg/m^3. Lower densities are commonly used for thermal insulation, while heavier mixes are used for retaining walls, crash cushions, and fillers.

The thermal conductivity of cellular composites, including cement-based foam, has been extensively studied. These studies have revealed that a composite's thermal conductivity is influenced by the volume fraction of its solid constituents and the geometrical distribution of the void phases [3, 4]. Cement-based foam's microstructure consists of a solid phase of hydrated cement paste and a void phase formed by adding foam to the mix. Researchers have previously investigated the thermal conductivity of the solid phase, accounting for the hydrated cement paste's inherent porosity [5].

Dombayci et al. [6] found that using optimal insulation thickness reduced SO_2 and CO_2 emissions by up to 42% when using coal as the energy source and expanded polystyrene as the insulation. There is another study which reports that CO_2 emission can be reduced by 63% and costs by 40% through applying the optimal thickness [7]. Building envelops can either be insulated with external insulations or internal insulations. External insulation is considered as the better option in most cases, but strict building codes or the preservation and restoration of historic buildings can hinder the feasibility of exterior applications therefore the only viable solution to improve is internal insulation. The use of indoor insulation is dangerous due to salt efflorescence, cervice condensation, frost damage, and development of mold growth. These internal insulation systems are either airtight or vapor permeable. Vapor-open insulation allows for vapor exchange between the room climate and the masonry but can cause interstitial condensation during the heating season as vapor from the warm room diffuses into the cold masonry. However, airtight insulation systems require complete tightness and impeccable workmanship, and will work more effectively only if the system has no leakage problems. This system also limits the tendency of the walls to dry inwards, increasing the moisture content of the wall.

In previous studies [8-14], researchers have developed biodegradable insulation materials including hemp, wool, flax, and jute, which are sustainable and have good hygroscopic properties. These properties are important for creating a healthy indoor space, as physical and chemical factors such as ventilation, temperature, lighting, relative humidity, and the presence of bacteria and molds in the air can all impact indoor air quality. From the previous studies [15-18], it is recommended that the indoor temperature be between 19 °C and 29 °C and that the relative humidity level be less than 65%, with a range of temperature between 20 °C to 24 °C during the winter and 23 °C to 26 °C during the summer for optimal comfort. Insulation materials can reduce relative humidity and improve humidity comfort.

This study aims to evaluate the hygrothermal performance of foamcrete with pozzolanic admixtures as an insulation material, as previous researchers have not yet assessed this [19]. The hygrothermal simulation was conducted using the WUFI tool to estimate the hygrothermal behavior of foamcrete for extreme climatic conditions. The feasibility of foamcrete as a multilayer wall infilled insulation material was investigated to assess the hygrothermal behavior of the wall assembly.

Materials and Method

Materials

In this numerical simulation foamcrete mix of cast density 400 kg/m^3 was used with three different pozzolanic admixtures. To create the foamcrete, cement was substituted with fly ash, silica fume, and metakaolin in varying proportions, up to a maximum of 20% of the weight of cement. The preparation and manufacturing details of these mixes can be found in investigation conducted by Batool and Bindiganvalie [20-22]. Moreover, the mix proportion of the materials used in the wall assembly are tabulated in table 1, whereas the physical and hygrothermal properties can be found in table 2 [20-22]. The hygrothermal properties of normal concrete, cement lime plaster and weather resistance barriers were taken from WUFI Pro 6.0 [23] software. Materials used are nanoscale.

Simulation method

In this study WUFI Pro 6.0 [23] software was used for performing hygrothermal analysis. This software delivers a dynamical simulation that better suits the hygrothermal wall behavior in comparison with a steady-state calculation. To assess the hygrothermal behavior of multilayer concrete wall, water content, temperature variation, relative humidity, mold development and heat loss through the wall have been evaluated.

