An Investigation of the Ventilation Requirements to Prevent Deterioration of Timber and Mould Growth beneath Suspended Floors

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ABSTRACT: The importance of sub-floor ventilation as long been appreciated to prevent the deterioration of the timber structure of suspended floors. In mid-1999 the Building Code introduced amendment 5 to include uniform ventilation requirements of sub-floor spaces of Class 1 and 10 buildings based on climatic conditions. This amendment was based on work by Cole (1997) at CSIRO. Here ventilation areas are calculated based on a scientific method, given certain wind and humidity conditions, so that the underfloor humidity does not exceed a critical value that was assumed will lead to the deterioration of timber. The vent requirements vary according to three humidity zones defined to cover Australia. Recent concerns to improve the thermal resistance (R-value) of the building fabric have lead to a critical examination of ventilation requirements. This paper will present a re-evaluation of the Cole work and applying a "first principles" ventilation model to investigate the performance of sub-floor conditions to prevent deterioration of timber and possible health hazards due to mould growth. The implications for the present BCA requirements are discussed.

Conference theme: Construction and materials
Keywords: sub-floor, ventilation, condensation, mould, building code.

INTRODUCTION

The importance of sub-floor ventilation for preventing the deterioration of the timber structure of suspended floors and reducing dampness to avoid possible health problems has long been recognised as an article of faith. The ArchiCentre website says "The sub floor harbours many disease-causing pests like rats, cockroaches and ants, and destructive things like termites and mould-spore-producing dry rot. The drier and more ventilated the sub floor the healthier it is" (ArchiCentre 1997). A check of the internet reveals a number of companies in Australia offering sub-floor ventilation and damp proofing systems.

Good house construction practice in Australia has required sub-floor ventilation. Da Costa in 1974 gave examples of ventilation requirements in Australia ranging from 1400 mm^2 per m of perimeter wall (NSW specification) to 10,600 mm^2 per m (Light Timber Framing Code). While observing that "the data for an objective calculation of requisite ventilation are not available…" he reviewed the factors that should enter into such a calculation.

The Building Code of Australia (BCA 1996 edition) contained a constant requirement for sub-floor ventilation: "*Internal and external wall vents to be provided at a rate of not less than 7300 mm^2/m length of wall*." In mid-1999 the Building Codes Board introduced amendment 5 to include uniform ventilation requirements of sub-floor spaces of Class 1 and 10 buildings as a function of climatic conditions. This amendment was based on a preliminary investigation by Cole (1997) at CSIRO, who combined data from field measurements with calculations to propose that, given certain wind and humidity conditions, the ventilation areas required to ensure that the underfloor humidity did not exceed a critical value that was assumed would lead to the deterioration of timber. He also suggested that the vent area requirements could be varied according to three humidity zones defined to cover Australia as shown in Figure 1.

Cole calculated the steady-state moisture content of the sub-floor air as a function of the ventilation rate, outdoor air moisture content, and the evaporation rate of moisture from the ground surface. The evaporation rate was based on the work of Abbott (1983) at BRANZ. The sub-floor ventilation rate as a function of vent area and wind speed was based on a simple model proposed by Walsh (1975) at CSIRO.

Rose and Ten Wolde writing in the North American context suggested that "whether or not to ventilate a crawl space is probably the most controversial issue concerning crawl-space design". They concluded after examining the available research data that providing sub-floor drainage is adequate,

- "*there is no convincing technical basis for current code requirements for ventilation.*
- *heated crawl spaces should not be vented with outdoor air.*

- *unheated crawl spaces may be vented, but there is no overriding need to do so for moisture control if an effective ground cover is present.*" (Rose and Ten Wolde 1994 p14)

(Note – crawl-space is the term adopted in the US for sub-floor space.)

The recent impetus in Australia to improve the thermal resistance of the building fabric has led to a re-examination of the thermal resistance of sub-floor spaces, which in turn has led to a critical examination of the sub-floor ventilation model (Williamson and Delsante 2006) and a re-evaluation of the ventilation requirements and the work of Cole.

