Energy for Sustainable Development 38 (2017) 48–66

Contents lists available at ScienceDirect

Energy for Sustainable Development

Field study of the building physics properties of common building types in the Inner Himalayan valleys of Bhutan

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ARTICLE INFO

Article history:
Received 15 October 2016
Revised 25 February 2017
Accepted 1 March 2017
Available online 2 April 2017

Keywords:
Building monitoring
Air tightness
U-value
Indoor climate
Himalaya
Climate data

ABSTRACT

Traditionally, buildings in the Inner Himalayan valleys of Bhutan were constructed from rammed earth in the western regions and quarry stone in the central and eastern regions. Whilst basic architectural design elements have been retained, the construction methods have however changed over recent decades alongside expectations for indoor thermal comfort. Nevertheless, despite the need for space heating, thermal building performance remains largely unknown. Furthermore, no dedicated climate data is available for building performance assessments. This paper establishes such climatological information for the capital Thimphu and presents an investigation of building physics properties of traditional and contemporary building types. In a one month field study 10 buildings were surveyed, looking at building air tightness, indoor climate, wall U-values and water absorption of typical wall construction materials. The findings highlight comparably high wall U-values of 1.0 to 1.5 W/m²K for both current and historic constructions. Furthermore, air tightness tests show that, due to poorly sealed joints between construction elements, windows and doors, many buildings have high infiltration rates, reaching up to 5 air changes per hour. However, the results also indicate an indoor climate moderating effect of more traditional earth construction techniques. Based on these survey findings basic improvements are being suggested.

Introduction

Situated in the Eastern Himalayas the Kingdom of Bhutan is characterised by three distinct climates: the alpine conditions of the High Himalayas to the North, the more temperate highland climate of the Inner Himalayas in the centre of the country and humid subtropical conditions to the South (Dujardin, 1994). Up to the late 1950s/early 1960s when the country started opening up economically to the outside world, the Bhutanese society was essentially a rural subsistence economy engaged in the sectors agriculture, forestry and livestock (Ura, 1994). This also reflected in the way settlements were laid out and buildings were constructed. Traditionally, villages in the Inner Himalayan valleys, which are the focus of this study, were built at the base of mountain slopes overlooking fields in a river valley with a fast-flowing mountain stream (Nock, 1995). Villages typically consisted of a number of dispersed farmhouses often loosely grouped around a lhakhang (temple) or located in close proximity to a dzong (fortress) built at a strategic point of the valley (Watson and Bertaud, 1976; DoWHR, 1993; Dujardin, 1994; Nock, 1995). However, depending on topography and the availability of arable land, dispersed settlements of isolated farmsteads were also common (DoWHR, 1993). Whilst these village layouts are still to be found today in the majority of valleys in the Inner Himalayan region of Bhutan, new urban settlements no longer follow this pattern (Walcott, 2009). The capital city Thimphu for example now covers large parts of the Thimphu valley, replacing the farmland that was previously present there.

Due to its history Bhutan is essentially a country without a long standing urban tradition (Dujardin, 1994; Herrle et al., 2014), with the two major conurbations of the country, Thimphu in the western Bhutan region and Phuntsholing to the south on the Indian border, having experienced rapid growth over recent decades as a result of large migration pressures from the countryside for employment opportunities (Walcott, 2009). This has created new challenges not only in terms of societal development but also for the construction sector as the requirements for buildings and the surrounding infrastructure have changed alongside these developments. In addition, the introduction of new construction methods and materials previously unknown to the country have played a significant role in the changes that have happened to the construction sector (DoWHR, 1993; Herrle et al., 2014).

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http://dx.doi.org/10.1016/j.esd.2017.03.001

Residential and commercial building types in the Inner Himalayas of Bhutan

Traditional village farmhouse buildings in the Inner Himalayan valleys of Bhutan follow a common archetype, albeit with local variations in material use and design details (DoWHR, 1993; Dujardin, 1994). Farmhouses typically have two to three floors and are constructed of the locally available materials earth, quarry stone and timber (Nock, 1995; Herrle et al., 2014). As can be seen in Fig. 1, the ground floor, which was traditionally used as cattle barn, always consists of solid walls (DoWHR, 1993). The upper floors were used for storage and residential purposes (DoWHR, 1993). Where the building has three floors, the middle floor is typically also made entirely of solid walls (MoWHS and CIT, 2010). Depending on the total amount of floors the upper one or, rarely, two floors partly consist of solid walls and partly of a timber-frame structure usually with mud plastered infills on a bamboo grid, the so-called ekra (DoWHR, 1993; MoWHS, 2014). This timber-frame structure which is termed rabsel is cantilevered about 15 cm beyond the main structural walls, which in the western parts of Bhutan are usually made out of about 60 cm to 100 cm thick rammed earth on a quarry stone foundation protruding about 40 to 80 cm above ground level and in the central and eastern regions out of quarry stones with mud mortar (DoWHR, 1993; Sethna, 2008; MoWHS, 2014). Whilst the solid walls often hardly contain any openings at all the rabsel element is characterised by elaborate window openings. As seen in Fig. 1 the roof is an open structure on timber stilts built over a flat roof with the space in-between traditionally being used for drying and storing crops and hay for the livestock as well as for storing equipment (Watson and Bertaud, 1976; DoWHR, 1993; Nock, 1995; Lang et al., 2013). This roof structure which is sometimes described as an adaptation of the flat roofs found on the Tibetan Plateau to suit the monsoonal climate of Bhutan (Nock, 1995; MoWHS and CIT, 2010) has a slope of about 15° and was formerly covered with wood shingles secured by stones but now, for maintenance reasons, more often with imported corrugated steel sheets. The eaves are rather broad on all elevations in order to prevent rain from causing damage to the walls which, as described above, always contain some fraction of clay (MoWHS and CIT, 2010).

Traditional farmhouses built prior to the 1960s when the modern economic development of the country started (Ura, 1994) are now rare in the Thimphu valley where the study presented in this paper was conducted. Already in the 1990s the number of old buildings was deemed insufficient to give reliable clues on the historic local particularities and design features specific to the Thimphu valley (DoWHR, 1993). However, what still remains today clearly follows the house archetype design with rammed earth walls as described above. A detailed architectural survey of some of these buildings was undertaken in 2009 in the Thimphu area with 4 houses in the village of Babesa and 1 in Changjiji having been extensively surveyed and documented with a set of detailed drawings highlighting their architectural features (MoWHS and CIT, 2010).

Buildings constructed in the Thimphu valley since the city was made capital of Bhutan no longer follow the traditional space usage patterns. New usages emerged as a result of the growing demand for central administration and the need to cater for private businesses that developed alongside government administration (Dujardin, 1994). The main new house archetypes span purpose built governmental office buildings, single family homes, multi-storey apartment buildings with and without business units/shops on the bottom floors and purpose built hotels to cater for international tourists. Whilst traditional buildings were constructed on the basis of mutual help from the village community under guidance of skilled craftsmen (Watson and Bertaud, 1976; Dujardin, 1994; Nock, 1995; Bajaj, 2014), these new buildings are increasingly being designed by architects and civil engineers (DoWHR, 1993; Dujardin, 1994). Until recently these architects and civil engineers were exclusively trained in foreign countries, mostly India, and the design was often undertaken and supervised by government bodies employing them. An example of this is the two-storey apartment building shown in the foreground of Fig. 2. This was completed in 2001 as part of a social housing programme.

The most common contemporary construction method for buildings of all types in Bhutan is a reinforced concrete frame structure with single leaf brick infills (Nock, 1995; Lang et al., 2013; Herrle et al., 2014). The walls are usually plastered with cement render and have a thickness of typically around 25 cm including rendering. Windows are made directly on site and are usually single glazed with aluminium or, more commonly, wooden frames. Structural design and material specifications are in compliance with Indian quality standards and building codes which means that there are some similarities with Indian buildings (Dujardin, 1994; Lang et al., 2013). However, according to the 'Bhutan Building Rules 2002' (DoUDH, 2002), architectural appearance and features such as the external façade design and roof structure should comply with national design guidelines as originally laid out in the 'Traditional Architecture Guidelines' (DoUDH, 1993). In 2014 these were superseded by the 'Bhutanese Architecture Guidelines' (MoWHS, 2014) which give guidance on the application as well as the proportions and the sizing of design elements that follow traditional Bhutanese architectural patterns. Further to this, recommendations are provided

Fig. 1. Traditional farmhouse constructed with rammed earth in the Paro valley in the western part of Bhutan, however with some modifications to the traditional façade structure and roofing.

Fig. 2. Government constructed apartment buildings in Thimphu in reinforced concrete frame construction with brick infills and concrete formwork for architectural design elements.

for roof designs. The guidelines also permit the use of contemporary materials such as pre-cast concrete elements which, as can be seen in Fig. 2, are now commonly used for façade and window details instead of wood. The use of such precast elements is, however, often criticised by western scholars since the material requirements and the structural reasons that exist for the corresponding woodwork often no longer apply for the contemporary designs (Watson and Bertaud, 1976; Nock, 1995; Walcott, 2009; Langenbach, 2010; Herrle et al., 2014). In Bhutan itself however, the view is taken that the development of architecture should be guided by the cultural heritage, but that at the same time there should also be “flexibility for creativity and innovation for new designs” (MoWHS, 2014).

In Thimphu and other urban areas the construction sector largely relies on foreign contractors and migrants mostly from India and Nepal for manual labour (Dujardin, 1994; Walcott, 2009). This means that the workers have little to no connection to the traditional architecture of Bhutan. Similarly, large fractions of the contemporary construction materials used in Bhutan are imported from India (Watson and Bertaud, 1976; Bajaj, 2014). Whilst cement, sand and timber are sourced locally, reinforcing steel, bricks, glazing, aluminium and any synthetic materials used in construction are imported from India, with people often even aspiring towards the use of such imported materials (MoWHS, 2013a).

Whilst reinforced concrete frame constructions with imported brick infills represent the bulk of new buildings in urban areas in Bhutan, other types of construction also exist. For example, instead of using brick infills locally manufactured hollow concrete blocks or so-called cement stabilised earth blocks (CSEB), produced with a ratio of cement to earth of about 1:6 to 1:10 (MoWHS, 2013a), are also occasionally used (Lang et al., 2013). One or two storey high buildings without reinforced concrete frames also exist. The materials used for these may be adobe blocks with mud mortar, dressed natural stone with cement mortar or hollow concrete blocks/CSEBs laid in cement mortar (Lang et al., 2013) with the latter two often having reinforcement steel introduced into the walls for earthquake resistance reasons (MoWHS, 2013c). Common to all materials used in contemporary buildings in Bhutan, whether domestic or imported, is that little to no knowledge exists about the exact material properties or their structural, thermal and water absorption performance since production methods, processing and treatment on site vary considerably.

Investigating Bhutanese buildings under a building physics perspective

The aforementioned changes in construction methods and materials choice alongside with changes to the working conditions and the standard of living in Bhutan have resulted in the development of urban areas with buildings of up to five or six floors that have uses hitherto unknown to the country such as apartments or office units (Herrle et al., 2014). Due to influences from the increasing exchange with other countries and the rising availability of fuel sources other than firewood, in particular electric heating, expectations for indoor climate conditions have also changed over recent decades, with people now expecting higher thermal comfort standards. However, whilst elements of traditional architectural design are required to be adhered to in an adapted form in new buildings as detailed in the ‘Bhutanese Architecture Guidelines’ (MoWHS, 2014), the novel construction techniques are mostly ill-suited to the local climate conditions. The reason for this is that these construction methods mostly stem from India (Dujardin, 1994) and are thus intended for a warmer climate than that found in Bhutan (DoWHR, 1993). The former Department of Works, Housing and Roads (DoWHR) of the Royal Government of Bhutan already concluded in 1993 that this has “resulted in many buildings with an exceptionally poor thermal performance” (DoWHR, 1993). Nevertheless, thermal insulation is still not routinely applied in the Bhutanese construction sector almost 25 years later, even though clear recommendations for doing so exist in the respective governmental guidelines (MoWHS, 2013a, 2013b). Furthermore, no dedicated insulation materials are readily available on the local market, nor is there a skills base for their application in the construction sector. Further to this poorly sealed joints and cracks are common in buildings of all types and ages which increases potentially unwanted air infiltration.

Increased concerns about the energy demand for space heating coupled with incentives for the use of local materials as well as a rising awareness of the shortcomings in the thermal performance of large parts of the current building stock all have led to an understanding for the need to integrate building physics considerations into the building construction process (MoWHS, 2013a, 2013b). However, to date no climatic baseline information that would support this is available at the planning stage, nor are the thermal properties of current construction materials or the buildings produced with them known. This work aims at establishing such information for the first time in the context of Bhutan by assessing available climate data and presenting building performance field study results.

Climate conditions in the Thimphu valley

In order to assess the requirements for climate responsive building design and to establish the needs for building services systems such as space heating it is vital to gain an understanding of the underlying climate conditions of a location (CIBSE, 2002). However, to date no construction industry specific climatological data such as the climatic design condition information published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for almost 6500 locations worldwide (ASHRAE, 2013) is readily available for Bhutan. Therefore, data gathered by the Department of Hydromet Services (DHMS) of Bhutan was reviewed in its suitability for establishing such design condition information. The DHMS has daily and monthly data available for 21 weather stations of which Simtokha was selected as a reference since it is situated in the Thimphu valley which is the focus of this study.