In total five models of wall assemblies were created in the software. The reference wall which was modeled without foamcrete consist of concrete embedded with plaster layer on both sides (Table 3). Along with weather-resistive barrier that has been used on the exterior surface of the wall. Four models were created in which insulating materials were embedded in the normal concrete in such a way that the thickness of wall assemblies remains same as of the reference wall. Insulating materials used in this numerical simulation study includes the pure foamcrete, foamcrete with pozzolans including fly ash, silica fumes, and metakaolin. For simulation of walls monitoring position were set on the interior surface, insulation material, and exterior surface of the wall. These positions were later used by the software for hygrothermal simulation of wall

Table 1: Mix properties of materials.

Material ID	Materials	Bulk density	Cement	Water	Measure foam volume	Pozzolanic admixture	Water-binder ratio
		[kg/m^3]	[kg/m^3]	[kg/m^3]	[%]	[kg/m^3]	[-]
NC	Concrete	2300	350	175	-	0	0.5
FC	Foamcrete	400	237	164	76	0	0.69
FC + FA	Foamcrete + Fly ash	400	198	164	86	40	0.69
FC + SF	Foamcrete + Silica fume	400	198	164	83	40	0.69
FC + MK	Foamcrete + Metakaolin	400	198	164	64	40	0.69

Table 2: Wall components physical and hygrothermal characteristics.

Material ID	Materials	Bulk density	Porosity	Specific heat	Specific heat capacity	Thermal conductivity	Water vapor diffusion resistance factor	Free water saturation
		[kg/m³]	[m³/m³]	[MJ/m³K]	[J/(kgK)]	[W/(mK)]	[-]	[kg/m³]
WRB	Weather resistive barrier	130	0.001	-	2300	2.3	100	-
CLP	Cement lime plaster	1900	0.24	-	850	0.8	19	210
NC	Normal concrete	2300	0.18	-	850	1.6	180	-
FC	Foamcrete	400	0.796	0.305	762.5	0.076	34.71	75.14
FC + FA	Foamcrete + Fly ash	400	0.822	0.341	852.5	0.088	49.58	
FC + SF	Foamcrete + Silica fume	400	0.7742	0.4	1000	0.09	69.41	
FC + MK	Foamcrete + Metakaolin	400	0.8308	0.432	1080	0.097	38.56	

Table 3: The simulation input for wall assemblies.

Wall assembly	Insulation layer thickness	Total wall thickness
	[mm]	[mm]
WRB + CLP + NC	0	226
WRB + CLP + NC + FC	75	226
WRB + CLP + NC + FC + FA	75	226
WRB + CLP + NC + FC + SF	75	226
WRB + CLP + NC + F C + MK	75	226

assemblies. Moreover, climatic conditions of Harbin city of China have been selected as it is the coldest region of China. With initial boundary conditions set for 20 °C and 80% relative humidity while simulation was performed for the period of 5 years. As an input, climate file of Harbin city was taken from literature [24]. In addition to this, the height of the building was taken as 20 m and the inclination of vertical wall was 90 °. Considering the standard practices, outside and inside surface coefficients of heat transfer were selected between 17 W/m²K and 8 W/m²K, respectively. Moreover, the temperature and relative humidity of the indoor air was established according to EN 15026. After incorporating all the required parameters, simulation was performed for each wall assemblies with the methodology of adapted convergence for numerical parameters and increased accuracy while heat and moisture transport was set as the mode of calculation. In the results of which mold development, temperature variation, heat loss through the wall and moisture were analyzed and quantified.

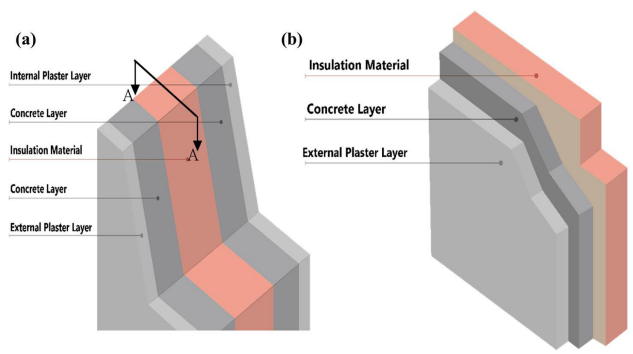


Figure 1: Assembly of insulated wall: **(a)** 3D View and **(b)** Section A-A View.

