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Hygrothermal analysis of technical solutions for insulating the opaque building envelope

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Abstract

The application of insulating materials for energy refurbishment of buildings improves the thermal transmittance of the envelope. However, if not properly planned and realized, it could reduce the wall's drying potential, modifying its original features and leaving it generally more humid. This can lead to moisture damages, humid insulation material and risk of mould growth. To avoid any problem related to the increased presence of water in the building envelope, it becomes therefore essential to perform the so-called hygrothermal assessments. In this regard, the international standards offer, beside the traditional Glaser method based on the mere vapour transport, the use of dynamic hygrothermal simulations. These allow to simultaneously consider the transport and storage of heat and moisture in building materials, the influence of climate (including rain and solar radiation in different locations), user behaviour and initial conditions. The aim of this paper is to compare Glaser and dynamic methods and to highlight their advantages and disadvantages, considering the different approaches to the evaluation not only of superficial and interstitial condensation, but also of durability, considering biological attack, freeze/thaw cycles, corrosion, etc.

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Keywords: hygrothermal simulation; insulation system; Glaser method; WUFI®Pro.

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Nomenclature

A	water absorption coefficient [$kg/m^2h^{0.5}$]	t	time [s]
c	specific heat capacity [J/kgK]	T	absolute temperature [K]
D_φ	liquid conduction coefficient [kg/m s]	w	water content [kg/m^3]
U	thermal transmittance [W/m^2K]	δ_p	water vapour permeability [kg/m s Pa]
$f_{risk,max}$	risk temperature factor [-]	ε	porosity [m^3/m^3]
H	total enthalpy [J/m^3]	λ	thermal conductivity [W/mK]
h_v	evaporation heat of water [J/kg]	μ	vapour resistant factor [-]
p_{sat}	saturation vapour pressure[Pa]	ρ	density [kg/m^3]
RH	relative humidity percentage [%]	φ	relative humidity [-]
R_{critic}	risk minimum resistance [m^2K/W]		

1. Introduction

Recent studies [1] have shown that buildings, dated before 1970, are about 60% of the total number of existing ones erected in Italy (the amount rises to more than 80% if considering buildings of the ’80s). These constructions are strongly responsible for the consumption of more than 40% of energy and 50% of air pollutant emissions, due to significant heat losses through the envelope [2]. For this reason, the increase of the energy performance of assemblies has been assuming a key role in improving energy efficiency of the whole building. Though, envelope refurbishment needs a complex design, which considers not only the immediate reduction of heat losses, but also specific issues such as durability, sustainability, users’ health and comfort. The energy refurbishment consists in adding thermal insulation on roofs, basements and walls, either on the external or the internal side of the envelope. The standard rehabilitation is represented by the application of exterior thermal insulation, which eliminates thermal bridges, increases thermal inertia and decreases the risk of condensation and mould on interior surfaces [3]. However, for the preservation of the architectural heritage, interior thermal insulation becomes essential, even though it has not the same advantages of exterior insulation [4]. Sometimes also cavity insulation is used for walls with an air gap, even though it represents an irreversible solution. It has similar features of the exterior insulation, but the humidity stress of the external layer increases, the thermal bridges are not eliminated and the moisture flow is reversed, due to solar radiation [5]. Each of these applications may have other negative consequences on the envelope performances: loss of vapour permeability, humid insulation materials and moisture damages, which might lead to biological, chemical, or physical degradation of the assembly [6]. Hence, hygrothermal evaluations are extremely important to predict the effects of new insulating materials on existing buildings, by considering several factors, such as environmental and climatic loads, indoor moisture level, initial conditions, moisture accumulation of materials, degradation mechanisms, etc. [7].

Hygrothermal analysis could be performed by means of laboratory tests and on-site assessments, which are expensive and long-lasting. For the design process these two methods are replaceable by Glaser method and dynamic simulations. Glaser method is a simplified procedure, based on pure diffusion moisture transport in one-dimensional steady-state condition. This method ignores some issues, such as moisture and heat accumulation in materials and built-in moisture. Moreover, it does not consider the dependence of material properties on humidity and temperature, the capillary transport of liquid water and the rising damp [8]. In order to overcome the limits of steady-state dew-point calculations and to better predict the climate dependent moisture behaviour of construction assemblies, in the last decades dynamic simulations have been developed. Unlike Glaser method, they consider the latent heat exchange, the convection air movements in air gaps and the weather loads (e.g. solar radiation, wind and driving rain). Dynamic simulations enable the analysis of: interstitial condensation in variable regime, influence of solar radiation and rain on the vapour migration, phenomena related to the drying of the structures and users’ behaviour [9].