The available data for Simtokha weather station (27.44°N, 89.66°E) at an altitude of 2310 m included the following parameters: daily minimum and maximum dry bulb temperature, daily precipitation, daily mean wind speed and wind direction (in bins of 15°) as well as monthly mean relative humidity and sunshine duration data. Data was generally available for the timeframe from July 1995 to June 2014 inclusive. Whilst this data represents a good basis for gaining an understanding of the general climate conditions affecting building design, there is however not sufficient information for developing design conditions tables as provided by ASHRAE (ASHRAE, 2013) since this would require hourly climate information. Nevertheless, some basic climatological information relevant to building physics studies could be derived from the data as detailed in the following.

Dry bulb temperature

Reference information for dry bulb temperature was established guided by the basic principle for generating typical meteorological years (TMY) for building performance simulation where long term data is analysed on a month by month basis in order to identify the most typical months from the data for a given location and then construct an artificial “typical year” from these months (Wilcox and Marion, 2008). However, using cumulative distribution functions in conjunction with the Finkelstein-Schafer statistics (Finkelstein and Schafer, 1971) in order to identify these candidate months as it is commonly done for generating reference years such as the TMY data files (Wilcox and Marion, 2008; ISO 15927–4:2005) was not deemed sensible due to the coarse resolution of the available daily minimum (T_{min}) and maximum dry bulb temperature (T_{max}) data at steps of typically 0.5 K. Instead, the monthly average daily minimum and maximum dry bulb temperatures were calculated for all available months and these then ranked in descending order. The months with the 50th percentile rank, i.e. the median or rank 10 of the total 19 nodes for each calendar month, were then chosen as candidate months. However, as the candidate months for minimum and maximum dry bulb temperature rarely coincided, the most typical months for both parameters needed to be established. This was done by calculating the deviation of the average T_{min} and T_{max} of the remaining 18 nodes per calendar month from the respective candidate months' values, with the month of the year with the smallest sum of these deviations then becoming the overall candidate month. The selected years for the candidate months are given in Table 1 which also displays the daily average T_{min} and T_{max} of these months.

Fig. 3 shows the diurnal T_{min} and T_{max} profile of the temperature reference year produced using the method detailed above. Where months of different years were put together, data adjustments between the last and the first few days of the month were not deemed necessary, since a strong variation in both T_{min} and T_{max} is common for the given location. This can, for example, be seen in the T_{min} data for mid-January, March, October or December and the T_{max} data for mid-March, July or December. Fig. 3 also clearly highlights that the daily minimum temperatures frequently go below freezing for about three to four months of the year (50 days in total) and that the daily maxima in winter are typically close to or even above 15 °C. Only 32 days have maxima below 15 °C and 3 days below 12 °C respectively. This highlights the need for space heating from about November to March but at the same time also shows the potentials of using thermal mass as a strategy to moderate the indoor climate, in that a time lag can be created between the external T_{min} and the occurrence of the lowest indoor temperatures, reducing night-time space heating requirements.

Sunshine duration

The potential for the application of thermal mass is further illustrated in Fig. 4 which shows the average daily sunshine duration per calendar month. This data represents the median values of the available monthly data, in this case data from July 1995 to October 2014, albeit with selected months in 2002, 2007 and 2009 as well as the entire year 2011 missing from the data. It can be clearly seen, that those months with the lowest night-time minimum temperatures shown in Fig. 3 are, at the same time, the months with the longest sunshine hours. As illustrated in Fig. 4, in the four months from November to February the sunshine hours represent around 60% of what would be astronomically possible, as calculated following the solar geometry equations given in CIBSE Guide J (CIBSE, 2002). Given the latitude of Thimphu (27.47°N) and an appropriate siting of a building in relation to the local topography in order to avoid extensive shading effects, solar gains could thus be utilised in winter for supporting space heating as already highlighted in the 'Bhutan Green Building Design Guidelines' (MoWHS, 2013a).

Precipitation

The precipitation data shown in Fig. 5 was derived from long-term July 1995 to June 2014 data and represents the monthly means over this time period. The number of days with rain specify days with 1 mm or more precipitation. In conjunction with the temperature data given in Table 1 Fig. 5 highlights that the Thimphu valley can be classified as a Cwb climate on the Köppen–Geiger climate classification system (Kottek et al., 2006), i.e. a subtropical highland climate with dry winter. The dry winter with limited cloud cover, which is clearly visible in Figs. 4 and 5, is a further indication of the general applicability of passive design principles in order to sustain comfortable indoor climate conditions (MoWHS, 2013a). In view of this the question arises, why measures such as a high thermal mass are not more widely applied in new constructions in Thimphu, even though the benefits are clearly apparent. Fig. 5 also clearly shows the summer monsoon season typical of the Inner Himalayas which necessitates appropriate roof designs in order to avoid structural damage.

Other climate parameters

A further climate parameter of great relevance to the construction industry is humidity information, in particular for estimating cooling loads (ASHRAE, 2013). However, as only monthly average data was available for relative humidity, it was not possible to derive any relevant design condition information for the Thimphu valley. Further to this, the diurnal temperature profile shown in Fig. 3 does not imply an extended need for space cooling, as the summer day-time temperatures rarely exceed 30 °C and the night-time temperatures typically are around 15 to 16 °C.

As the mean wind speed is a function of surface roughness, topography and obstacles (CIBSE, 2015), the applicability of the daily mean wind speed data provided by the DMHS is rather limited for building design purposes in a mountainous terrain such as Bhutan, since local microclimatic particularities prevail. Locally sourced information such as the fact that winds typically tend to pick up in the early afternoon in the Thimphu valley is, therefore, potentially of greater relevance for building design. Similarly, taking reference in traditional village layouts where individual buildings and trees were arranged in order to provide some shielding from strong and often cool local winds (Watson and Bertaud, 1976; DoWHR, 1993) requires local microclimatic studies and is not possible on the grounds of general weather station data.

Heating degree-days

Where detailed climate information such as the Typical Meteorological Years (TMY) or Test Reference Years (TRY) used in building performance simulation tools is not readily available, such as is the case in Bhutan, other methods need to be employed in order to gain an understanding for space heating requirements. The heating degree-day method which has been used for this purpose over many decades can help to provide an estimate for space heating requirements through manual calculations (VDI 4710–2:2007; ASHRAE, 2013; CIBSE, 2006). Alternatively, TMY data could be theoretically created via a weather generator (Lhendup and Lhundup, 2007). However, due to the mountainous terrain with distinct microclimates and the scarcity of supporting baseline data this is not a trivial task for Bhutan. Therefore, it was decided to derive heating degree-day information which has the further benefit of being useful for simple manual calculations.

Heating degree-days are derived on the basis of external dry bulb temperature information and in essence represent the sum of temperature differences to a base temperature over a defined period of time (CIBSE, 2006). Hereby the base temperature represents the daily mean external temperature below which the heating system would be considered as being operational in order to maintain a comfortable indoor climate (CIBSE, 2006; VDI 4710–2:2007). As such the base temperature

Table 1
Months selected to represent a temperature reference year for the Thimphu valley on the basis of data from July 1995 to June 2014 from Simtokha weather station, also including the average daily minimum and maximum dry bulb temperatures of the respective months. (Data source: Department of Hydromet Services (DHMS), Bhutan.)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Selected year	1999	2011	2005	2008	2008	2006	2007	2009	2007	1999	2001	2004
Average daily T_{min}	−2.1	1.0	3.4	7.8	11.5	15.3	16.0	16.3	14.7	9.7	3.7	0.2
Average daily T_{max}	15.3	17.4	20.0	22.6	25.3	26.8	27.1	27.6	26.2	22.7	19.6	16.3

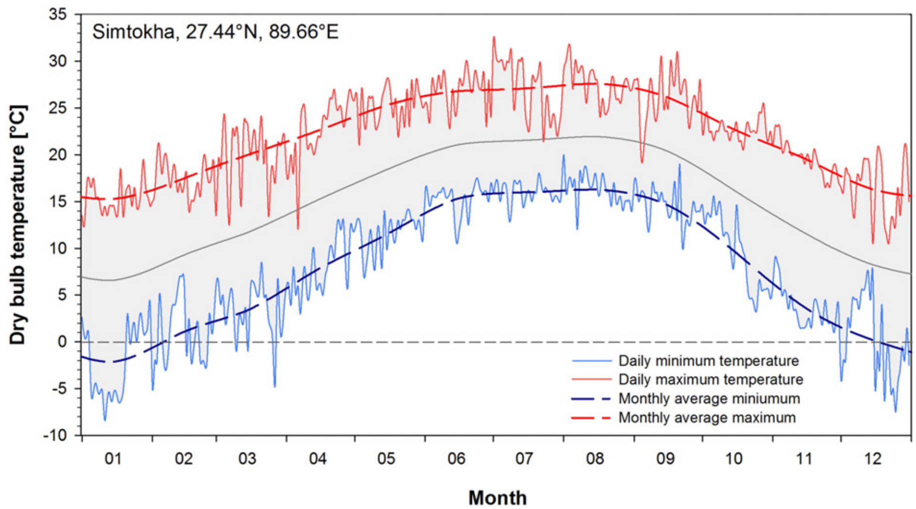

Fig. 3. Diurnal profile of the daily minimum and maximum dry bulb temperatures for a "typical year" in the Thimphu valley area, constructed from daily temperature data of Simtokha weather station from July 1995 to June 2014.
(Data source: Department of Hydromet Services (DHMS), Bhutan)

is dependent on building fabric quality, internal loads and the aspired internal room temperature. Due to the increased complexity, the results obtained by using the heating degree-day method are known to reduce in their significance for buildings of a higher thermal insulation standard (VDI 4710–2:2007). However, in the case of Bhutan where thermal insulation is not routinely used, the method can deliver valuable information for assessing space heating requirements.

The available daily T_{min} and T_{max} data from Simtokha weather station for the full years 1996 to 2013 were used to calculate the monthly mean total heating degree-days for a range of base temperatures. As shown in Table 2, values are provided in steps of 2 K from 8 to 22 °C, also integrating the base temperature references commonly used by ASHRAE: 18.3 °C (ASHRAE, 2013) and the Chartered Institution of Building Services Engineers (CIBSE): 15.5 °C (CIBSE, 2006). Given that only single daily readings of T_{min} and T_{max} were available, it was not possible to conduct hourly degree day calculations such as recommended by VDI 4710–2:2007 or CIBSE, 2006. Instead, the UK Meteorological Office equations dating from the 1920s (CIBSE, 2006) were used to establish the data given in Table 2. In the absence of daily mean data these work on the basis of T_{min} and T_{max} data, although it needs to be noted that this method comes with greater uncertainties than hourly integrated data in particular for lower base temperatures (Day and Karayiannis, 1998).

With annual heating degree-days of 495 Kd to a base of 10 °C and 1787 Kd to 18.3 °C Thimphu displays similar overall values to the coastal city of Thessaloniki in Greece which, according to ASHRAE, has 430 Kd and 1801 Kd annually for the same base temperatures (ASHRAE, 2013). However, due to the highland climate the degree days are a little more dispersed over the months in Thimphu as compared to Thessaloniki, essentially smoothing the profile as can be seen in Fig. 6. Nevertheless, the values imply a need for space heating for about 4 to 5 months of the year.

Provided that basic building information such as fabric U-values, building component surface areas, air infiltration rate and internal building volume are known, the degree-day information given in Table 2 can be used to estimate monthly or seasonal heating energy demands in Thimphu, for example, by using the equations given in CIBSE TM41 (2006). However, the required information on the thermal conductivity of common building materials as well as air infiltration rates of typical buildings is essentially unavailable in Bhutan. The field study detailed in the following represents a first attempt at establishing such data.

Field study results

In order to gain an understanding of the current building physics properties and the environmental performance of buildings in the

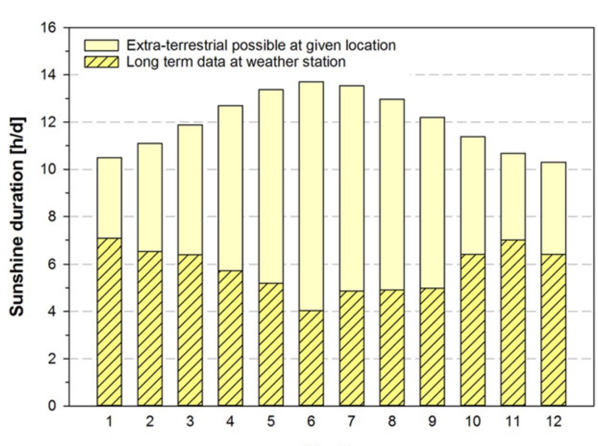

Fig. 4. Average daily sunshine duration for Simtokha weather station.
(Data source: Department of Hydromet Services (DHMS), Bhutan)

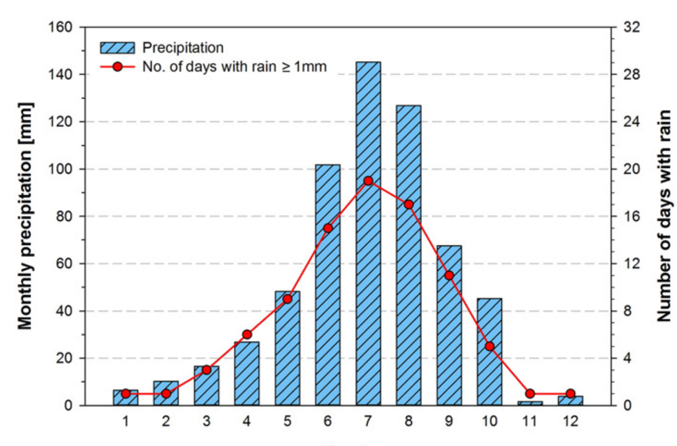

Fig. 5. Average precipitation and number of days with rain for Simtokha weather station.
(Data source: Department of Hydromet Services (DHMS), Bhutan)

Table 2
Mean total heating degree-days for the Thimphu valley area derived from climate data from 1996 to 2013 from Simtokha weather station (27.44°N, 89.66°E, altitude: 2310 m). For the annual total heating degree days the standard deviation (Std Dev) is also given.