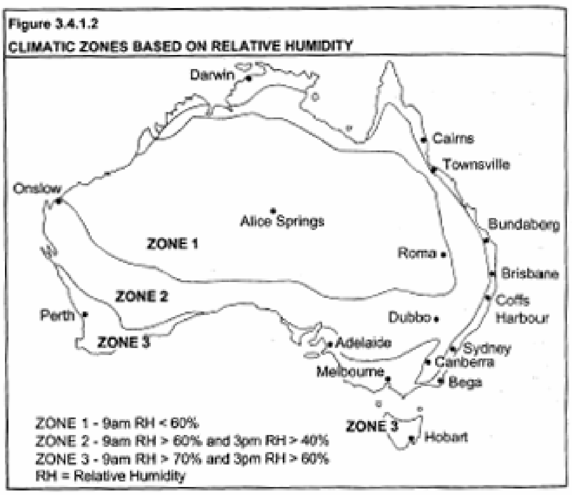

Table 3.4.1.2 SUB-FLOOR VENTILATION AND CLEARANCE

CLIMATE ZONE (see Figure 3.4.1.2)	Minimum sub-floor ventilation (mm^2/m of wall)		Minimum height from ground surface (mm)	
	No membrane	Ground sealed with impervious membrane	Termite inspection not required	Termite inspection required (see note)
1	2000	1000	150	400
2	4000	2000	150	400
3	6000	3000	150	400

Note:
On sloping sites, 400 mm clearance may be reduced to 150 mm within 2 m of external walls in accordance with **Figure 3.4.1** Diagram b.

Figure 1: Building Code of Australia Sub-Floor Ventilation Requirements, Class 1 and 10 Buildings.

1. COLE'S METHODOLOGY

The moisture balance in Cole's methodology is given by solving the relationship,

$$h\frac{dm_{sf}}{dt} = K_1K_2\left(m_s - m_{sf}\right) + nh\left(m_{ex} - m_{sf}\right) \qquad (1)$$

where,

m_s, m_{ex} & m_{sf} are the absolute humidity (g/m3) of soil, external air and sub-floor respectively.

K_1 & K_2 are constants, with K_1 derived from the sub-floor evaporation rates determined by Abbott (1991).
n is the ventilation rate in air changes per sec.
h is the sub-floor height (m).

A solution to this mass flow equation can be found as follows.

Abbott (1983) working at BRANZ found that when ground water approached the surface, especially during winter, the sub-floor evaporation rates were practically independent of soil type and was very near the evaporation rate of free water. He developed a relationship for the moisture evaporation from soil beneath a suspended floor as,

$$Q = 4(p_s - p_{sf}) \quad \text{g/(m}^2\text{.hr)} \qquad (2)$$

Where

p_s is the saturation vapour pressure at ground temperature (mbar)

p_{sf} is the vapour pressure in the sub-floor airspace (mbar)

Converting Eq (2) to SI units (1 mBar = 1/10 kPa),

$$Q = 4*10*10^{-3}\left(p_s - p_{sf}\right)/3600 \ldots \text{kg/(m}^2\text{.s)} \qquad (3)$$

Since the pressures are now in the units of kPa

$$Q = 1.111*10^{-5}\left(p_s - p_{sf}\right), \text{...kg/(m}^2\text{.s).} \qquad (4)$$

From psychrometrics the vapour pressure of moist air (p) can be estimated as,

$$p = \frac{wp_t}{0.622 + w} \qquad \text{kPa} \qquad (5)$$

where p_t is atmospheric pressure, and w is the moisture content of air in kg/kg. If we say that w is around 0.007 (corresponding to T=19°C and RH=50%), and using p_t = 101.325 kPa, then Eq (5) can be linearised to,

$$p = 1.61*10^2 w. \qquad \text{kPa} \qquad (6)$$

From a mass balance on the sub-floor air we can determine that in time δt, the mass of moisture added to the sub-floor volume is given by,

$$\delta M = 1.111*10^{-5}*1.61*10^2\left(w_s - w_{sf}\right)A\delta t + \rho\dot{V}\delta t\left(w_{ex} - w_{sf}\right), \text{ (kg)} \qquad (7)$$

where
A = ground surface area (m^2)
h = height of sub-floor (m)
$\dot{V}$ = ventilation rate (m^3/s)
w_{ex} = moisture content of outdoor air (kg/kg)
w_{sf} = moisture content of sub-floor air (kg/kg)
w_s = moisture content of saturated air above free water on ground (kg/kg)
ρ is the air density. (assuming 1.2 kg/m^3)