Results and Discussion

Effect of pozzolans on mold development

Figure 2 illustrates the effect of pozzolans admixture on the development of mold index and mold growth rate. To assess the mold development, monitoring position has been set on the intersection between insulating layer and concrete layer. It can be observed that reference wall (RW) has negligible mold index and with the proceeding years the mold growth rate increases but under the acceptable range. The wall assembly consisted of pure foamcrete has the highest mold index value and mold growth rate. The mold index of pure foamcrete wall reaches to the peak value of 0.78 in the first year of simulation, then it starts to decrease gradually and reaches to zero in next 4 years. While the mold growth rate of increases consecutively throughout the years and after 5 years it reaches to the maximum value of 300 mm/year. Addition of pozzolanic admixtures reduces the mold development in foamcrete. The major drop in the mold development has been observed in the foamcrete mixed with silica fumes. The maximum value of

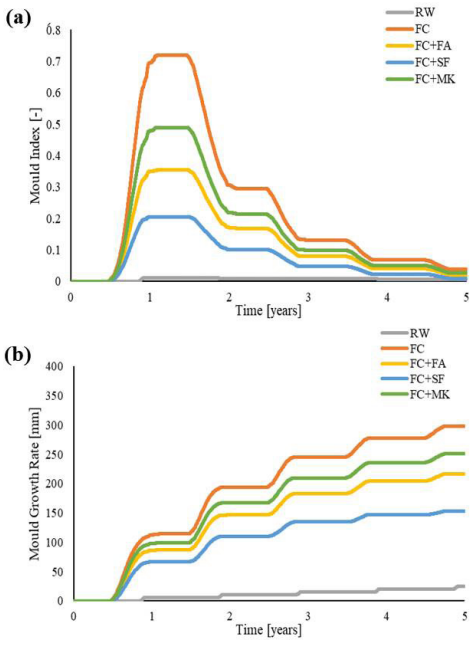


Figure 2: Effect of pozzolan on mold development: **(a)** Mold index and **(b)** Mold growth.

mold index reaches to 0.2 with in the span of 1 year whereas the mold growth rate reaches to 150mm/year in the span of 5 years.

Critical water content in spores

The critical water content (CWC) is the minimum amount of water required for mold to grow in building materials. Figure 3 illustrates the CWC and water content of spores for various wall types, including the RW, FC, FC + FA, FC + SF, and FC + MK. For the reference wall, the water content of spores remains below the CWC from June to September and then gradually decreases. The water content in spores for the first year was 200 kg/m^3 and remained constant for the next five years, with the peak value occurring in September. Since the water content of spores remains below the CWC, there is a low probability of mold development in the wall assemblies.

In the case of insulated wall assemblies, the water content of spores increases compared to the reference wall but still remains below the CWC. For pure foamcrete, the maximum water content of spores reaches up to 500 kg/m^3. However, the addition of pozzolanic admixtures decreases this value. Silica fumes perform better than other pozzolanic admixtures.

Effect of pozzolans on temperature and relative humidity

Figure 4 depicts the annual variation in temperature and relative humidity for all wall assemblies in the Harbin city. In this city relative humidity ranges from 60 to 100% and maximum temperature reaches up to 27.1 °C during the summers. Figure 4 demonstrates that, in comparison to the reference wall, the wall assemblies with insulation layers had less variations in relative humidity and temperature. Also, insulated walls showed a significant increase in internal surface temperature in winter and a slight decrease in summer. The interior surface temperature of reference wall during winter is noted at 0.2 °C while the maximum temperature during summer reaches to 27.1 °C. Addition of pure foamcrete increased the minimum temperature to 12 °C while the maximum temperature has been reduced to 24 °C. There is a significant reduction of relative humidity variation with the addition of pozzolans in the foamcrete. The pure foamcrete shows the variation in relative humidity in between 50 to 70% whereas the pozzolans including fly ash, silica fumes, and metakaolin decreases the variation in relative humidity to 45%.