Base temp. [°C]	Mean total heating degree-days [Kd]												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year (Std Dev)
8	103	61	34	9	1	0	0	0	0	7	35	80	330 (92)
10	146	91	53	18	4	0	0	0	0	14	52	117	495 (114)
12	195	130	80	31	10	1	0	0	1	25	79	162	714 (132)
14	245	173	117	51	20	3	1	1	4	41	116	210	982 (152)
15.5	286	208	149	73	32	8	2	3	10	58	149	248	1226 (170)
16	300	220	161	81	37	10	3	5	13	65	161	261	1317 (176)
18	358	270	210	120	61	22	13	15	28	99	208	316	1720 (203)
18.3	367	278	218	127	65	25	15	17	30	105	215	325	1787 (207)
20	418	323	263	166	96	41	29	31	49	141	259	375	2191 (227)
22	480	379	320	215	140	72	55	57	84	189	314	437	2742 (253)

Thimphu area it was decided to try to cover as many of the building and construction types described above in the field study as possible. Tests included (a) air tightness tests using the so-called 'blower door' method, (b) indoor climate measurements spanning the parameters dry bulb temperature, radiant temperature, relative humidity and air speed, (c) heat flux density measurements in order to determine U-values of typical wall constructions and (d) on-site water absorption tests of wall construction materials. However, given that there was only a time frame of one month available for the tests (2nd of October to 2nd of November), only a limited number of buildings could be examined, especially since indoor climate and heat flux density measurements require several days of continuous monitoring in order to deliver meaningful results.

10 buildings were surveyed in total, the set comprising of 6 residential buildings, 3 offices and one library. As can be seen in Fig. 7, the surveyed buildings included a traditional and two more recent rammed earth buildings with a timber-frame structure on the upper floors, a building constructed with cement stabilised earth blocks, a building with dressed natural stone, 4 reinforced concrete frame buildings with imported brick infill walls and a reinforced concrete building with walls of imported aerated concrete blocks, this building representing the first of its kind in Bhutan. The buildings are all located in the Thimphu valley and, as shown in Fig. 8, span locations from the inner area of town (buildings 6, 7, 9), the edge of town (buildings 1, 3, 4, 8, 10) and the more rural area of Kabesa to the north of Thimphu (buildings 2, 5). However, as the town is only a little more than 3 km wide at its widest expanse, is not very dense and only has buildings of a maximum of 5 to 6 storeys, the impact of the city on the microclimate

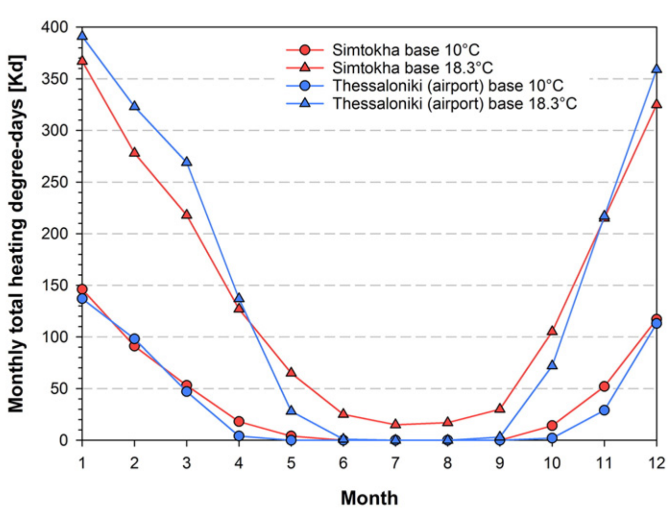

Fig. 6. Monthly heating degree-days for Simtokha weather station and Thessaloniki Airport for the base temperatures 10 and 18.3 °C.
(Data source Thessaloniki Airport: ASHRAE, 2013)

is not likely to amount to a level where significant effects on the field study results would be expected. All buildings are located at altitudes between 2300 and 2520 m so that altitude effects should also not have a significant influence that would adversely impact on the comparability of results.

Air tightness tests were conducted in 9 of the investigated buildings with only the historic rammed earth building not being studied since, due to the investigated space being uninhabited, not all windows had glazing which prevented building-up of the required pressure difference for the test. Indoor climate measurements were successfully conducted in 4 buildings or secluded parts thereof (buildings 1, 3, 4, 7). Wall U-values could be determined for 4 constructions spanning rammed earth (building 1), compressed stabilised earth blocks (building 4), imported bricks (building 7) and aerated concrete blocks (building 10). This was complemented by a U-value test of a locally manufactured double glazing unit with air infill on building 3. Water absorption tests were conducted on the following materials: rammed earth, cement stabilised earth blocks, cement plaster, imported bricks and aerated concrete blocks. Table 3 gives an overview of the key results obtained from the field survey measurements, with the following sections providing more detail on the exact testing methods and the key results of the measurement campaign.

Building air tightness tests

Building air tightness measurements were carried out using the 'blower door' method according to the procedures detailed in EN 13829:2000, where a pressure difference (under- and overpressure) is created in various steps between the inside and the outside of a building in order to monitor the air flow through a fan which translates into an air change rate to compensate for leaks in the building envelope. In order to find these air leaks in the building envelope, in a second step a constant underpressure of 50 Pa was created, leaks sought manually and the air flow through these leaks investigated using a thermoanemometer. As detailed in Table 3 air tightness tests were conducted in 3 office units and 5 residential buildings of various construction types, looking at overall building air tightness as well as for determining and logging typical air leaks. Further to this a reading room in the library building was tested but, due to air flows through the internal walls separating the room from the rest of the building, the overall air tightness results were not deemed representative for external infiltration into the building and were, therefore, not considered in the data evaluation. Nevertheless, leaks in the building envelope were examined and noted down (Table 3).

Method B of EN 13829:2000 was followed, where deliberate openings such as ductwork for ventilation purposes or extraction fans are sealed off during the test. This was the case in buildings 4, 6 and 9. Further to this, floor drains in the bathrooms of buildings 4 and 9 had to be sealed as a result of strong airflow due to apparently missing syphons. Due to building size, building geometry, build quality and ownership structure it was not possible to conduct a full building assessment on any of the investigated constructions. In buildings 4, 8

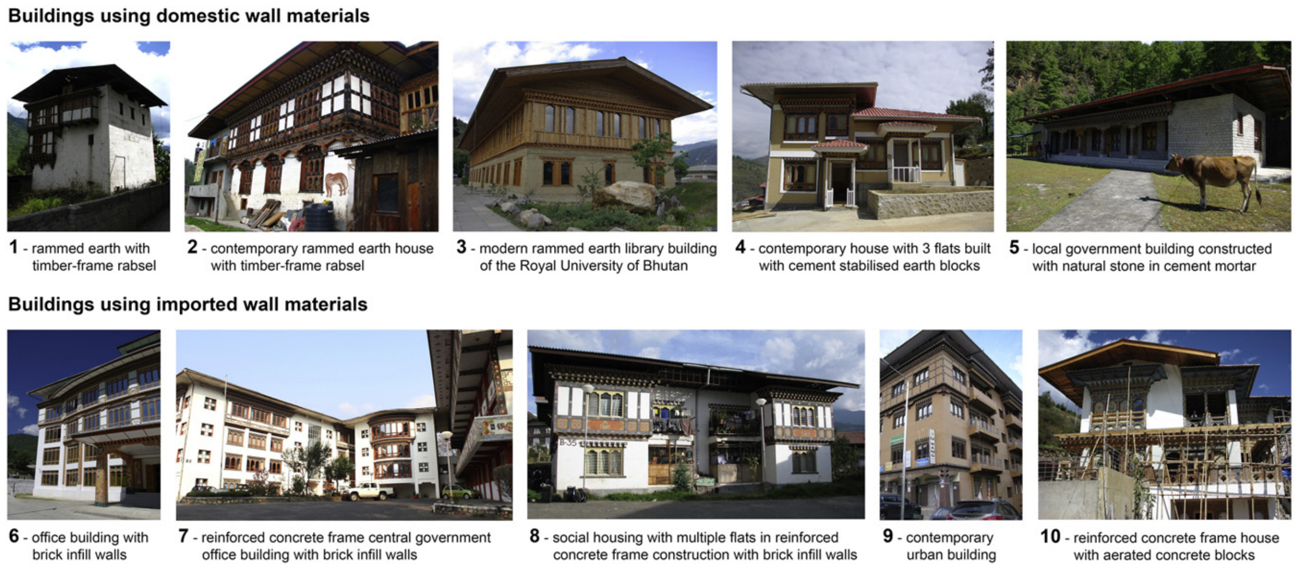

Fig. 7. Buildings investigated in the building physics field study in the Thimphu valley.

and 9 individual residential units were tested, with the 'blower door' fan unit always being installed in the entrance door to the flat. Similarly, in buildings 6 and 7 secluded office units separated from the rest of the building were tested. However, in buildings 2, 5 and 10 it was only possible to conduct tests in one or two rooms. The reasons for this were: (a) poor overall air tightness of the building (buildings 2 and 5) and (b) the building not yet being fully completed (building 10). Where doors to other building parts existed, these were sealed off during the test.

The most common measure for comparing the air tightness of buildings is the air change rate at 50 Pa pressure difference, the so called n_{50} value, which represents the mean value of under- and overpressure measurements at 50 Pa (EN 13829:2000). For example, in Germany the Energy Saving Regulations (ENEV) 2007 state that the n_{50} value of a new building tested following EN 13829:2000 must not exceed 3 h^{-1}. As can be seen in Table 3 and the box plot in Fig. 9 none of the investigated buildings in Bhutan met this requirement, with the best performing building, i.e. the social housing unit (building 8), displaying a value which is almost 4 times higher at $n_{50} = 11.7\ h^{-1}$. This is also higher than the value of 7.5 h^{-1} given in EN 15242:2007 for a leaky detached house and demonstrates that the values determined in the field study in Bhutan significantly exceed those for both new and existing buildings in Europe. This is further illustrated by Fig. 9 via the comparison with the work of Alfano et al. (2012) for southern Italy and Sfakianaki et al. (2008) for the Attica region in Greece. These studies both spanned 20 residential buildings of various ages in areas with some similarities to Thimphu in terms of heating degree days (ASHRAE, 2013), even though the work of Alfano et al. (2012) shows some variation in the heating degree day information for the investigated buildings which is probably related to the exact building location (coastal, inland) and altitude. It can be clearly seen in Fig. 9 that, apart from some outliers in the southern Italian study (Alfano et al., 2012), the bulk of the

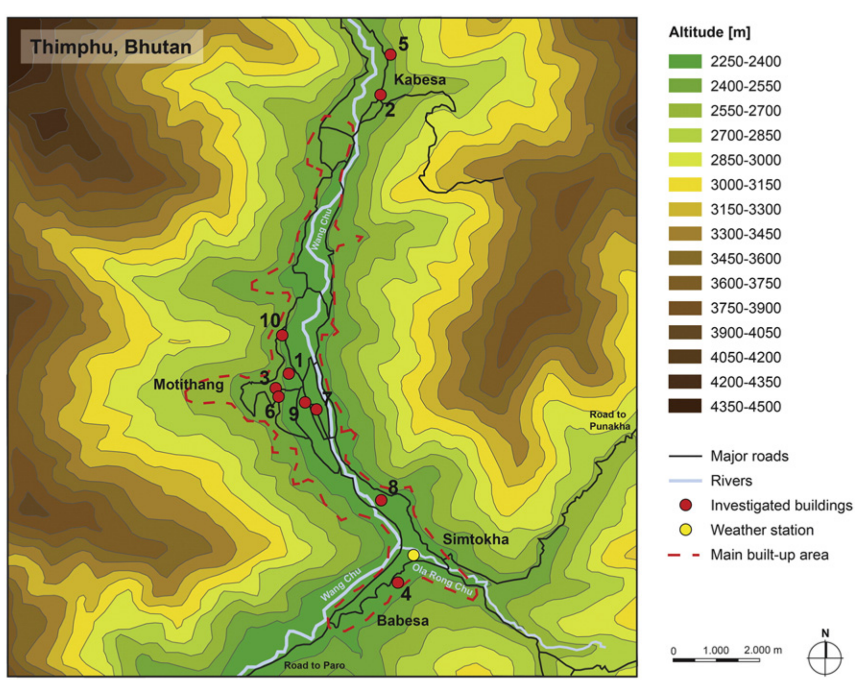

Fig. 8. Area map of the Thimphu valley detailing the location of the 10 buildings investigated in the field study. (The numbering follows Fig. 7. Simtokha weather station is also shown.)

investigated buildings display a much greater air tightness than found in Bhutan, with all buildings being in a comparably rather narrow band for the n_{50} value.