In this paper, a study on the hygrothermal behaviour of insulation techniques applied to old buildings masonry walls in different Italian climatic conditions is presented. This analysis was performed to evaluate the influence of some energy refurbishments that could increase the envelope thermal resistance, but also decrease its hygrothermal performance over the time. The study compares the results, obtained from both simplified and enhanced hygrothermal methods, showing advantages and disadvantages of steady-state and unsteady evaluation methods, according to the current national legislation.

2. Simulation method and analysis criteria

Wall performances were evaluated by means of Pan® 7.0 for Glaser method and WUFI® Pro 6 for dynamic simulation. Pan® 7.0 is a tool developed by ANIT for quasi-steady hygrothermal assessment of opaque building envelopes. It is based on the standard UNI EN ISO 13788 [10] and in agreement with DM 26/6/2015 [11, 12]. WUFI® Pro 6 is a dynamic one-dimensional model, based on *Künzel* transport and storage equations [7]:

$$\frac{\partial H}{\partial T}\cdot\frac{\partial T}{\partial t} = \nabla(\lambda\cdot\nabla T) + h_v\cdot\nabla(\delta_p\cdot\nabla(\varphi\, p_{sat})) \tag{1}$$

$$\frac{\partial w}{\partial \varphi}\cdot\frac{\partial \varphi}{\partial t} = \nabla(D_\varphi\nabla\varphi + \delta_p\cdot\nabla(\varphi\, p_{sat})) \tag{2}$$

Unlike *Luikov* [13] and *De Vries* models [14], the chosen equations consider relative humidity as driving force for vapour and liquid transport. Consequently, the required material data are easier to define and, at the same time, more accurate information about the envelope behaviour is given.

When the evaluation was performed by means of Pan®, only condensation and mould risk were assessed. Otherwise, using WUFI®, the following issues and related control criteria were considered:

- Interstitial and surface condensation, which occurs if surface temperature is lower or equal to the dew point and/or material water content grows until reaching surface saturation. According to the national legislation, limits on water content are stricter than the materials should have to avoid degradation problems. The international regulations set softer limits, as shown in Table 1. However, in this study, the hygrothermal assessment was performed following the Italian law, hence an assembly works when no-moisture accumulation occurs.
- Mould formation, which could develop for RH ≥ 80 %. Though, surface temperature and duration of the critic values are also important factors to be taken into account: indeed, if RH overcomes for more than two weeks the RH threshold and the temperature is quite low, further analysis with WUFI® Bio [15, 16] was carried out.
- Freeze/thaw risk, when RH ≥ 95 % and T ≤ 0 °C.
- Reduction of the drying potential.
- Energy performance decay.

3. Case studies

The technical solutions were defined according to UNI/TR 11552 [17] and [1], in order to evaluate common Italian types of construction. Figure 1a presents a sketch of the three case studies. The analysis was limited to residential buildings, due to their predominance in the Italian context and the wide need of maintenance. Each construction is provided with a plaster coating on both sides of the wall. An exception occurs with limestone, which has no coating on the external side. The thickness given in this study is only indicative but still within the range of size given by [17]. The masonry properties were selected from WUFI® *Material Database* [18] and then compared with [17] and UNI 10351 [19]. In case of discrepancy, the properties were modified according to Italian regulations and context. Plasters were defined by the guidelines issued by [20]. Limestone wall consists of 20 mm lime-pozzolana plaster on the interior surface. Concrete and hollow bricks walls have respectively 20 mm lime-cement plaster on the exterior surface and gypsum plaster on the interior one. For exterior plasters, attention was payed to water absorption and vapour permeability. For original plasters, an absorption coefficient A of 2 $kg/m^2h^{1/2}$ was chosen, which offers no rain water protection to the wall. For new applications, however, plasters with water repellent capacity were selected (A = 0.1 $kg/m^2h^{1/2}$). Polymeric coatings were avoided in order to not compromise the breathability of the envelope.