Effect of pozzolans on heat losses through the wall

Figure 5 depicts the effect of material on the reduction of heat loss in the wall assemblies for Harbin city. The lowest temperature observed at the interior surface of reference wall is 0.43 ° C and the heat loss at a rate of 70.64 W/m^2. With the addition of pure foamcrete in the concrete wall, the heat loss has been reduced to 56.23 W/m^2. Moreover, the pozzolanic admixture shows a significant reduction in heat loss as well. The best results have been observed with the addition of fly ash and the heat loss through the wall has been reduced to 44.57 W/m^2. While the heat loss through the walls containing silica fume and metakaolin are 45.66 W/m^2 and 47.56 W/m^2, respectively.

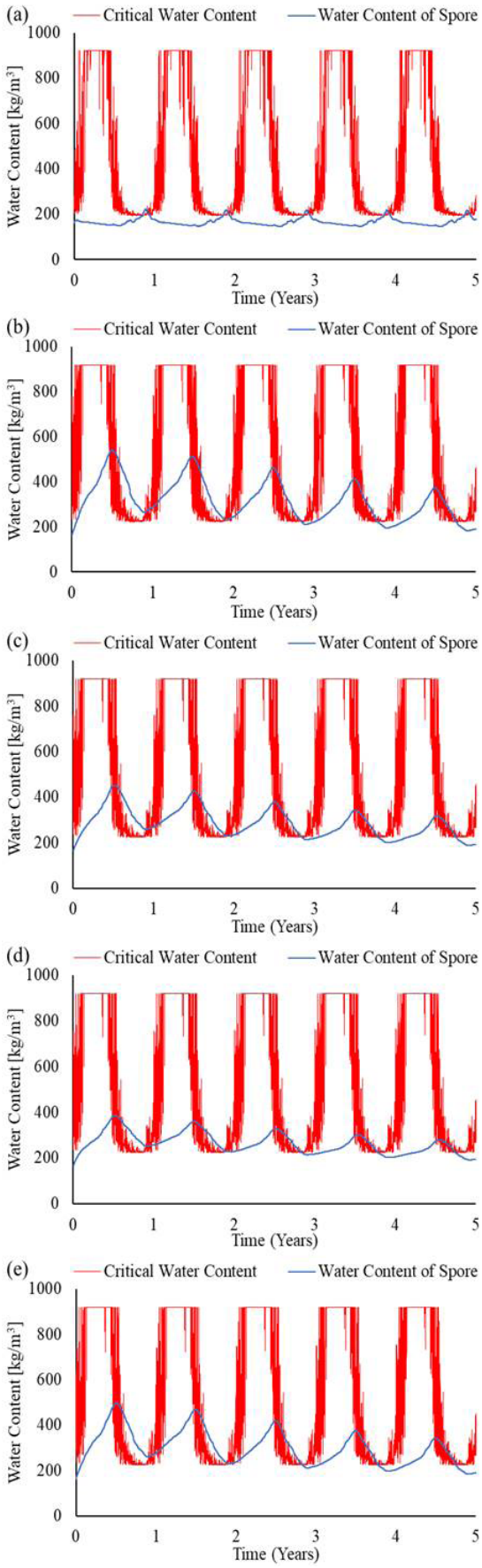


Figure 3: Water content in spores for different wall assemblies: **(a)** RW; **(b)** FC; **(c)** FC + FA; **(d)** FC + SF; and **(e)** FC + MK.