The increase in sub-floor air moisture content is

$$\delta w_{sf} = \frac{\delta M}{\rho A h}, \qquad (8)$$

Thus

$$\frac{dw_{sf}}{dt} = \frac{1.491*10^{-3}}{h}\left(w_s - w_{sf}\right) + \frac{\dot{V}}{Ah}\left(w_{ex} - w_{sf}\right) \qquad (9)$$

This is of the form

$$\frac{dw_{sf}}{dt} = F - Gw_{sf} \qquad (10)$$

where $F = \dfrac{1.491*10^{-3}w_s}{h} + \dfrac{\dot{V}w_{ex}}{Ah}$ and $G = \dfrac{1.491*10^{-3}}{h} + \dfrac{\dot{V}}{Ah}$.

The solution is

$$w_{sf} = \frac{F}{G} - \left(\frac{F - Gw_{sf0}}{G}\right)\exp(-Bt) \qquad (11)$$

where w_{sf0} is the initial value of w_{sf}. At steady state, $w_{sf} = F/G$, or

$$w_{sf} = \frac{1.491*10^{-3}Aw_s + \dot{V}w_{ex}}{1.491*10^{-3}A + \dot{V}}. \qquad \text{Kg/kg} \qquad (12)$$

If we write $\dot{V}$ in terms of n air changes per second, we have $\dot{V} = nAh$, (or alternatively $\dot{V} = NAh$ where N is air changes per hour) and so

$$w_{sf} = \frac{1.491*10^{-3}w_s + nhw_{ex}}{1.491*10^{-3} + nh} = \frac{5.37w_s + Nhw_{ex}}{5.37 + Nh} \qquad (13)$$

This can now be compared with Cole's equation, which, when corrected for errors is given by:

$$m_{sf} = \frac{K_1K_2m_s + nhm_{ex}}{K_1K_2 + nh}. \qquad (14)$$

Note that w and m are related by $m = \rho w$. Hence (13) and (14) are directly comparable.

However, from Cole's paper $K_1K_2 = 4*10^{-3}*1.4*10^{-2} = 5.6*10^{-5}$, which is wildly different from the constant in Eq (13) ie $1.491*10^{-3}$ (assuming Cole's n relates to air exchanges per second). The formulation on which the BCA sub-floor ventilation provisions are based would appear to be incorrect. The implications of this are examined below.

VENTILATION CRITERIA

In order to use Eq (13) criteria for sub-floor ventilation must be established. The Building Code performance requirement related to sub-floor ventilation says,

> Moisture from the ground must be prevented from causing—
> (a) Unhealthy or dangerous conditions, or loss of amenity for occupants; and
> (b) Undue dampness or deterioration of building elements.

Cole (1997) reviewed surveys of sub-floor moisture conditions and while commenting on the "paucity of information" concluded that observed moisture problems appeared to be associated with high timber Equilibrium Moisture Content (EMC) generally in excess of 18. His calculations of sub-floor ventilation areas were therefore based on the "ventilation required to guarantee that the sub-floor RH does not exceed 80% for a given external RH". The relationship between EMC and Relative Humidity can be seen in Figure 2.

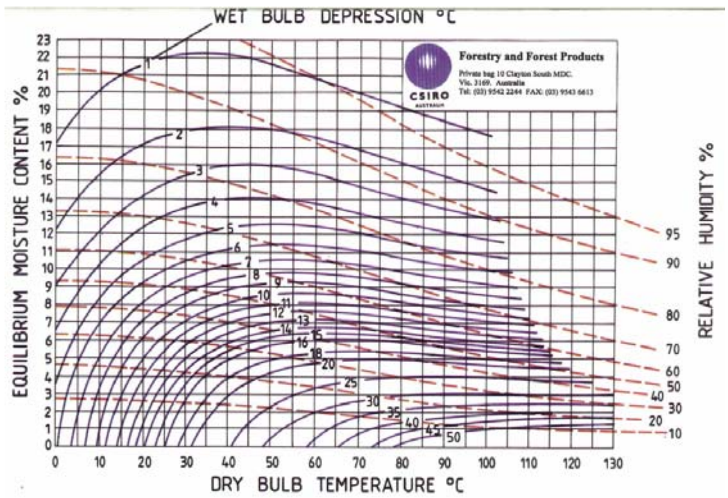

Figure 2: Equilibrium Moisture Content of Wood as a Function of Dry Bulb Temperature and Relative Humidity