The rehabilitation work was represented by the application of three kinds of insulation boards: EPS, typha and calcium silicate; typha is an innovative and eco-sustainable material, developed at Fraunhofer IBP [21]. Two alternative applications were studied, considering both exterior and interior insulation. For the latter one, two monitor position were chosen (Fig. 1b) on the cold side of interior insulation, where the risk of condensation is higher. Due to the different thermal conductivity values of each assembly, the thickness of the insulation boards is different, thus following the limit values of thermal transmittance U defined in [11]: $U = 0.40$ W/m^{2}K for vertical wall in Bari, $U = 0.30$ W/m^{2}K in Milan. The climatic data of Bari and Milan refer respectively to the climatic zones *C* and *E*, according to [22]. The indoor climate condition was defined by means of the moisture concentration class, according to UNI EN ISO 13788 [10]. A moisture concentration *class 3* (i.e. normal moisture load) was used for the calculations. Material properties are shown in Table 2. Heat transfer coefficients follow UNI EN ISO 6946 [23].

Table 1. Comparison among German, English, Italian and European regulations about the maximum amount of condensation allowed.

Regulation	Water Content Limit
EN 13788 (Europe) [10]	200 g/m²
DIN 4108 (Germany) [24]	500 g/m²
BS 5250 (UK) [25]	150 g/m² with 23° slope
	70 g/m² with 45° slope
	30-50 g/m² with 90° slope
DM 26/06/2015 (Italy) [11]	0 g/m^2 (no condensation allowed)

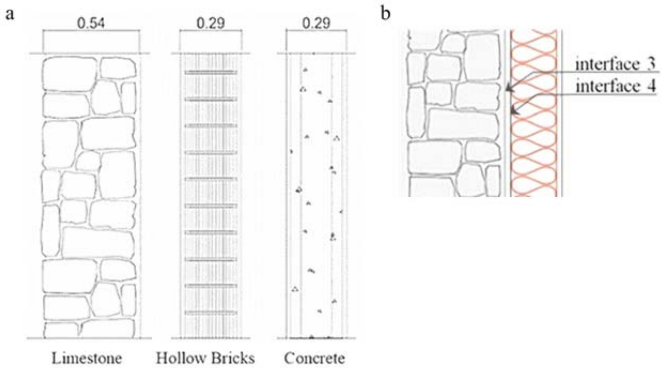

Fig. 1. (a) Masonry walls selected for the study; (b) interfaces chosen for the assessment. Measures are expressed in meter.

Table 2. Material properties (LP = lime-pozzolana; LC = lime-cement; Ca-Si = calcium-silicate).

		Wall			Plaster			Insulation		
Parameter	Unit	Concrete	Bricks	Limestone	LP	LC	Gypsum	Typha	EPS	Ca-Si
ρ	[kg/m^3]	2300	800	2600	1566	1900	850	260	15	180
ε	[m^3/m^3]	0.18	0.60	0.13	0.39	0.24	0.65	0.75	0.95	0.93
λ	[W/mK]	2.30	0.40	2.30	0.50	0.80	0.20	0.048	0.040	0.060
c	[J/kgK]	1000	850	1000	850	850	850	1500	1500	920
μ	[-]	130	15	200	7.4	19	8.3	30	30	2.1

4. Glaser method results

The outdoor climatic data are related to the monthly average values of outdoor air temperature, vapour pressure, global solar radiation on horizontal plane and wind speed, according to UNI 10349 [26]. With Glaser method, only risk of mould and condensation were evaluated.

Surface condensation and mould formation are identified by calculating if the resistance of the wall exceed critical resistance values, determined as follow:

$$R_{critic} = \frac{1}{4 \cdot (1 - f_{risk,max})} \quad (3)$$

Risk factors are derived from the minimum surface temperature, which depends on the indoor climate:

$$f_{risk} = \frac{T_{si,min} - T_e}{T_i - T_e} \quad (4)$$

Results show that no construction presents surface condensation or mould. Interstitial condensation calculation is based on the vapour saturation pressure and the vapour pressure inside the assembly, by verifying if the latter is lower than the former. In case of condensation risk, the amount of accumulated water was analysed.