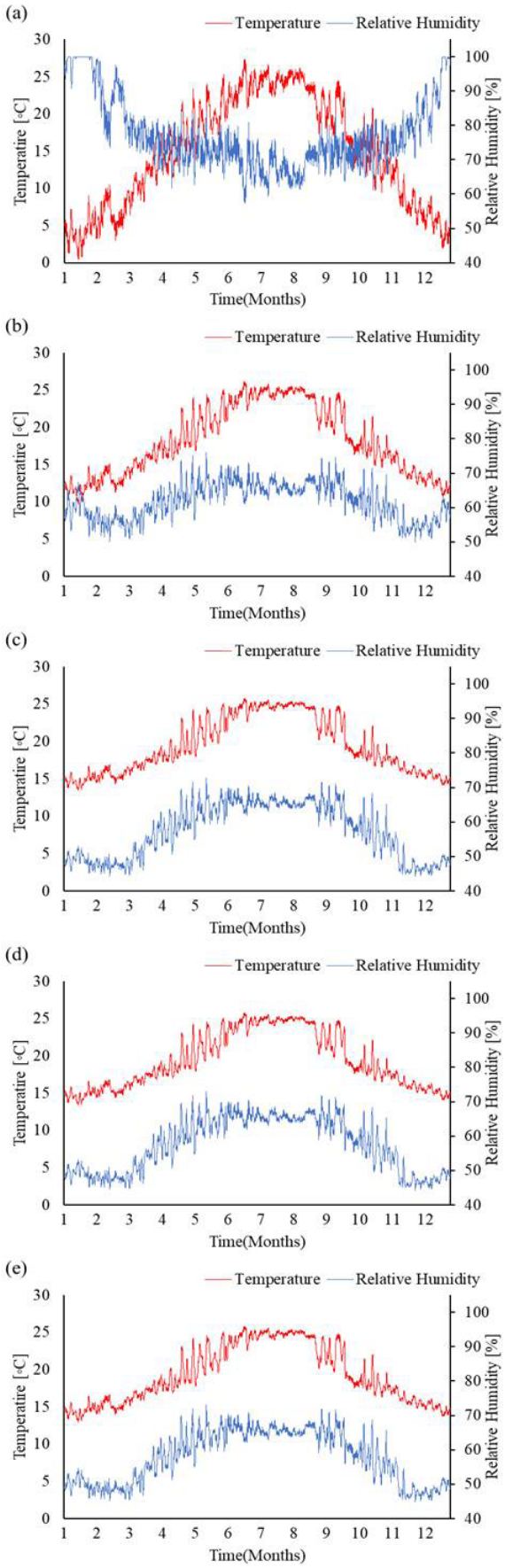


Figure 4: Variation of relative humidity and temperature at the interior surface: **(a)** RW; **(b)** FC; **(c)** FC + FA; **(d)** FC + SF; and **(e)** FC +M K.

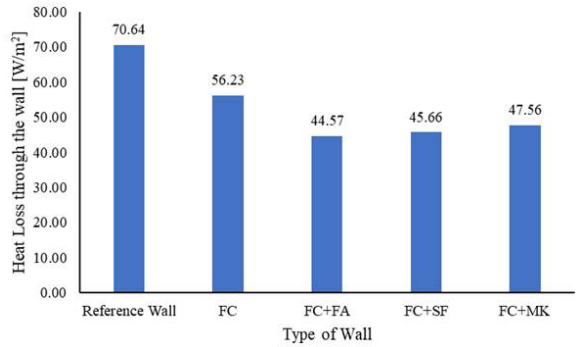


Figure 5: Heat loss through wall assemblies.

Effect water content on wall assembly

Figure 6 shows the water content of wall assemblies over the simulation period of five years. The total water content of the reference wall showed a small decline in water content