While a total of 8 buildings is not a sample size that would be in itself sufficient to be deemed representative, there are, however, some initial conclusions that can be drawn from the tests in Bhutan. Firstly, and probably most importantly, the worst performing buildings were those using traditional materials and construction methods, i.e. the timber-frame rabsel construction of building 2 with $n_{50} = 75.7\ h^{-1}$ and building 5 using dressed natural stone with $n_{50} = 55.8\ h^{-1}$ (Fig. 7). In both cases joints between elements of the timber structure such as joists, floor boards, window casements, window frames and lintels with decorative elements as well timber-frame members in the façade were identified as major causes for air leaks. Similarly, joints between timber elements and other materials were also frequently found to be significant sources of air leaks. In the case of building 5 poor timber quality was a further reason for air leaks, since there were cracks in the wood as well as open knotholes in the window frames (Table 3).

Overall, the buildings constructed with solid walls and floors performed significantly better than those following traditional methods. Four buildings, i.e. buildings 6, 8, 9 and 10, had n_{50} values in a band of between 11.7 and 15.4 h^{-1} with the main leakages being joints between windows and walls, window casements and frames, unsealed balcony doors, poorly sealed wall break-throughs or, where present, revision openings to risers. It was found that using imported sliding aluminium frame windows such as in buildings 8 and 9 in principle leads to a better performance than integrating locally produced wooden windows, provided, that the windows are sized correctly (see notes on building 9 in Table 3).

Of the buildings with wooden windows buildings 6 and 10 were found to perform best at 14.2 and 14.7 h^{-1} respectively (Table 3). Both of these buildings have inward opening windows, yet without rabbet edges. However, for the central government office building 7 a much higher n_{50} value of 27.8 h^{-1} was observed. The reasons for this observation were that this building has outward opening wooden windows without rabbet edges of poor quality workmanship with large gaps between the side hung casements and the window frames, coupled with a large window to wall ratio of 0.34. Similarly, the wooden sliding windows of building 4, albeit of a higher timber quality and better workmanship than in building 7, contributed to a rather high n_{50} value of 27.6 h^{-1}, highlighting the difficulty to produce an airtight window with this construction type if no seals are being used. The potentials of an improved window design could, however, be demonstrated on building 4, in that all windows were sealed off with plastic sheeting and the overpressure test series rerun. In this case the n_{50} value reduced to 10.2 h^{-1}. Furthermore, leakage detection with a thermoanemometer on the double glazed windows with rabbet edge frames of the library building 3 revealed that, apart from small air leaks around the hinges, these windows were significantly tighter than the windows of any of the other buildings. This included building 10 which had windows with sealing strips but no rabbet edges, with the seals in some places being too small to close the gap between window frame and casement and thus not working as intended.

From the n_{50} data the mean air infiltration n_{inf} into the buildings under natural pressure conditions was inferred using Eq. 60 of section 6.3.1.2 of DIN V 18599–2:2011, which in the absence of a mechanical ventilation system or any other wall break-throughs for ventilation purposes becomes:

$$n_{inf} = n_{50} \cdot e \tag{1}$$

where e is the wind shielding coefficient. For buildings with more than one façade exposed to wind that are moderately shielded by surrounding trees and buildings this coefficient assumes a value of $e = 0.07$, as given in table C.4 of ISO 13789:2007. This was deemed representative for all buildings investigated in Bhutan and leads to a range of air infiltration rates of $n_{inf} = 0.8$ to 5.3 h^{-1} for the field study buildings. However, for building 6, which is the first building in Bhutan with a mechanical ventilation system, additional infiltration due to the ventilation system would need to be considered in compliance with DIN V 18599–2:2011. Nonetheless, these calculations could not be conducted due to the required data on the ventilation system being unavailable. Therefore, the infiltration rate of $n_{inf} = 1.0\ h^{-1}$ stated in Table 3 for building 6 is potentially too optimistic.

The above highlights a dilemma in that traditional construction methods, although politically favoured (MoWHS, 2013a, 2013b), were those identified to be worst performing in terms of air tightness and this to a level, where significant implications for winter indoor thermal comfort would be expected. Nevertheless, at infiltration rates of 0.8 h^{-1} or more the other buildings are also likely to deliver significant heat losses and uncomfortable drafts in winter. However, it is also important to note that an air tightness to a European standard with air infiltration rates of less than 0.2 h^{-1} would neither be achievable given the current skills base in the Bhutanese construction sector nor would it actually be desirable, since this comes with new risks for structural damage previously unknown to the country such as moisture condensation risks on building elements, for example as a result of improperly installed air tightness barriers. Given the above observations, a realistic aim would be to bring the building stock to a standard of $n_{inf} = 0.7\ h^{-1}$ which equals a 'blower door' air tightness test value of about 10 h^{-1} at 50 Pa (n_{50}). This could probably be achieved with comparably simple improvements to construction methods and build quality. In view of the findings on air leaks presented in Table 3 and the case of building 4, where an n_{50} value of 10.2 h^{-1} was achieved by sealing the windows alone, key measures for realising such an improved air tightness could for example be:

- Improved wooden window designs with side hung casements with one rabbet each in the casement and the frame, also including one revolving rubber seal in the casement and appropriate metal fittings to tightly close the opening. (The same applies to entrance doors.)
- Seals between window frames and walls using either polymer materials such as polyurethane spray foam or, as a more sustainable alternative, hemp covered with wooden profiles as plaster keying strips on both faces of the wall.
- Use of timber of a wood moisture < 15% for woodwork and windows in order to prevent the development of cracks and large gaps between individual members at a later stage as commonly observed in current buildings. (At present timber of a higher wood moisture is routinely used.)
- Proper sealing/plastering of any wall break-throughs added to solid walls during construction or at a later stage.

However, given these suggestions, it also needs to be noted that in Bhutan LPG stoves are widely used for cooking and, in rural areas, even still traditional flueless wood stoves (Lhendup et al., 2010). Furthermore, whilst most heating is electrical, firewood and flueless kerosene heaters also represent a significant fraction of the fuel sources used for space heating (Lhendup et al., 2010). Due to carbon monoxide poisoning risks such systems cannot be utilised in more airtight buildings without taking appropriate measures to properly ventilate the products of the combustion process such as carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM) and nitrogen oxides (NO_x) and to supply the required fresh air. Therefore, regulations to the use of combustion systems and indoor air quality must be considered alongside any improvements proposed to the air tightness of the current building stock in Bhutan.

Indoor climate assessments

Indoor environment parameters were measured with equipment meeting the standards detailed in ISO 7726:2001, looking at dry bulb temperature, radiant temperature, relative humidity and air speed.

Table 3
Summary of key results from the building physics field survey of buildings in Bhutan.

Bldg.	Building type, year of construction, altitude	Object of investigation, timeframe & space usage	Construction elements of investigated area (walls from the outside to the inside) & window type	Air tightness test	U-value & indoor climate measurements
1	***Description:*** 3 storey historic farmhouse built in rammed earth with the upper two floors partially in timber-framed structure (rabsel) with wood plank infills (soma) ***Year of construction:*** ca. 1800 ***Altitude:*** 2377 m	***Object of investigation:*** indoor climate and U-value of rammed earth wall in former shrine niche in the living room on the 2nd floor ***Timeframe:*** 15–22/10/2015 ***Space usage:***room uninhabited, used as a storage space	***Wall construction:*** 77 cm rammed earth ***Ceiling:*** timber covered with mud plaster ***Floor:*** wooden floorboards ***Window type***: 2 level windows with 2 or 3 window panes per level in the living room adjacent to shrine niche, top level with 2 openable side hung casements, remaining panes in the middle and bottom part of the window with fixed glazing, single glazing, wooden frame, no sealings, shrine niche without windows ***Notes:***wall thickness based on investigated area on the 2nd floor	***Floor area:*** 31.6 m^2 ***Internal volume:*** 66.4 m^3 ***Air leaks:*** no test possible due to missing glazing in some windows + large cracks in rammed earth wall	***Wall orientation:*** north ***Wall U-value***[a]***:*** 1.1 to 1.2 W/m^2 K ***Measurement duration:*** 3 nights indoor climate/3 nights U-value ***Indoor climate:*** climate moderating effect of rammed earth walls shows in temperature and relative humidity ***Notes:*** room not heated, for U-value detection former shrine niche temporarily separated from former living space with plastic sheeting and heated >25 °C
2	***Description:*** 2 storey residential building in traditional rammed earth construction with the upper floor partially in timber-framed structure (rabsel), extensions in reinforced concrete frame construction (northwest side) and adobe bricks/timber-frame (southeast side) ***Year of construction:*** 1995 ***Altitude:*** 2478 m	***Object of investigation:*** air tightness test of two interconnected rooms on the upper floor in area with timber-framed external walls ***Timeframe:*** 16/10/2015 ***Space usage:*** inhabited living space	***Wall construction infill panel:*** 3 cm cement plaster 2.5 cm pine wood 1.5 cm mud plaster ***Member size main structure:*** 15 cm ***Ceiling:*** exposed timber joists with boards on top ***Floor:*** wooden floorboards ***Window type:*** 2 level windows with 4 window panes per level, made on site, two side hung casements centrally in top level, remaining panes to the side and bottom part of the window with fixed glazing, single glazing, wooden frame, no sealings ***Notes:*** wall thickness based on investigated rooms on the 1st floor	***Floor area:*** 33.6 m^2 ***Internal volume:*** 85.6 m^3 ***Wind speed:*** 3.5 m/s ***Air change rate at 50 Pa pressure difference (n_{50}):*** 75.7 h^{-1} ***Deduced air infiltration:*** 5.3 h^{-1} ***Air leaks:*** revolving between floor and timber-frame structure, joints between window casements and frames, joints infill panels to timber-frame structure, joints in the ceiling area ***Notes:*** back wall rammed earth, adjacent room to the side: door sealed with tape for measurement but risk of unnoticed leaks hidden behind furniture (joints between the wall and the floor/ceiling)	---
3	***Description:*** 2 storey library building of the Royal University of Bhutan with rammed earth walls (ground floor) and timber frame construction (1st floor) ***Year of construction:*** 2014 ***Altitude:*** 2445 m	***Object of investigation:*** air tightness test in future reading room on the ground floor, indoor climate and U-value of glazing ***Timeframe:*** 10–12/10/2015 ***Space usage:*** space not in use	***Wall construction:*** 60 cm rammed earth ca. 20 cm air layer/battens 2 cm chipboard panels ***Ceiling:*** chipboard panels fixed between ceiling joists ***Floor:*** wooden floorboards ***Window type:*** single-leaf casement with rabbet edge, however without sealing, double glazing with air infill, wooden frame ***Notes:*** wall thickness based on investigated rooms on the ground floor, architectural design modern interpretation of traditional construction methods	***Floor area:*** 55.3 m^2 ***Internal volume:*** 187.7 m^3 ***Wind speed:*** 2.0 m/s ***Air leaks:*** hinge-joints of windows, joints between window frames and walls, ventilation ducts (Ø 20 mm) below windows (purpose not evident), joints to suspended ceiling (unclear whether leaks are connected to the outside air) ***Notes:*** results not considered reliable due to detected strong air exchange with the interior volume of the remaining building through internal walls and ceiling/entire building too large for building up the required pressure difference with the available fan	***Wall orientation:*** north ***Glazing U-value:*** 2.55 to 2.7 W/m^2 K ***Measurement duration:*** 2 nights ***Indoor climate:*** orientation to the north with comparably air tight building envelope + wood panelling of walls result in rapid warming of the space in the early morning, relative humidity in a narrow band between 40 and 55% ***Notes:*** room heated
4	***Description:*** 2 storey residential building on a slope with three flats, constructed with cement stabilised earth blocks (CSEB) ***Year of construction:*** 2014 ***Altitude:*** 2354 m	***Object of investigation:*** air tightness test, indoor climate and U-value of cement stabilised earth block wall in flat on the ground floor consisting of 2 rooms with bathroom and kitchenette ***Timeframe:*** 02–08/10/2015 & 12–15/10/2015 ***Space usage:*** uninhabited	***Wall construction:*** 15 cm cement stabilised earth blocks 0.6 cm PE-insulation 15 cm cement stabilised earth blocks 1 cm cement plaster ***Ceiling:*** suspended plywood ceiling ***Floor:*** wooden floorboards on concrete floor plate ***Window type:*** 2 level windows with 3 window panes per level, made on site, two sliding casements in top level, remaining panes in the centre and bottom part of the window with fixed glazing, single glazing, wooden frame, no sealings ***Notes:*** first 1.2 m of the internal face of the external walls covered with wood panelling, reinforcement bars integrated into external leaf of CSEBs, apparently PE footfall sound insulation material used as thermal insulation in walls	***Floor area:*** 47.3 m^2 ***Internal volume:*** 130.5 m^3 ***Wind speed:*** 2.4 m/s ***Air change rate at 50 Pa pressure difference (n_{50}):*** 27.6 h^{-1} ***Deduced air infiltration:*** 1.9 h^{-1} ***Air leaks:*** joints between window casements and frames: in particular the sliding casements, joints between the wood panelling on the wall and the floorboards, wall break-through for cooker hood in the kitchen, wall sockets ***Notes:*** air change rate of 10.2 h^{-1} at 50 Pa overpressure when all windows were sealed off with plastic sheeting => proof that significant improvements could be achieved with an improved window design	***Wall orientation:*** north ***Wall U-value***[a]***:*** 1.05 to 1.25 W/m^2 K ***Measurement duration:*** 6 nights indoor climate/3 nights U-value ***Indoor climate:*** despite strong variations in the external dry bulb temperature (5.9–26.3 °C) the inside air temperature remained within a temperature band of about 18 to 23 °C: positive effect of the thermal mass of the CSEB wall, relative humidity in a large band between about 30 and 70% ***Notes:*** room not heated, heated >25 °C for U-value detection