In case of interior insulation, interstitial condensation occurs in almost every assembly located in Bari, except hollow bricks envelope insulated with typha and EPS, as can be observed in Figure 2 (here only critical cases are displayed). Interface 3 (Fig. 2a) turns out to be the more critical point for condensation risk, whereas at interface 4 only few constructions accumulate condensate (Fig. 2b).

Also in the climate of Milan interior insulation is critical: indeed, interstitial condensation on the cold side of interior insulation has been found in each construction, regardless of the insulation material used, as shown in Figure 3 (here again only critical cases are displayed). At interface 3 (Fig. 3a), Glaser calculation indicates little amount of condensation, hence lower than the 200 g/m^3 imposed by the European regulation but enough for the Italian law. If interface 4 (Fig. 3b) is considered, constructions with calcium-silicate insulation reach water amounts greater than 1800 g/m^2, exceeding all the limits defined in Table 1.

Summarising, according to the threshold fixed by DM 26/06/2015 of 0 g/m^2, all solutions with interior insulation fail both in Bari and Milan, except hollow bricks envelope insulated with typha and EPS in Bari.

No interstitial condensation occurs in any assemblies with external insulation, no matter of the climate.

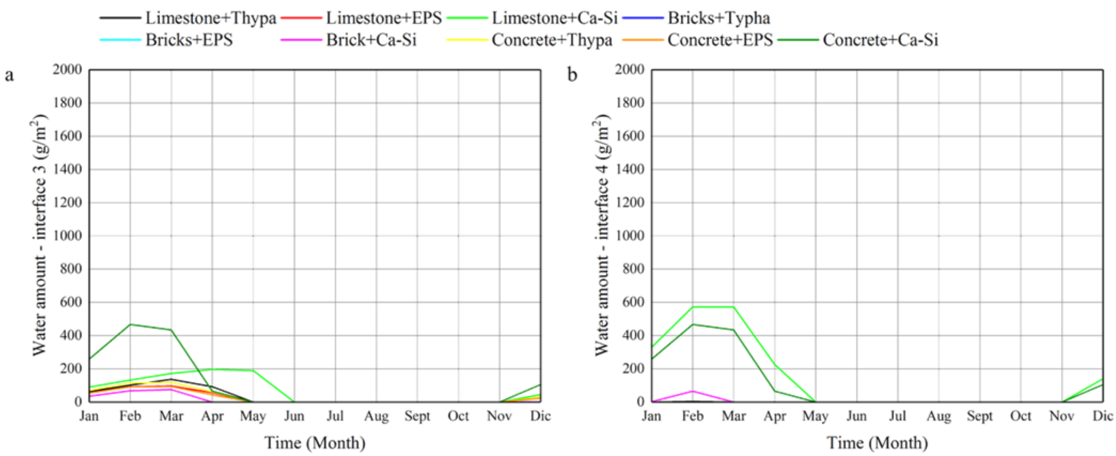

Fig. 2. (a) Water amount at interface 3 and (b) at interface 4 during one year in Bari (interior insulation).