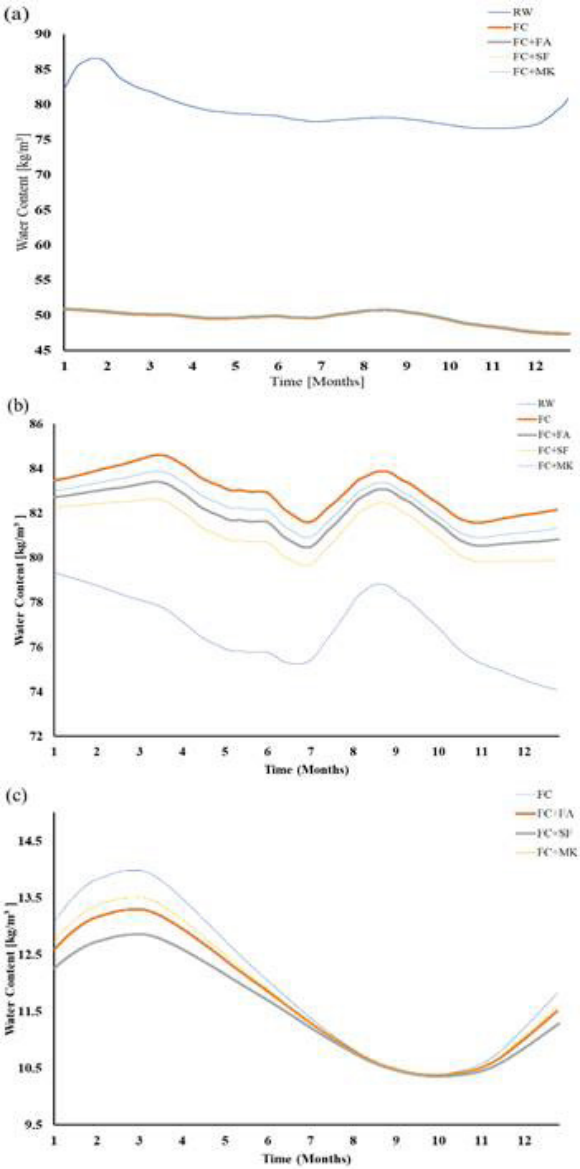


Figure 6: Effect of water content on wall assemblies: **(a)** Total water content; **(b)** Concrete layer; and **(c)** Insulation layer.

over time. The initial total water content of the wall assembly is 82.5 kg/m^3 which remains approximately same though out the year. Whereas the insulated wall has shown a significant drop in the total water content of the wall assembly, i.e. 52.3 kg/m^3.

Figure 6b shows the water content of the concrete layer of the walls. Due to less permeability, the water content is not transferred through the insulation material, therefore the concrete before insulating materials shows a greater amount of water content for the insulated walls, whereas the water content of concrete layer in the reference wall is less.

Figure 6c shows the water content in the insulating material and from the figure it can be observed that pure foamcrete carries the highest water content with the maximum value reaches up to 14.1 kg/m^3 while foamcrete with silica fume as pozzolanic admixtures shows the lowest water content with the maximum value reaches up to 12.8 kg/m^3. From the results it can be concluded that silica fumes perform better in comparison with other pozzolanic admixtures.

Variation of temperature, relative humidity, and moisture distribution

WUFI films provides a profile for the variation in the moisture content, relative humidity and temperature, through the different layers of the wall. Figure 7 shows the profile of all the wall assemblies for the numerical simulation over the period of 5 years which has been exposed to Harbin city. From