Da Costa (1974) had a different view saying "…it must be realised that we are usually trying to prevent condensation….. wood does not decay as a result of high humidity alone, in the absence of condensation….Condensation is usually associated with condensation of water vapour on the cold floor from the relatively warm moist air below..". A CSIRO Information Service sheet of 1977 says, "Decay of timber flooring from fungal attack is not uncommon, especially in older houses and commercial premises. The term "dry rot" is commonly used to describe the problem, but this is misleading as it is essentially a fungal attack requiring dampness to proceed." (CSIRO 1977) Condensation would occur on the underside of a floor if its temperature was below the dew point temperature of the sub-floor air. Such a condition may well occur in summer conditions if the interior of the house is cooled. And as Da Costa (1974) notes, "Forced ventilation with warm air might pick up water vapour where it enters the sub-floor space and deposit it as condensate when it meets colder floors further on."

While condensation as a design criteria is relatively straight forward the health or amenity effects of sub-floor dampness is not so easy to define. Bornehag, Blomquist, et al (2001) reviewing 590 peer-reviewed articles on dampness in buildings concluded that "*Dampness* in buildings appears to increase the risk for a number of health effects such as cough, wheeze, asthma, airways infections, tiredness, and headache. However, with the exception of mite-exposure, it is not known which humidity related agents in indoor air that are responsible for the health effects". Recent research undertaken as part of the timber industry durability program to understand the environmental conditions required to initiate decay has confirmed that RH alone does not lead to decay and that the presence of "free water" is required to initiate decay (Iskra 2006). This same research has also shown that mould growth may occur when the relative humidity is above 80% and the temperature is above 12^{o}C, with the higher the RH the faster the mould grows. However while restricted to the surface of the timber, mould can lead to an odour or smell being present. Confirming this as a problem Kurnitski (2001) in Finland conducted experiments on a full-size crawl space because "Over the last years mould and moisture problems, appearing usually as mould smell… have been considered typical".

The relative humidity (*RH*) of the air is the most critical factor considering the mould growth in the structures of the sub-floor space. A relative humidity over 80–85% during a period of several weeks or months can cause mould growth (Samuelson 1994).. Hukka and Viitanen (1999) described the severity of mould growth by an index where,

0 no growth
1 some growth detected only with microscopy
2 moderate growth detected with microscopy (coverage more than 10%)
3 some growth detected visually
4 visually detected coverage more than 10%
5 visually detected coverage more than 50%
6 visually detected coverage 100%

The Mould Growth Index related to temperature and humidity conditions is shown in Figure 3.

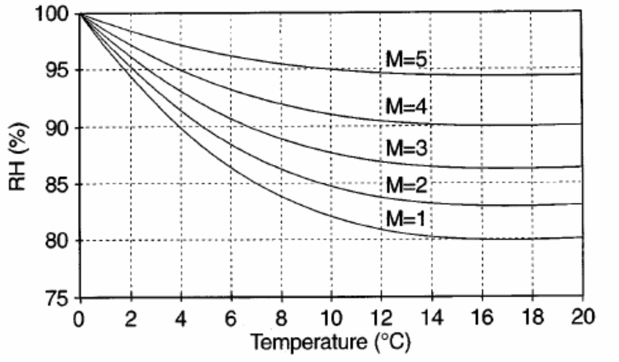

Figure 3: Temperature dependent critical relative humidity needed for mould growth at different values of mould index.
Source: Hukka and Viitanen (1999)

In addition (Hukka and Viitanen 1999) give a regression model describing the response time in days needed for the first visual appearance of mould growth (M=3) as,

$$t_v = \exp(-0.74\ln(T) - 12.72\ln(RH) + 0.06W + 61.50) \qquad \text{(days)} \qquad (15)$$

where
T & *RH* are the ambient temperature and relative humidity conditions,
W is a factor depending on the timber species (0 = pine, 1 = spruce), taken as 0 in calculations below.