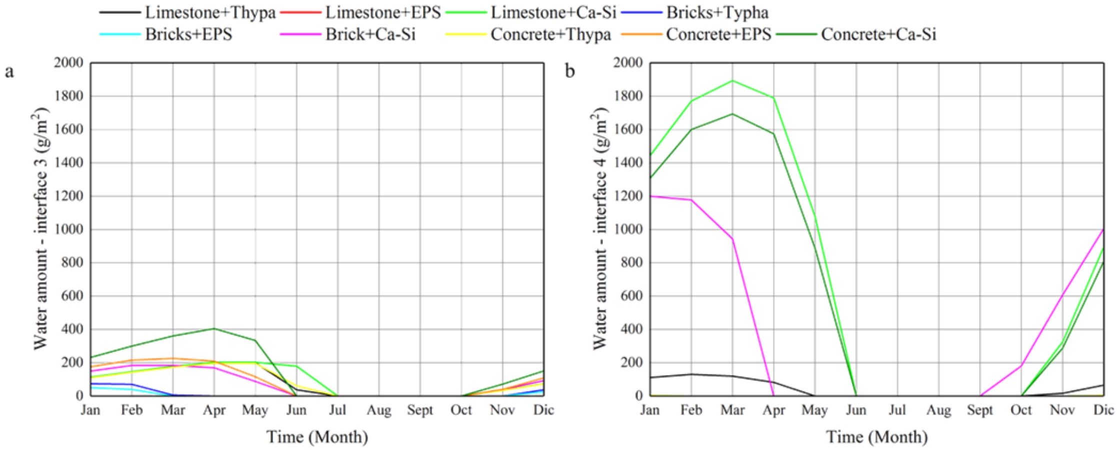

Fig. 3. (a) Water amount at interface 3 and (b) at interface 4 during one year in Milan (interior insulation).

5. Dynamic simulation results

To define outdoor environmental condition, hourly data set included wind direction and rain amount were necessary. For Bari, location not included in the WUFI® *Climate Database*, a sort of *Test Reference Year* was created with the last three years (2014, 2015 and 2016) of climatic data, which were provided by *Ministry of Agriculture, Food and Forestry* (MIPAAF) and then further developed [27]. A rainfall infiltration of 1 % [28] was considered within the first 5 mm of the layer behind the exterior insulation, in order to investigate the performance of walls in case of typical constructive imperfections. Orientation of envelopes was defined for each city according to the dominant wind direction. Initial levels of humidity and temperature in the external insulation masonry were considered constant and in equilibrium with air at 80 % RH and 20 °C. In case of internal insulation, a preliminary simulation was performed for each case, with the aim to calculate the initial water content of the existing construction. Table 3 reports the main settings used for the calculations.

By means of simulations, condensation risk analysis was performed, following the criteria described in § 2. In every solution interstitial condensation occurs (Fig. 4 for Bari and Fig. 5 for Milan), even in calcium silicate interior envelopes, where the humidity level is over 90 %. In both locations, a first analysis suggested possible mould formation on the cold side of insulation: especially calcium silicate overpasses the limit of 80 % RH. However, as there is no air gap between insulation and wall, in this case no mould growth is possible. Further investigations, performed with WUFI® Bio, showed no risk of microbiological attack. Frost-defrost risks were also excluded, even though moisture reached 95 % RH, due to the temperature over 0 °C.

Simulations highlight that the application of interior insulation produces a rise of water amount in concrete and hollow bricks walls over the time. The moisture content refers to the water, that each material stores, and it cannot be considered as condensation. The rise of water amount in these cases is a consequence of the reduced drying potential of walls. This indicates that the solutions work, but that a water repellent-plaster should be used. Therefore, the rise of the water content does not affect the thermal performance of the insulation layers (their thermal conductivity reduction is about 10^{-4} W/mK) and hence of the whole assemblies. For external insulation, the water content decreases slightly or remains constant during all the simulation period.

Table 3. Summary of the main simulation settings.

Exterior surface		Other	
Short-Wave Radiation Absorptivity [-]		Moisture source for exterior insulation [% of rain]	1
Standard plaster	0.4	Calculation period [year]	10
Limestone	0.9		
Adhering fraction of rain [-]	0.7		