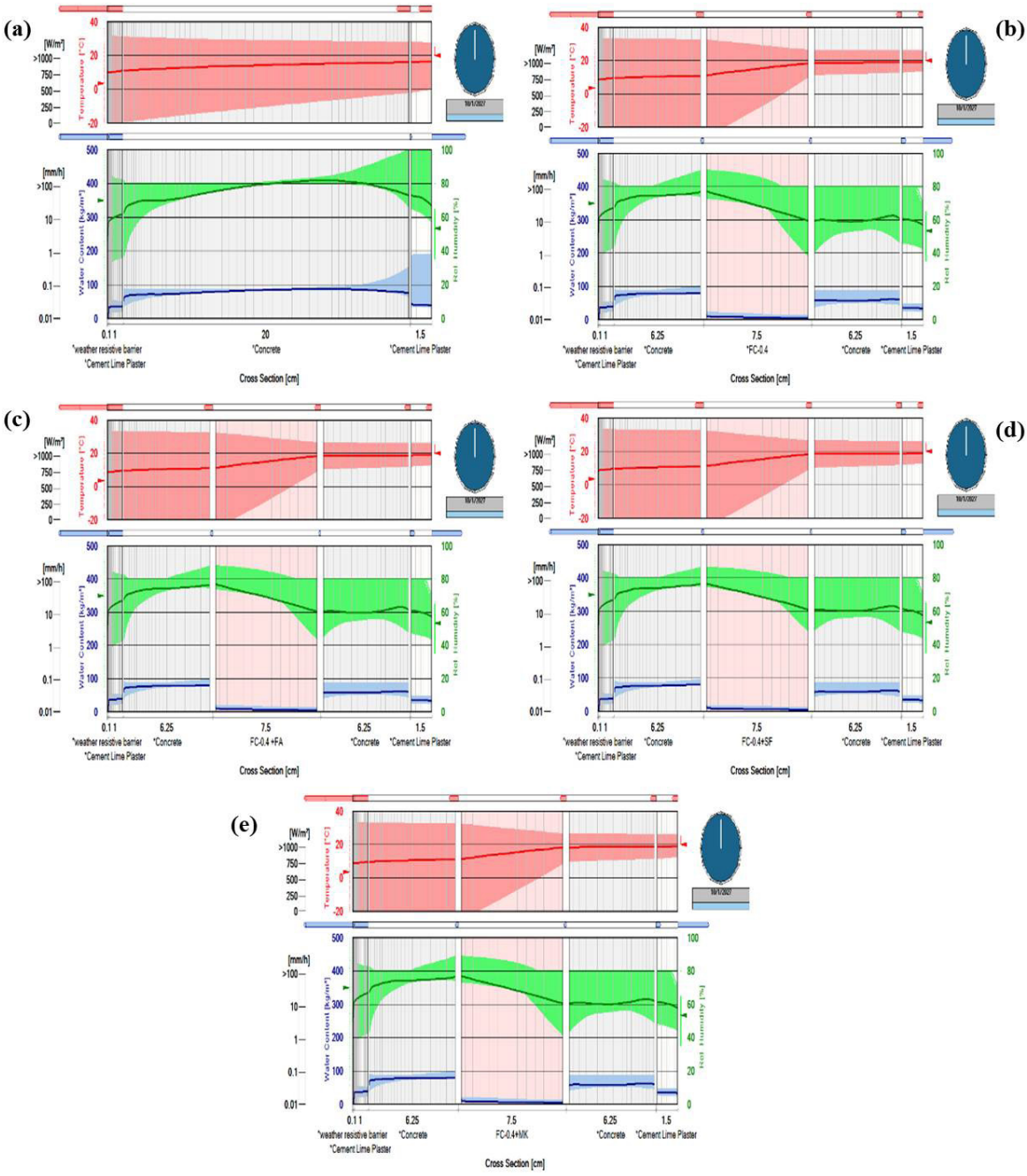


Figure 7: Variation of temperature, relative humidity, and moisture content: **(a)** RW; **(b)** FC; **(c)** FC + FA; **(d)** FC + SF; and **(e)** FC + MK.

the figures it can be evaluated that relative humidity and moisture content across the reference wall is at high level and it is considered as a wet wall. For the reference wall the variation in temperature has been observed from 0 °C to 27 °C (Figure 6a). A significant part of the wall had relative humidity values of above 80%. Relative humidity and internal temperature are affected by the insulating layer (Figure 6b to 6e). For the insulated wall assemblies, the relative humidity reduced to 40% while the minimum temperature has been increased to more than 12 °C. This variation shows the improvement in the indoor temperature and proper insulation.

Conclusions

This numerical simulation was performed to analyze the hydrothermal properties of foamcrete with pozzolanic admixtures. Considering the simulation results following are the conclusions:

- Foamcrete layer in the wall assembly increases the risk of mold development in the wall. However, the addition of pozzolans can reduce that risk and keeps it under the acceptable range, i.e., 2.
- Foamcrete layer blended with pozzolans have increased the thermal comfort of the residents. The temperature at the interior surface of the wall has been increased from 0.43 °C (RW) to 14.06 °C (FC).
- Among all pozzolans, fly ash was found to be particularly effective, with a 36.91% reduction in heat loss. However, silica fumes reduced the heat loss by 35.37% and metakaolin reduced the heat loss by 32.68 % in comparison with normal concrete wall.
- Addition of foamcrete layer reduced the range of relative humidity of wall assemblies from 57 - 100% (RW) to 42 - 68% (Insulated walls).

Acknowledgements

None.

Conflict of Interest

None.

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