SUB-FLOOR CONDITIONS

Data of measured sub-floor conditions in Australia is scarce. Olweny, Williamson, Delsante, et al (1998) conducted a detailed monitoring program of 4 houses in Melbourne during the years 1997-1998. Figures 4 & 5 show a selection of measured temperature and humidity conditions for these houses. House 1 had a highly ventilated sub-floor while the other three houses had more conventional ventilation openings in the sub-floor wall.

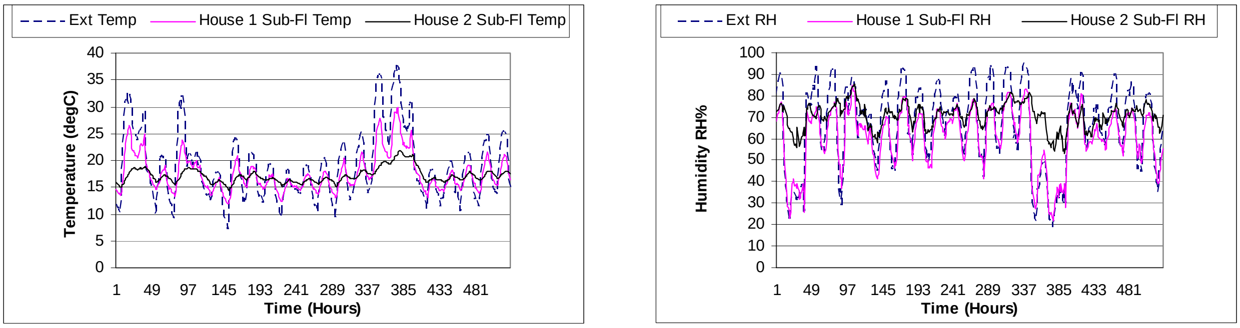

Figure 4: Sub-Floor Temperature and RH conditions Houses 1 & 2 Melbourne, Period Dec 1996-Jan 1997

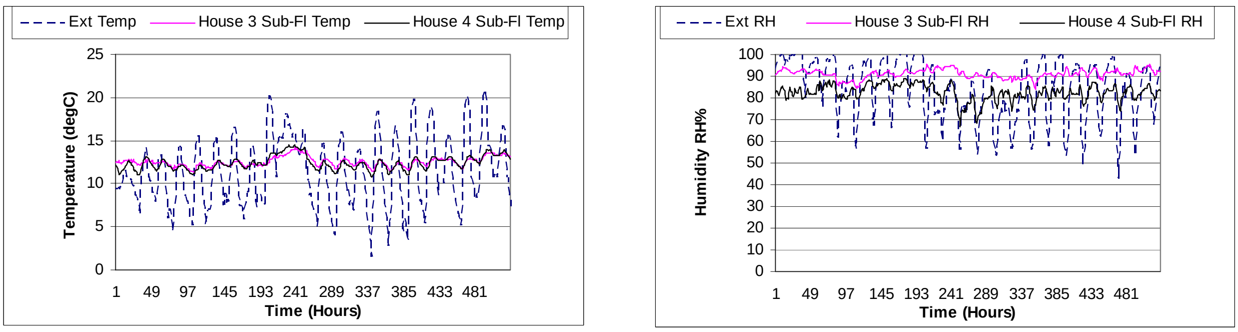

Figure 5: Sub-Floor Temperature and RH conditions Houses 3 & 4 Melbourne, Period Aug 1998

In summer conditions the soil surface at the sub-floor space remains cooler than the average outdoor air temperature, acting as a heat sink and decreasing the ambient air temperature at the sub-floor space. This is amplified if the interior of the house is cooled. In winter the opposite occurs as the heat flow from the deeper and warmer subsoil layers together with heat losses from the floor component increases the average temperature at the sub-floor space.

Kurnitski (2001) in experiments on a full size sub-floor space (in Finland) found that for natural ventilation rates in the range 1-2 ACH the long term soil moisture evaporation rate was 3.6 g/m^{2}h. Abbott (1983) on the other hand found average evaporation rates around 12.5 g/m^{2}h and no influence of sub-floor air exchange rates. It would appear however that Abbott was dealing with relatively high air change rates, probably in excess of 10 ACH.