5	***Description:*** 1 storey community centre with offices and veterinarian surgery, constructed with dressed natural stone ***Year of construction:*** 2009 ***Altitude:*** 2520 m	***Object of investigation:*** air tightness test of a single office ***Timeframe:*** 19/10/2015 ***Space usage:*** in use	***Wall construction:*** 37.5 cm dressed granite with cement mortar 5.5 cm cement plaster ***Ceiling:*** exposed timber joists with boards on top ***Floor:*** screed with vinyl sheeting on concrete floor plate ***Window type:*** 2 level windows with 3 window panes per level, made on site, side hung casements at the sides of both levels, central 2 panes with fixed glazing, single glazing, wooden frame, no sealings ***Notes:*** thickness of internal cement plaster to account for unevenness of dressed stone	***Floor area:*** 12.2 m^2 ***Internal volume:*** 36.2 m^3 ***Wind speed:*** 0.8 m/s ***Air change rate at 50 Pa pressure difference (n_{50}):*** 55.8 h^{-1} ***Deduced air infiltration:*** 3.9 h^{-1} ***Air leaks:*** joints between window casements and frames, knotholes in casements, joints between window frames and walls, joints to ceiling joists, joints timber elements over entrance door ***Notes:*** door to adjacent room sealed with tape for the measurement	---
6	***Description:*** 5 storey central government office building in reinforced concrete frame construction with brick infill walls ***Year of construction:*** 2013 ***Altitude:*** 2418 m	***Object of investigation:*** air tightness test of a secluded executive office area on the top floor consisting of a lounge area, one office room and a lavatory ***Timeframe:*** 06/10/2015 ***Space usage:*** internal finishes completed, space not yet in use	***Wall construction:*** 1 cm cement plaster 25 cm brick wall 1 cm cement plaster ***Ceiling:*** suspended plasterboard ceiling ***Floor:*** wooden floorboards on concrete floor plate ***Window type:*** 2 level windows with 4 window panes per level, made on site, 1 side hung casement at the side of bottom level, remaining with fixed glazing, single glazing, wooden frame, no sealings ***Notes:*** window frames extended to the floor: bottom panel filled with plywood to the inside and glazing to the outside, building mechanically ventilated	***Floor area:*** 85.0 m^2 ***Internal volume:*** 226.3 m^3 ***Wind speed:*** 1.5 m/s ***Air change rate at 50 Pa pressure difference (n_{50}):*** 14.2 h^{-1} ***Deduced air infiltration:*** 1.0 h^{-1} ***Air leaks:*** joints between window casements/fixed panes and frames, revision opening to riser, joints of the wooden air duct boards, wall/floor sockets, pipe break-through for sink drain ***Notes:*** second door to corridor in lounge area sealed with tape for the measurement, sealing of air inlets of the ventilation system in the suspended ceiling	---
7	***Description:*** 4 storey central government office building in reinforced concrete frame construction with brick infill walls ***Year of construction:*** 2007 ***Altitude:*** 2333 m	***Object of investigation:*** air tightness test of a secluded executive office area on the 2nd floor consisting of a reception, one office room, a meeting area, a storage room and a lavatory; indoor climate and U-value of brick wall in an open plan office on the ground floor ***Timeframe:*** 27/10–02/11/2015 ***Space usage:*** 2nd floor office: in use; ground floor office: not in use	***Wall construction:*** 1.5 cm cement plaster 24 cm brick wall 1 cm cement plaster ***Ceiling:*** suspended fibreboard ceiling ***Floor:*** screed with carpet on concrete floor plate ***Window type:*** 2 or 3 window panes per window with glazing bar in the bottom third, made on site, 2 openable side hung casements to the sides, outward opening, central pane fixed glazing (for windows with 3 panes), single glazing, wooden frame, no sealings ***Notes:*** probably air pockets present in external walls	***Floor area:*** 80.8 m^2 ***Internal volume:*** 197.8 m^3 ***Wind speed:*** 1.3 m/s ***Air change rate at 50 Pa pressure difference (n_{50}):*** 27.8 h^{-1} ***Deduced air infiltration:*** 1.9 h^{-1} ***Air leaks:*** joints between window casements and frames, joints between the glass panes and the window frame/in one instance missing wooden strip to secure position of glass pane ***Notes:*** lavatory not accessible – therefore, the door was sealed off during the air tightness tests	***Wall orientation:*** west ***Wall U-value[a]:*** 1.25 to 1.45 $W/m^2 K$ ***Measurement duration:*** 2 nights indoor climate/4 nights U-value (sensor moved after 2nd night) ***Indoor climate:*** due to shielded location in the building relatively even inside air temperatures between about 17 and 20.5 °C, relative humidity drops below 30% around noontime ***Notes:*** U-value measurement on west façade shielded from direct sunlight by embankment with retaining wall, room heated >20 °C for U-value detection
8	***Description:*** 2 storey social housing block with 8 flats in reinforced concrete frame construction with brick infill walls ***Year of construction:*** 2001 ***Altitude:*** 2319 m	***Object of investigation:*** air tightness test of a flat on the upper floor consisting of 3 rooms with bathroom and kitchen, with balcony ***Timeframe:*** 12/10/2015 ***Space usage:*** inhabited living space	***Wall construction:*** 1 cm cement plaster 25 cm brick wall 1 cm cement plaster ***Ceiling:*** plastered reinforced concrete ceiling ***Floor:*** wooden floorboards on concrete floor plate ***Window type:*** living space: industrially manufactured sliding windows with 3 panes, central pane with fixed glazing, single glazing, aluminium frame, no sealings; bathroom & kitchen: side hung casement windows, made on site, single glazing, wooden frame, no sealings ***Notes:*** wooden balcony door	***Floor area:*** 58.7 m^2 ***Internal volume:*** 159.6 m^3 ***Wind speed:*** 5.8 m/s ***Air change rate at 50 Pa pressure difference (n_{50}):*** 11.7 h^{-1} ***Deduced air infiltration:*** 0.8 h^{-1} ***Air leaks:*** aluminium frame windows: 1 window not closing properly, joint between sliding window pane and fixed glazing, wooden frame windows: joints between window casements and frames, doorsill balcony door, joint between riser for electric cabling to the ceiling/open roof space	---
9	***Description:*** 6 storey multi-purpose apartment block on a slope (back side 4 storeys) with offices,	***Object of investigation:*** air tightness test of a flat on the 4th floor consisting of 2 rooms with bathroom and kitchenette, with 2 balconies	***Wall construction:*** 1 cm cement plaster 25 cm brick wall	***Floor area:*** 67.5 m^2 ***Internal volume:*** 186.2 m^3 ***Wind speed:*** 2.1 m/s	---

(continued on next page)

Table 3 (*continued*)

Bldg.	Building type, year of construction, altitude	Object of investigation, timeframe & space usage	Construction elements of investigated area (walls from the outside to the inside) & window type	Air tightness test	U-value & indoor climate measurements
	commercial units for shops/restaurants and flats, reinforced concrete frame construction with brick infill walls ***Year of construction:*** 2011 ***Altitude:*** 2371 m	***Timeframe:*** 30/10/2015 ***Space usage:*** inhabited living space	1 cm cement plaster ***Ceiling:*** plastered reinforced concrete ceiling ***Floor:*** wooden floorboards on concrete floor plate ***Window type:*** industrially manufactured sliding windows with 2 or 3 panes, central pane with fixed glazing where 3 pane windows, single glazing, aluminium frame, no sealings ***Notes:*** wooden balcony doors	***Air change rate at 50 Pa pressure difference (n_{50}):*** 15.4 h^{-1} ***Deduced air infiltration:*** 1.1 h^{-1} ***Air leaks:***joints between window casements and frames, holes drilled in the window frames, joints between balcony doors and door frame, floor drain in bathroom (siphon missing), sliding window in bathroom of a too large dimension for window hole = > 1.5 cm permanent gap ***Notes:*** floor drain in bathroom sealed for test, air change rate of 13.7 h^{-1} at 50 Pa when bathroom door sealed to exclude leak in sliding window	
10	***Description:*** 3 storey detached house on a slope (back side 2 storeys), reinforced concrete frame construction with double leaf aerated concrete infill walls ***Year of construction:*** 2015 ***Altitude:*** 2300 m	***Object of investigation:*** air tightness test and U-value of aerated concrete wall of a single room on the top floor ***Timeframe:*** 21–27/10/2015 ***Space usage:*** under construction, work in room completed	***Wall construction:*** 1 cm cement plaster 10 cm aerated concrete blocks 3.6 cm PE-insulation 17 cm air layer 10 cm aerated concrete blocks 1 cm cement plaster ***Ceiling:*** exposed timber joists with boards on top ***Floor:*** wooden floorboards ***Window type:*** 2 level windows with 3 or 4 window panes per level, made on site, openable side hung casements on both levels, single glazing, wooden frame, with sealings ***Notes:*** apparently PE footfall sound insulation material used as thermal insulation in walls	**Floor area:** 23.5 m^2 **Internal volume:** 72.8 m^3 **Wind speed:** 3.3 m/s ***Air change rate at 50 Pa pressure difference (n_{50}):*** 14.7 h^{-1} ***Deduced air infiltration:*** 1.0 h^{-1} ***Air leaks:*** joints between window casements and frames – thickness of sealing not sufficient to bridge air gap, window lintel, wall sockets	***Wall orientation:*** west ***Wall U-value***[a]***:*** 0.35 to 0.43 W/m^2 K ***Measurement duration:*** 2 nights ***Indoor climate:*** measurement not possible as building was still a construction site ***Notes:*** U-value measurement on west façade shielded from direct sunlight by roof overhang, room heated >25 °C for U-value detection, heating started 2 days prior to installation of sensors, thermal insulation layer attached to outer layer of aerated concrete blocks, size of air layer is a function of pillar size, thermal bridges in pillar area

[a] The quoted wall U-values are indicative only as the time frame for the measurements was rather short and the conditions not fully stable with thermal mass influencing the measurements.

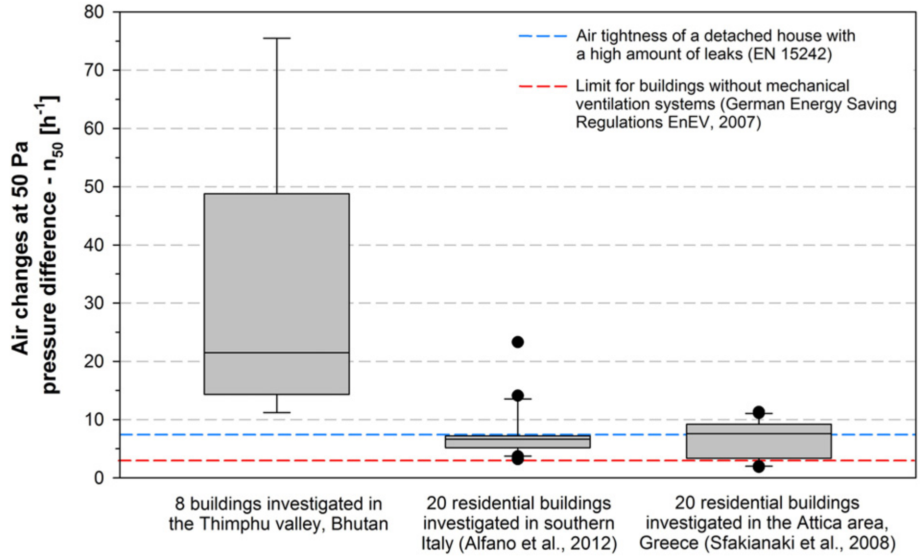

Fig. 9. Air changes at 50 Pa pressure difference for the 8 buildings investigated in Bhutan in comparison to air tightness tests conducted in southern Italy (Alfano et al., 2012) and in Greece (Sfakianaki et al., 2008).