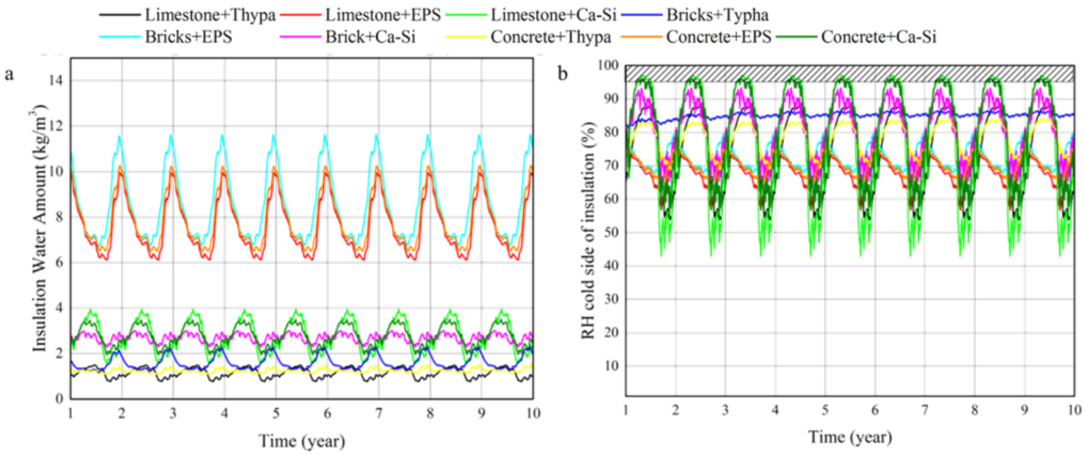

Fig. 4. (a) Water content and (b) RH of walls for interior insulation, in Bari.

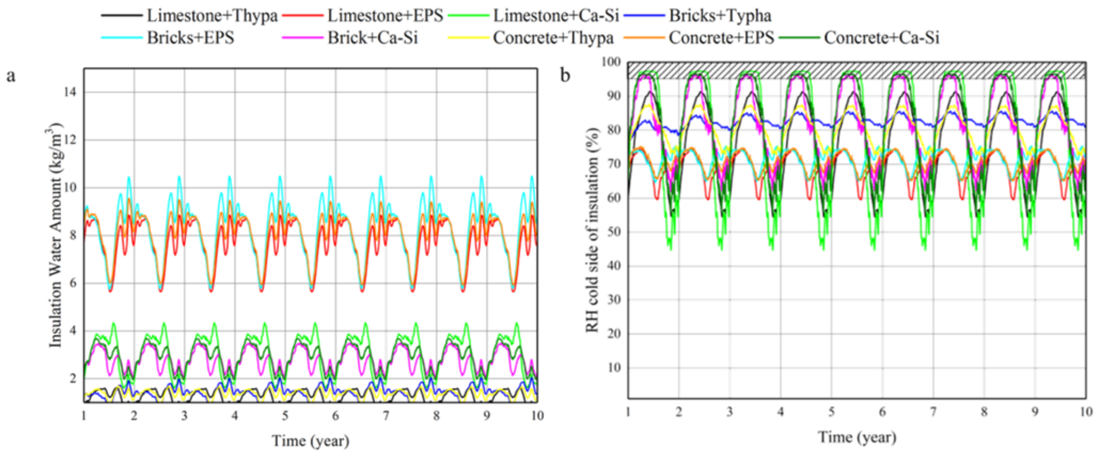

Fig. 5. (a) Water content and (b) RH of walls for interior insulation, in Milan.

6. Results comparison and conclusions

Table 4 summarizes the results obtained with both Glaser and dynamic simulations. When the insulation layer is on the external side, both methods show similar results. In case of interior insulation, instead, Glaser method (UNI EN ISO 13788) is much more conservative than dynamic simulations in assessing the hygrothermal behaviour of the building envelope.

Indeed, hygrothermal simulations allow, if used correctly, to evaluate almost all phenomena relevant to building practice, such as water absorption, rainfall, solar radiation, vapour diffusion, moisture accumulation, liquid transport, built-in moisture drying, long-lasting moisture accumulation, etc. The evaluation is performed accurately for rainfall and solar radiation in each climatic location.

Though, since the quality of simulation results directly depends on the quality of the input data, it is necessary to have adequate and reliable climatic data and material properties.

Hygrothermal simulations hence entail greater responsibility for the designer than Glaser calculation, but they allow a much more complete and specific assessment of the hygrothermal behaviour of building components.

Table 4. Comparison of the results obtained with Glaser and simulations.

Insulation systems	Wall	Interface	Glaser Method						Dynamic Simulation					
			Typha		EPS		Ca-Si		Typha		EPS		Ca-Si	
			Bari	Milan	Bari	Milan	Bari	Milan	Bari	Milan	Bari	Milan	Bari	Milan
External	Limestone		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Concrete		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Bricks		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Internal	Limestone	3	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓
		4	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓
	Concrete	3	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗
		4	✓	✓	✓	✓	✗	✗	✓	✓	✗	✓	✓	✓
	Bricks	3	✓	✗	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓
		4	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓

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