SUB-FLOOR VENTILATION

Williamson and Delsante (2006) have shown that the sub-floor wind driven ventilation rate appropriate for estimating timber deterioration may be estimated by

$$Q_w = 0.42\, f_w \varepsilon P v' \qquad (\mathrm{m^3/s}) \qquad (16)$$

where
ε is the area of ventilation openings per perimeter length of under floor space, in m²/m;
P is the exposed perimeter of the floor (m);
v' is the average wind speed at 10 m height, in m/s;
f_w is a wind shielding factor as given in Table 1.

Table 1. Wind shielding factors for sub-floor vent calculations

Location	Example	f_w
Sheltered	City Centre	0.03
Average	Suburban	0.10
Exposed	Rural	0.18

Note: The wind shielding factors are calculated assuming a building roof height 3m.

INVESTIGATION OF SUB-FLOOR CONDITIONS AND VENTILATION REQUIREMENTS

A convenient place to start this investigation is with the humidity zones introduced by Cole (1997) and adopted by the BCA. As he explains "in zone 3 the RH exceeds 70% for a significant length of time, in zone 2 it exceeds 60% for a considerable length of time, while in zone 1 the RH does not exceed 60% for an appreciable length of time". It is immediately obvious when considering the conditions that define these three zones that they are not comprehensive. The situation may exist where the 9am RH > 60% but the 3pm RH<40%. This extra condition has been designated as zone 4. Although these zoning criteria are essentially arbitrary they will be used in this study.

Data were obtained from the Bureau of Meteorology for each station that had comprehensive monthly 9am and 3pm temperature, RH and wind speed measurements over a long period of time. In all 1126 stations were available. For each station the month with the highest 9am RH was identified. The station was allocated a zone based on the criteria set down in the BCA (with the addition of zone 4). It was noted that July or January were often not the month with the highest RH as stated by Cole. Stations were further divided into those with the highest RH month in the period November to March (designated with an A, Hot/Humid Regions) or the period April to October (designated with a B, Cold Regions).. Each post code area was allocated a humidity zone based on the BoM station closest to the centre of the post code area. The average distance between a BoM station and the post code centre was less than 18 Km. An examination of Figure 6 with the eight humidity zones plotted into postcode areas reveals a somewhat different picture to the relative humidity zones depicted in the BCA (Figure 1 above). In addition, for each station, the "average" temperature and "average" RH was determined for the whole designated period based on the month with the highest RH. Because mould growth occurs over a long period (several weeks or months) the period average values (shown in Tables 2 and 3) were used as the basis for the mould growth calculations.

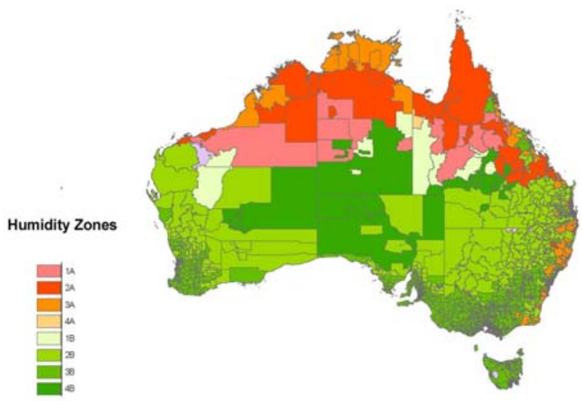

Figure 6: Climate Relative Humidity Zones via Post Codes (1996 Version)

Table 2: Average 9am Conditions when Maximum RH occurs in Period April-October

Zone	Average 9am RH%	Average 9am Temperature	Average 9am Wind (m/s)
1A	55%	14.7	3
2A	78%	11	2.5
3A	85%	8.7	3.2
4A	65%	11.7	2.5

Table 3: Average 9am Conditions when Maximum RH occurs in Period November-March

Zone	Average 9am RH%	Average 9am Temperature	Average 9am Wind (m/s)
1B	54%	30.0	3.4
2B	73%	26.9	2.6
3B	80%	25.0	3.1
4B	61%	28.7	3.8