Following the recommendations of ISO 7726:2001 the sensors were installed at 1.1 m height which represents the head height of a seated person. They were placed as centrally in the room as permitted by the room geometry and furniture layout. In addition, surface temperatures were also monitored on the inside and outside face of a wall that was not exposed to direct sun. Four buildings were surveyed in total, spanning typical Bhutanese construction types: the former living space with shrine niche on the top floor of building 1 with rammed earth/ timber-frame walls, a ground floor reading room behind the rammed earth wall of the library building 3, the ground floor flat of building 4 with cement stabilised earth block (CSEB) walls and a ground floor office in building 7 with reinforced concrete frame construction and brick infill walls (Table 3). Data was logged at 5 min intervals for three nights in building 1, six nights in building 4 and two nights in buildings 3 and 7. In addition, the outside temperature and relative humidity (RH) conditions were logged with a small data logger in clean air in close proximity to the respective building in order to capture the local micro-climatic conditions as a climate reference. Table 4 provides an overview of key results from the indoor climate assessments.

Probably for book conservation reasons the reading room of the library building was heated via electric heaters, which, as can be seen in Table 4, led to night-time temperatures of above 17.8 °C and, in conjunction with the rammed earth walls, to a comparatively narrow relative humidity band which matches recommendations for library spaces of 40 to 60% (Pistohl, 2009). However, coupled with the comparably high air tightness of the building envelope (see section above on building air tightness tests), solar gains through the double glazed windows of the room, which is situated on the north-east corner of the building, led to a rapid rise of the internal temperature by 3 K within one hour in the early morning. Here it shows that the inside chipboard wall panelling hinders activation of the thermal mass of the rammed earth wall, which would perhaps be desirable for room climate stability reasons to conserve books.

The remaining three spaces had in common that they were not heated or occupied during the monitoring period so that impacts from building services equipment or occupants on the results can be excluded. Fig. 10 shows 24-hour plots of these three spaces for the monitored temperature and relative humidity as well as absolute humidity data calculated from these following the guidance given by ASHRAE (2013) for determining the partial pressure of water vapour and then the ideal gas law for determining absolute humidity. The 24-hour periods shown in Fig. 10 were selected on the grounds of the dry bulb temperature monitored in close distance to the respective buildings to represent days with a similar daily temperature profile in order to facilitate comparison. Whilst the weather conditions during the measurement campaign were fairly stable, there were, however, some differences in the daytime temperature peaks and the night-time temperature lows. As shown in Fig. 3, day to day temperature variations of several Kelvin are, however, typical of the given location. Therefore, given the limited amount of available data for each building, the day time peak dry bulb temperatures of the plots shown in Fig. 10 vary by about 4 to 5 °C between buildings 1 and 4, depending on the chosen dates. However, the night-time lows are rather similar.

Due to the unavailability of an appropriate shielding, exposure to direct sunlight of the small data logger installed externally could not be fully prevented. In the case of building 1 this led to about 2.5 h from 9:40 h onwards with one interruption and in the case of building 4 to almost 1 h of data from 7:30 h onwards being affected by direct sunlight. This could be determined via daily recurring significant temperature rises or drops within very short time spans of 5 to 10 min. Therefore, the dry bulb temperature data needed to be sanitised for these timeframes. This was done with the help of air temperature data monitored with a thermocouple about 20 cm in front of the north facing walls of the two buildings. Following this the relative humidity information for the respective nodes was also sanitised in line with the temperature data by applying the psychrometric calculation routines provided by ASHRAE (2013).

The free running nature of the buildings clearly reveals the impact of different construction types. Whilst the 77 cm thick rammed earth walls of building 1 led to rather stable but cool indoor air temperatures at a mean of 15.2 °C as well as almost unchanged relative humidity levels over the measurement period as can be seen in Table 4, building 4 with a similar material (CSEB) but significantly thinner walls at 31.6 cm showed a much higher mean internal air temperature at 19.8 °C (Table 4). This is further illustrated by Fig. 10 for a 24-hour time slot for both buildings which also shows a more pronounced temperature swing on the external north facing wall for building 4 than building 1. Given that the investigated room of building 1 was on the top floor and that of building 4 on the ground floor and that the main facades of the two rooms were facing east and west respectively, the strong temperature differences determined between the two buildings would not be expected, also since the timber-frame façade of building 1 had some broken windows and numerous air leaks. Here the impacts on the room climate of the large thermal mass walls of building 1 as well

Table 4
Overview of key results from the indoor climate assessments of the 4 buildings monitored in Bhutan.

Building	Control strategy	Measurement duration [h]	Indoor air temperature [°C]			Indoor relative humidity [%]			Indoor air speed [m/s]	
			Mean	Min	Band[a]	Mean	Min	Band[a]	Min	Max
Building 1: historic farmhouse	Free running	70	15.2	13.4	4.1	59.8	53.9	9.0	0.02	0.09
Building 3: library	Heated	42	19.4	17.8	4.8	48.9	41.2	11.9	0.02	0.08
Building 4: CSEB residential building	Free running	140	19.8	18.0	5.1	59.5	31.1	38.6	0.01	0.09
Building 7: central government office	Free running	48	17.8	16.9	3.5	42.8	27.8	20.4	0.01	0.10

[a] Band: difference between the minimum and maximum values determined during the measurements.

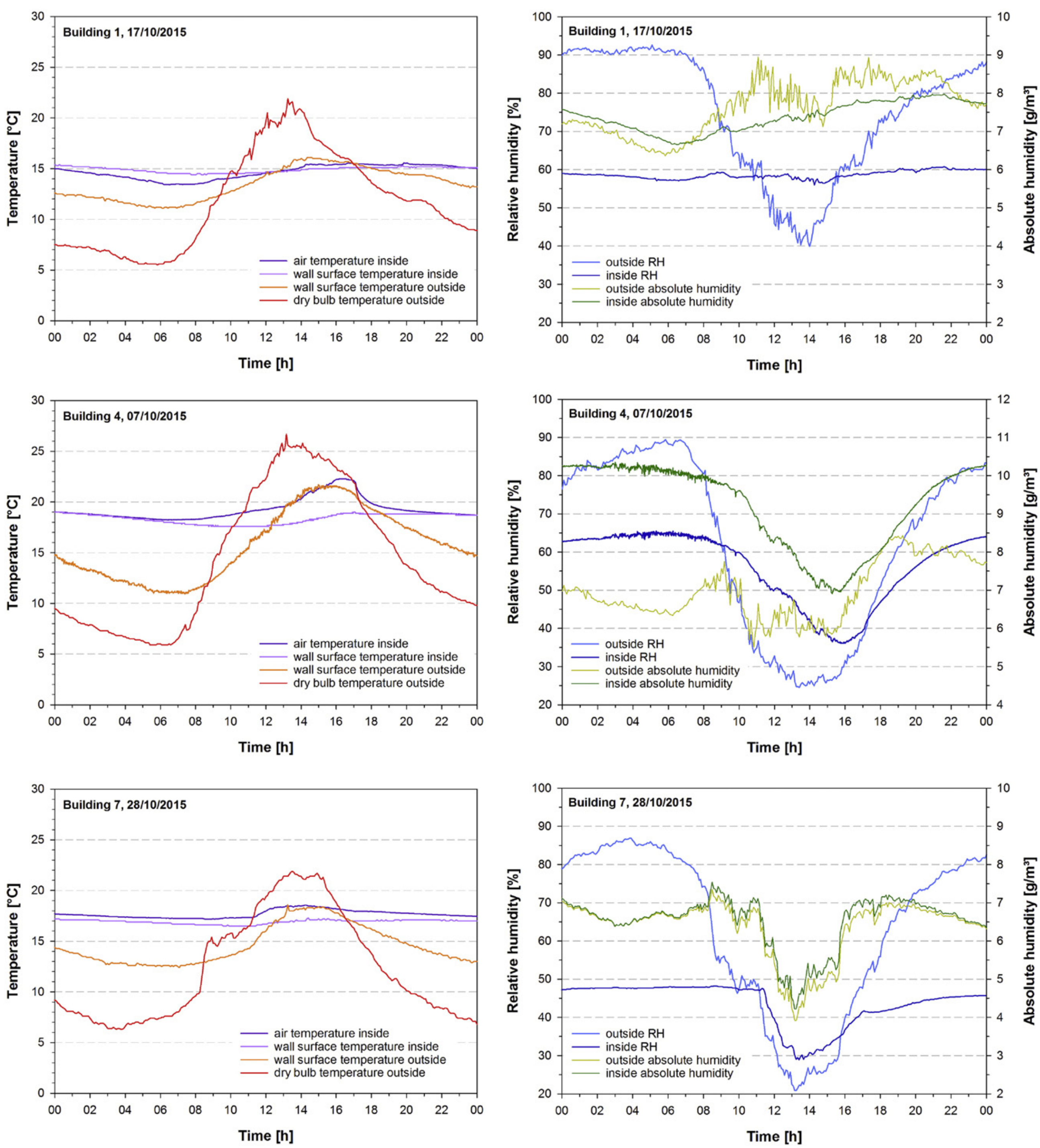

Fig. 10. 24-h plots of internal and external temperature as well as relative and absolute humidity data monitored in buildings 1, 4 and 7.

as the more exposed façade (no shielding roof overhang) and the larger glazed area of building 4 show.

The office room monitored in building 7 was situated on the ground floor, oriented to the west and, as detailed in Table 3, shielded from direct sunlight by an embankment with retaining wall. This shows in the internal air temperature plotted in Fig. 10 which only experiences a small rise during the day in the narrow temperature band highlighted in Table 4. Similarly, the external wall temperature shows a less pronounced swing than for building 4 with a similar wall thickness. However, it also needs to be noted that this was for a day with a less pronounced dry bulb temperature swing of about 15 °C instead of around 20 °C for building 4.

Both, Table 4 and Fig. 10 show that the relative humidity levels inside the 3 free running buildings were typically within 30 to 70% which are usually considered as the limits for meeting thermal comfort (Pistohl, 2009). Only inside building 7 the RH dropped below the 30% (Table 4). However, looking at the plots for inside and outside absolute humidity as well as the temperature data in Fig. 10, it becomes evident, that this drop is a clear function of the external weather conditions coupled with the internal temperature profile. Moreover, Fig. 10 shows a clear relation between the outside and inside absolute humidity data for building 7, which, in the absence of internal moisture sources, is as one would typically expect in a building with a high air infiltration rate such as building 7 at $n_{inf} = 1.9\ h^{-1}$ (Table 3). Interestingly, for building 1 Fig. 10 shows a different profile for absolute humidity with a smoothed curve for the inside data relative to the outside data. This highlights the impact of the rammed earth walls with their good ability to absorb and reemit moisture, which is also described in literature (Schroeder, 2013) and which is not present in the case of building 7 with its main construction materials brick and cement. Fig. 10 also highlights a comparably large relative humidity band for building 4 and, more importantly, a strong deviation of the inside an outside absolute humidity of up to more than 3.5 g/m^3 in the early morning. Given that the same sensors were used for all three buildings and that the external absolute humidity appears to match between the three days, the conclusion for the significantly higher moisture inside the building has to be the presence of a moisture source. In the absence people or plants inside the building or any activities involving water such as showers or cooking, the reasons for this are not readily apparent. However, during the monitoring of the, at the time, one year old building cracks, spalling of the external façade coating and even salt efflorescence were recorded on the base of the west facing external wall. These damages imply rising dampness inside the wall that cannot easily diffuse to the outside, thus potentially ending up inside the room. The findings regarding the water absorption of the CSEB wall and its base/foundation discussed further below as well as the absolute humidity data in Fig. 10 appear to confirm this. During the day and in particular the afternoon, when the sun was shining on the main west facing façade and the indoor air speed was highest inside the building, the absolute humidity dropped as the moisture was transported to the outside through the leaky building envelope with an air infiltration rate of $n_{inf} = 1.9\ h^{-1}$ (Table 3). Later in the day without sun and wind (the afternoon is typically the windiest time in the Thimphu valley) the difference between outside and inside absolute humidity increased again (Fig. 10). Overall, this case of a building which, for earthquake resistance reasons, does not have horizontal sealing against rising dampness highlights the complexity and risks of, for example, suggesting improvements to air tightness without at the same time considering the construction methods that are employed.

As can be seen in Table 4, the maximum indoor air speeds were rather low in all monitored buildings with 0.08–0.10 m/s, even though some of them were found to be rather leaky constructions (see section above on building air tightness tests and Table 3). The air speeds shown in Table 4 relate to the undisturbed room without window or door opening events and imply that, under the given external wind speed conditions, a good indoor air speed performance was achieved. Whilst the indoor air temperatures and the exterior climate during the monitoring period may not be representative for the heating season, these monitored low velocities may, however, be a possible explanation as per why sealing window joints or joints between construction elements has not received significant attention in Bhutan to date, even though the thermal losses through these cracks are significant.

The short timeframe of the comfort measurements and the limited amount of buildings surveyed do not permit drawing final conclusions on the Bhutanese building stock of the Inner Himalayas, especially since the October climate conditions of the Thimphu valley do not reflect winter conditions but a transition period as demonstrated by Fig. 3 and Table 2. Nevertheless, some initial conclusions for appropriate design strategies can be drawn from the measurements. These are as follows:

- In view of the strong temperature differences between night and day in the heating season (Figs. 3 & 10), thermal mass can help to exploit solar gains through south-facing glazing during the daytime (Fig. 4) in order to moderate the room climate during the night. This can be achieved by integrating appropriately exposed glazed areas to a double glazing standard with improved window frame designs into the building in conjunction with a better sealed building envelope.
- Bhutanese earth based wall materials can, in conjunction with their large mass, help to retain stable relative humidity conditions within a comfortable band by maintaining stable temperature conditions and by absorbing and releasing moisture as demonstrated by the absolute humidity data shown in Fig. 10 for building 1.
- Thermal mass in conjunction with the traditional Bhutanese roof overhangs that provide solar shading by reducing solar heat gains through glazed areas can help to maintain comfortable indoor climate conditions during the summer months. To prevent too cool indoor conditions in the transition seasons, opening of windows during the daytime may be required to maximise thermal gains.

Wall U-value determination

In order to calculate the heating demand of a building or to estimate the impacts of building fabric improvements on the future heating demand, basic information on the thermal conductivity λ [W/mK] of the building materials used for the building fabric is needed. This information can then be used as detailed in ISO 6946:2007 for determining the thermal transmittance U [W/m^2K] (U-value) of the main thermal elements of the building which is required for calculating the heating demand (CIBSE, 2006). However, as already indicated above, thermal conductivity information is not readily available for building materials applied in Bhutan, regardless whether these are domestic or imported from India. Furthermore, to determine the thermal conductivity of a material steady state conditions are required which are difficult to achieve in the field. Therefore, the heat flow meter method was applied following the procedures set out in ISO 9869–1:2014 in order to estimate the U-values of selected wall constructions in Bhutan. Four wall constructions were investigated: a rammed earth wall (building 1), a cement stabilised earth block wall (building 4), a brick wall (building 7) and a wall built with aerated concrete blocks (building 10). These are detailed in their material layer structure in Fig. 11. In addition, the double glazing of the library building 3 was tested.

As highlighted in Table 3, measurements were conducted over 2 to 4 nights which is rather short given that ISO 9869–1:2014 specifies a minimum of 72 h at stable temperature conditions around the heat flow meter for the measurements. However, given the available time for the field study it was not possible to conduct longer term measurements. Furthermore, the initial indoor climate measurements conducted on building 4 (see section above) revealed that the external temperature conditions in October with a comparably large diurnal temperature swing as shown in Fig. 10 were not ideal for the heat flow meter method as the internal air temperature T_i needs to be above the external air temperature T_e at all times in order to prevent a

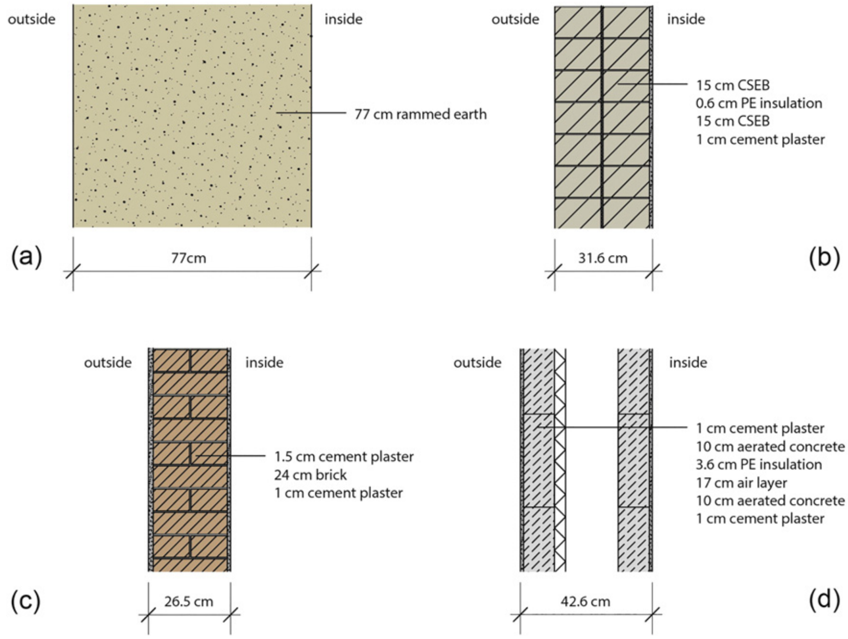

Fig. 11. Structure of the four investigated walls in Thimphu: (a) rammed earth wall, (b) cement stabilised earth block wall, (c) brick wall and (d) aerated concrete block wall.

reversing of the heat flux Φ [W] through the wall (ISO 9869–1:2014). As can be seen in Fig. 10, this was not the case for the free running buildings investigated in Bhutan since the external air temperatures exceeded the internal temperatures by several Kelvin in the middle of the day. Therefore, the spaces investigated for their wall U-values were fitted with electric heaters in order to ensure stable inside temperature conditions above the external dry bulb temperature. Nevertheless, the strong daily temperature swing of course remains as an important influencing factor.

The so-called average method detailed in ISO 9869–1:2014 was used to determine the thermal transmittance U through the wall. For this, in a first step, the thermal resistance R [m^2K/W] of the wall element was obtained by:

$$R = \frac{\sum_{j=1}^{n}\left(T_{sij} - T_{sej}\right)}{\sum_{j=1}^{n} q_j} \tag{2}$$

where:

T_{si} inside surface temperature of the thermal element, measured with a thermocouple [°C],
T_{se} outside surface temperature of the thermal element, measured with a thermocouple [°C],
q heat flux density, measured with a heat flow meter on the inside face of the wall [W/m^2].

From this the thermal transmittance of the wall can then be inferred by:

$$U = \frac{1}{R_T} = \frac{1}{R_{si} + R + R_{se}} \tag{3}$$

where:

R_T total thermal resistance [m^2K/W],
R_{si} inside surface thermal resistance [m^2K/W],
R_{se} outside surface thermal resistance [m^2K/W].

The inside and outside surface thermal resistances R_{si} and R_{se} can either be determined via additional air temperature measurements in close proximity to both faces of the thermal element that is being investigated or assume standard values from Table 1 of ISO 6946:2007. Whilst using the former method would be possible given that the air temperatures were actually measured, the latter method was followed since this is the standard method used for determining U-values for compliance calculations. It therefore represents a better baseline for comparison with literature data. Given that the heat flux through a wall is horizontal, the surface thermal resistances then become: $R_{si} = 0.13\ m^2\ K/W$ and $R_{se} = 0.04\ m^2\ K/W$ (ISO 6946:2007).

Fig. 12 shows the air and surface temperatures measured on the north facing wall of the CSEB building 4 as well as the heat flux density through the wall, with the negative values for the heat flux density denoting a heat flux from the room towards the outside. It can be clearly seen that, following the installation of electric heaters, it took more than 30 h for the internal air temperature and the inside surface temperature to level out to some extent. Furthermore, the heat flux density displays a remarkable pattern that appears counterintuitive in that a greater heat flux from the inside to the wall is visible during the daytime than during the night when the temperature difference between the internal and external surfaces is greatest. The explanation for this appears to be the wall's thermal mass. During the night there is a constant heat loss to the outside, leading to rather stable conditions. During the day, when the heat loss to the outside is smaller, more energy can be transferred to the wall to be released at a later stage.

A further unclear point seen in Fig. 12 is the observed scatter of the internal air temperature of about 1.5 °C as well as the corresponding scatter of the heat flux density. This appears to be related to the electric heating installed for the monitoring as Fig. 13 demonstrates which shows the data for the entire measurement period from noontime on the 15th to the morning of the 21st of October 2015 in the historic rammed earth building 1, i.e. the indoor climate assessment and the U-value determination test with heated space. When the heater is not running, no scatter is observed for either indoor air temperature or the heat flux density. This also shows in the power failure event on the 20th of October. Furthermore, during the free running indoor climate assessments on the 16th and 17th of October, one can clearly see a small heat flux from the inside of the room to the wall as the temperatures rise during the daytime. Conversely, during the night time low there is a heat flux from the wall to the room, highlighting the effect of the wall releasing energy back to the room as a result of its thermal capacity. This supports the findings detailed above for the heat flux density observed during the U-value determination tests in building 4. However,

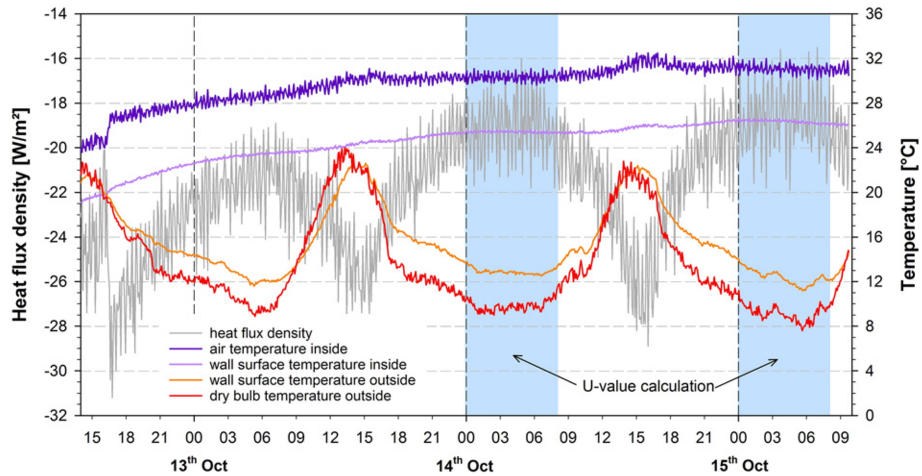

Fig. 12. Building 4, monitoring of inside and outside surface/air temperatures as well as heat flux density of the heated space for determining wall U-values.

it also needs to be noted that in both cases, buildings 1 and 4, saturation of the wall was not reached during the measurement period with space heating as demonstrated by the slow reduction of the heat flux density into the wall over time in Figs. 12 and 13. This means that there are some limitations as per the accuracy of the wall U-values that were derived from the tests. Therefore, the wall U-values presented in Table 3 can only be considered as indicative and have been specified as a range. As the heat flux through a low thermal mass element such as a glazed area levels out rather quickly, the glazing U-value for the locally manufactured double glazing unit with air gap present in the library building 3 can be quoted with greater confidence. At 2.55 to 2.7 W/m^2 K the double glazing unit corresponds to literature values for this glazing type at sheltered to normal exposure and performs significantly better than standard single glazing which is commonly quoted as U = 5.75 W/m^2 K (CIBSE, 2015).

As shown in Fig. 12 wall U-values were only calculated during the night-time hours when the temperature and heat flux conditions were comparably stable. Overall it can be concluded that typical historic as well as current wall constructions, i.e. buildings 1, 4 and 7, appear to have comparably high U-values of about 1.0 to 1.5 W/m^2 K which match those of similar constructions with known U-values (CIBSE, 2015). This is further illustrated by Table 5 which highlights the U-values determined in the measurements in comparison to calculated U-values. However, it is also important to note that the true surface resistances R_{si} and R_{se} calculated using the measured surface and air temperatures on both faces of the wall were often significantly higher than the default values as per ISO 6946:2007, consequentially leading to lower U-values than those quoted in Table 5 when inserted in Eq. (3). However, as it is not clear whether this is due to the prevailing climate conditions in Bhutan or just a coincidence of the selected case study period, these values are not considered here.

Since no thermal conductivity information was available for any of the building materials shown in Fig. 11, it had to be inferred in order to be able to determine U-values for comparison with the measured data. Rammed earth walls are quoted to typically have a gross dry density of 1800 to 2200 kg/m^3 (Schroeder, 2013). Therefore, it was assumed that the rammed earth wall investigated in Bhutan had a gross dry density of 2000 kg/m^3 for which DIN 4108–4:2013 specifies a thermal conductivity of 1.1 W/m^2 K. The gross dry density of the Bhutanese cement stabilised earth blocks was determined at 2000 kg/m^3 in laboratory assessments. Looking at thermal conductivity data published by Adam and Jones (1995), Webb (1988) and the ILO (1987) for CSEBs of various soils a thermal conductivity of 0.61 W/mK was inferred via linear regression for a block of a gross dry density of 2000 kg/m^3. The gross dry density of the bricks and the aerated concrete blocks used in Bhutan were determined locally at 1300 kg/m^3 and 650 kg/m^3 respectively. According to the data given in DIN 4108–4:2013 this corresponds to thermal conductivities of 0.53 W/mK and 0.21 W/mK respectively. For the cement plaster and the PE insulation used in some of the buildings the standard values provided in ISO 10456:2007 + Cor. 1:2009 were

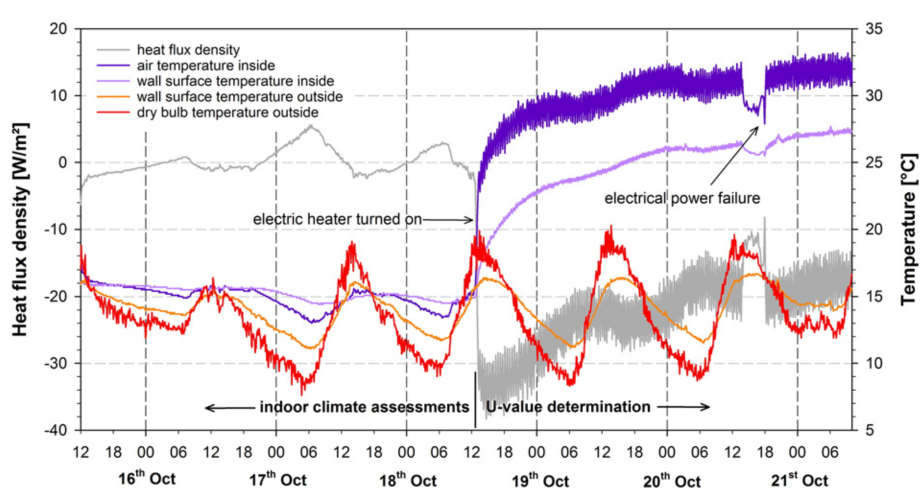

Fig. 13. Building 1, monitoring of inside and outside surface/air temperatures as well as heat flux density of the unheated/heated space for assessing the indoor climate/determining wall U-values.