Condensation vent areas for winter critical conditions are calculated assuming a uniform temperature equal to the external temperature. Given the relatively stable sub-floor temperatures this is likely to be a conservative approach. For summer critical conditions the sub-floor temperature is taken to be 22^{o}C (assuming interior air-conditioning). Again this is most likely a conservative approach. For the mould growth calculations suitable criteria are not so obvious yet are critical for determining the vent sizing. As a tentative beginning the vent areas were calculated assuming monthly average temperature conditions together with sub-floor humidity conditions estimated from Eq (15) equivalent to a response time of 30 days. Initial “required” vent areas based on these assumptions proved to be excessive; generally greater than 50,000 mm^2/m. Enquiries with architects, timber industry bodies, and Government authorities in hot-humid regions revealed that there were no known reports of sub-floor mould growth problems. (But as one respondent said, “nobody in this area builds in the sub-floor, they are all left open”.) This indicated that probably the evaporation rate was most likely being over estimated. The evaporation component of Eq (13) was therefore factored down to match the Kurnitski value of 3.6 g/m^{2}h as described above and assumed to be more applicable to situations when air exchanges rates are low. The results, ventilation areas for the condensation and mould risk, are shown in Table 4.

Table 4: Ventilation Areas for Condensation and Mould Control

Zone		Condition	Required Vent Area (mm^2/m)		BCA Requirements[2]
			Rural	Suburban	
HOT/HUMID REGIONS	1A	Condensation risk	110	195	2000
		Potential mould growth	1000	1860	
	2A	Condensation risk	940	1650	4000
		Potential mould growth	30500	Open[3]	
	3A	Condensation risk	400	700	6000
		Potential mould growth	22420	Open[3]	
	4A	Condensation risk	145	250	NA
		Potential mould growth	1100	2060	
COLD REGIONS	1B	Condensation risk	40	65	2000
		Potential mould grow	1550	2650	
	2B	Condensation risk	90	160	4000
		Potential mould grow	3130	5080	
	3B	Condensation risk	105	185	6000
		Potential mould growth	4295	6510	
	4B	Condensation risk	60	100	NA
		Potential mould growth	1180	3310	

Note: 1) Assumptions for these calculations include Area/Perimeter=2.5, building height=3m, sub-floor height=0.5m. Different geometries will change the results.
2) No membrane installed
3) Open - Implies that the sub-floor space should be left substantially open.

DISCUSSION

This preliminary investigation has raised more questions than it has solved. It has revealed that the relative humidity in the sub-floor space is determined by at least six factors linked together: ground moisture evaporation, soil type, air change rate, building geometry, ambient climate conditions and thermal behaviour of the sub-floor. The "one-size-fits-all" vent requirements within three humidity zones specified as deemed-to-satisfy in the BCA is a simplification of the science that seems not to be justified. The exploratory analysis on which the BCA requirements are based, while undertaken in good faith, does not warrant the important decisions that have flowed as a result.

Table 4 shows (if the assumptions can be believed) that condensation can be avoided with minimum vent areas and that potential mould growth is the more critical criteria on which ventilation requirements should be based. In the "hot/humid" zones 2A and 3A, it would appear that the BCA requirements if complied with could lead to amenity (and health) issues with the growth of mould. However this is not certain. While in Finland where mechanically ventilated sub-floor spaces are common the results from field measurements have shown a correlation between microbes in the sub-floor space and indoors (Airaksinen, Pasanen, et al 2004) in Australia detailed studies to ascertain the prevalence and significance of sub-floor mould growth or the extent that microbial contamination of indoor air may be due to sub-floor conditions have not been conducted.

The investigation reported in this paper commenced with a consideration of the thermal performance of suspended timber floors and the effect ventilation has on the overall thermal resistance (R-value) of the system. It pauses here with three observations; first, a detailed consideration of required sub-floor ventilation is likely to result in different vent areas than presently required for many locations; in many cases this is likely to result in a higher overall floor R-value, secondly, that an understanding of building performance (and especially where aspects are incorporated into regulation) requires the holistic application of building science, and finally, if this issue is to be advanced, further investigations are required to better understand both the physics of the sub-floor environment and its impact on the building occupants.

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