Table 5
Comparison of the U-values determined via the in-situ measurements in Bhutan and calculated U-values using inferred thermal conductivity data.

Wall type	Gross dry density ρ [kg/m³]/thermal conductivity λ [W/mK] of the applied building materials[a]		U-value [W/m²K]	
			Measured	Calculated
Rammed earth wall (building 1)	Rammed earth:	2000/1.10	1.10–1.20	1.15
Cement stabilised earth block wall (building 4)	CSEB: PE insulation: Cement plaster:	2000/0.61 60–80/0.05 1800/1.00	1.05–1.25	1.26
Brick wall (building 7)	Brick: Cement plaster:	1300/0.53 1800/1.00	1.25–1.45	1.54
Aerated concrete block wall (building 10)	Aerated concrete block: PE insulation: Cement plaster:	650/0.21 60–80/0.05 1800/1.00	0.35–0.43	0.49

[a] Layer structure and thicknesses are given in Fig. 11.

assumed. In the case of the aerated concrete block wall the large air layer shown in Fig. 11 was considered with a thermal resistance of 0.17 m^2K/W following the recommendations given in ISO 6946:2007. As can be seen in Table 5, the calculated U-values are similar to those determined in-situ, albeit generally slightly higher. However, as the exact thermal properties of the building materials are largely unknown, it can be concluded that the U-values determined in the measurements appear to be plausible.

The building with the best thermal performance of the walls was, as would be expected, building 10 constructed with aerated concrete blocks at a U-value between 0.35 and 0.43 W/m^2 K (Table 5). However, it needs to be mentioned that the walls of building 10 were constructed as infill walls in a reinforced concrete frame structure as it is usually done in Bhutan with the common brick walls. This also explains the rather large air layer of 17 cm which appears to be a function of the pillar size to create a flush wall on the inside. Similarly, the insulation material was found to be attached to the inside of the outer leaf of the wall as shown in Fig. 11. This appears to be a result of the construction process from the outer face towards the inside. As an important function of an air layer is to provide some ventilation to the outer leaf of a cavity wall in order to remove excess moisture that has penetrated the outer leaf of the wall, this position of the insulation material is perhaps not ideal. Furthermore, the construction of the wall as an infill wall leads to thermal bridges in the pillar areas. Infrared thermometer measurements in the heated room accordingly highlighted temperature differences of several Kelvin between walls and pillars, which increases condensation risks that do not exist in walls with a uniform poor U-value.

Building 10, which is a first attempt at improving the thermal standards of new constructions in Bhutan, as well as building 4 used some form of insulation material. However no data on the properties of these materials imported from India were available. Infrared spectroscopy measurements conducted on three probes of these materials from different buildings revealed that they are polyethylene based. Given the material thickness of between 0.6 and 1.8 cm and the visual appearance this suggests a diverted use of a PE footfall sound insulation material. Nevertheless, the consideration of such materials for insulation purposes highlights that there is a demand by local builders for wall insulation materials which cannot currently be satisfied. From the above the following conclusions can be drawn for thermal improvement of the building stock in Bhutan:

- Optimisation of existing wall construction materials to provide lower thermal conductivities via a higher porosity appears to be an option that could be considered, in particular for rammed earth and cement stabilised earth block walls.
- Given the glazing U-values and the results of the air leak investigation of the library building 3 (Table 3) double glazing can be classified as a comparably simple measure to reach some step change improvements to the building stock, provided that window frames also receive attention at the same time (see also section above on building air tightness tests).
- The construction sector has started to show interest in thermal insulation materials. To address this, localised solutions appear to be required that also include some guidance on how best to apply such materials and avoid thermal bridges as these could otherwise result in increased condensation risks in such constructions.

Water absorption of typical wall construction materials

The capillary water absorption tests of typical Bhutanese wall construction materials were performed following the procedures detailed in EN 16302:2013 and evaluated according to EN 1925:1999. This permits comparison of the water absorption coefficients W_w [kg/(m^2*h$^{0.5}$)] determined during the tests in Bhutan to published values of similar materials. The classification scheme given in Table 6 (Willems, 2012) was used for this purpose as it represents empirical values on the basis of previous studies.

The assessments which were all conducted in-situ at the sites of the respective buildings shown in Fig. 7 included the following materials: locally produced cement stabilised earth blocks (building 4), imported bricks (building 7), imported aerated concrete blocks (building 10) and rammed earth walls (buildings 2 and 3). However, only a very limited number of probes were investigated so that the results cannot be deemed conclusive. Furthermore, it was not possible to investigate the most common contemporary external façade type, i.e. buildings constructed with imported bricks and then plastered with cement plaster that is coated with lime paint (see also section above on building types in Bhutan). Due to the surface properties of this wall type which results in a low grip on the surface it was not possible to attach the test tubes for detecting water ingress to the wall. However, alternatively, a test could be undertaken on the concrete base of building 4 that was plastered with a cement plaster but otherwise untreated. Table 7 gives an overview of the water absorption coefficients that were determined during the tests in Thimphu.

When comparing the results of Table 7 to the classifications given in Table 6, it can be concluded that, apart from the coated CSEB wall, all construction materials and walls that were investigated can be classified as water absorbing. This implies that they should not be applied without

Table 6
Classification of water absorption coefficients W_w (Willems, 2012).

Designation	Water absorption coefficient W_w [kg/(m^2*h$^{0.5}$)]
Water absorbing	>2
Water inhibiting	$0.5 < W_w \leq 2$
Water repellent	$0.001 < W_w \leq 0.5$
Waterproof	≤ 0.001

Table 7
Results of the water absorption tests conducted on building materials/walls in Thimphu, Bhutan.

Construction material	Details/comments	Water absorption coefficient [kg/(m^2*h$^{0.5}$)]
CSEB (single blocks)	Not coated, age: 10 d and 1 a	11.1–15.4
CSEB (wall)	Coated with cement slurry and a double layer of emulsion paint, age: 1 a	0
Concrete base below the CSEB masonry	Not coated, high water absorption indicates a rather high water content in the concrete mixture	3.5–5.7
Aerated concrete blocks (single blocks)	Not coated	60.5–66.2
Bricks (single brick)	Not coated	76.7
Rammed earth	Not coated, age: 20 a	131.4
	Coated with lime paint, age: 20 a	101.7
	Not coated, age: 1 a	84.0–100.4

additional weather coatings which, in the case of the imported bricks and aerated concrete blocks, would not be common anyway since façades constructed with these materials are usually plastered. However, it is not clear, what water absorption properties common plasters in Bhutan have since, as described above, plastered walls other than the base of building 4 could not be investigated.

In the case of rammed earth walls, driving rain may, over time, cause damage due to high water absorption. Critical is in particular the water tightness observed for the coated CSEB wall of building 4, since imperfections in the coating, the missing horizontal sealing against rising dampness and the high water absorption of the concrete base may lead to water ingress into the wall. The high absolute humidity levels present inside the building as discussed above in the section on the indoor climate assessments appear to confirm this. In conjunction with the high vapour diffusion resistance of the emulsion paint on the outside and parts of the inside faces of the walls this can subsequently result in structural damage as the water cannot easily diffuse to the outside. Cracks and spalling of the façade coating documented in the splash water zone of building 4 appear to further support this conclusion.

In order to enhance durability of façades for protection against driving rain DIN 4108–3:2014 defines limiting values for plasters and coatings. As detailed in Table 8 requirements are given for the water absorption coefficient W_w as well as the equivalent air layer thickness for water vapour diffusion s_d. Given these recommendations, the following measures may be applied to buildings in Bhutan:

- Application of plasters or coatings with a low water absorption coefficient $W_w \leq 0.5$ so that a sufficient durability of the façade can be ensured.
- Consideration of the equivalent air layer thickness for water vapour diffusion to achieve a sufficient drying capacity.
- Review of the current roof overhangs in Bhutan of around 1.5 m in their suitability for protecting constructions against driving rain in relation to wall construction materials and building height. (This needs to be undertaken in conjunction with considerations for solar gains which may be desirable as detailed above in the section on the indoor climate assessments.)

Conclusions

The Bhutanese construction sector has, over the past decades, experienced a change from a rural subsistence system based on mutual help to a professional trade with architects, engineers and construction companies. Alongside this the main construction systems and construction materials have also changed from buildings constructed with earth, quarry stone and timber to reinforced concrete fame constructions with brick infill walls. This type of construction in its present form was found to have a limited suitability for the climate of the Inner Himalayan region of Bhutan, which is characterised by dry, sunny winters and a comparably large diurnal temperature swing throughout the year. However, the initial study of building physics properties of a range of construction types in the Thimphu valley area of Bhutan presented in this paper highlights that both, current and also traditional construction methods come with limitations with respect to providing comfortable indoor climate conditions for the occupants and have some risks as per climate induced structural damages.

Air tightness tests conducted on 9 buildings revealed that the current building stock needs to be classified as leaky, with traditional construction types being the worst performing structures. Whilst the air infiltration rates n_{inf} deduced from the air tightness tests for the two investigated buildings following traditional construction techniques were determined as 3.9 h^{-1} and 5.3 h^{-1}, the modern constructions showed infiltration rates n_{inf} of between 0.8 h^{-1} and 1.9 h^{-1}. Typical air leaks in all buildings were found to be joints between materials, timber structure joints and the joints of windows and doors made with wooden frames. Conversely, in terms of U-values the most common contemporary wall construction type of brick infill walls was found to perform worse at 1.25 to 1.45 W/m^2 K than traditional rammed earth walls at 1.1 to 1.2 W/m^2 K and the cement stabilised earth block construction technique derived from the traditional rammed earth walls at 1.05 to 1.25 W/m^2 K. However, due to the limited timeframe that was available for these measurements, there are limitations as per the accuracy of these values which, therefore, can only be considered as indicative. Indoor climate assessments conducted in 4 buildings following traditional and contemporary construction methods highlighted the thermal storage potentials of high thermal mass walls under the given climate in conjunction with exploiting solar gains through appropriately glazed areas. In addition, the humidity regulating abilities of construction systems involving earth materials were demonstrated in comparison to constructions based on bricks and concrete. Water absorption tests of typical wall construction materials revealed that all investigated common construction materials need to be classified as absorbing, whereas some coatings were found to be waterproof, henceforth increasing risks of structural damage by humidity trapped inside the construction.

The data gathered on building air tightness, indoor climate, wall U-values and the water absorption of construction materials in the field surveys give a first insight into the thermal performance of the Bhutanese building stock but can, by no means, be considered as exhaustive or representative for the entire building stock. Further studies need to follow to deliver a more complete picture. Nevertheless, the heating degree day information provided in this paper allows for heating demand calculations in the Thimphu valley, for which, within limitations as per the accuracy and transferability to other buildings, the U-value and air infiltration data obtained within this study may be used.

Table 8
Factors for the protection against driving rain of plasters and coatings (DIN 4108–3:2014).

Factors for the protection against driving rain	Water absorption coefficient	Equivalent air layer thickness for water vapour diffusion	Product
	W_w	s_d	$W_w * s_d$
	[kg/(m^2*h$^{0.5}$)]	[m]	[kg/(m*h$^{0.5}$)]
Water repellent	≤0.5	≤2.0	≤0.2

Both, the climate data analysis for the Thimphu valley as well as the results of the field study highlight that there are potentials for improvements to the building stock that take reference in traditional and contemporary construction methods. The further development of traditional design strategies of using local materials and exploiting thermal mass for room climate moderation appears to have significant potentials for achieving the goal of sustainable development which forms part of the national philosophy in Bhutan. This will need to include improvements to the air tightness by improved material joints and window designs together with considerations for improving wall surface treatment to enhance durability and improving wall U-values by, for example, using aggregates of a low thermal conductivity as well as by routinely applying double glazing. The result may be an adapted form of building design which takes reference in traditional design ideas but also includes adaptations that feed through to the design appearance in order to meet modern comfort and durability standards.

Acknowledgements

The work presented in this paper was funded by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany within the funding programme for collaboration between German researchers and partners in Asian-Pacific countries [grant number 01DP15004]. The funding source had no involvement in the preparation of this article and the sole responsibility for its content lies with the authors.

The authors are grateful to the owners and inhabitants of the buildings investigated within the framework of this research for granting the permission of conducting on-site building performance measurements. The raw weather data required for developing Figs. 3 to 6 and Tables 1 and 2 was kindly provided by the Department of Hydromet Services (DHMS), Bhutan. Special thanks go to Sarinya Jentsch for preparing the drawings for Fig. 11.

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