Journal of Engineering Science and Technology
Special Issue on STAAUH, November (2021) 1 - 14

ASSESSING THERMAL COMFORT OF TRADITIONAL CORAL STONE BUILDING IN THE TRADITIONAL VILLAGE OF WEIZHOU ISLAND, CHINA

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Abstract

Shengtang village of Weizhou Island is a traditional Chinese village protected by the government. It is famous for large numbers of unique traditional coral stone buildings (TCSB). More than 150 years ago, village ancestors used coral stones as building materials for coastal area construction to resist corrosion. That the amazing properties of the coral stones make TCSB warm in winter and cool in summer. As income improved, villagers built modern brick concrete buildings (MBCB). The villagers complained that the thermal comfort of MBCB is not good as TCSB. However, it lacks quantitative data to verify this claim. Therefore, this study aims to assess the indoor thermal comfort of TCSB and MBCB, identifying the reasons for the differences. The study employs an experimental method. Samples were selected for both types of buildings having the same floors, orientation, and volume. These houses were used to assess and compare their indoor thermal comfort. The air temperature, relative humidity (RH), and predicted percentage of dissatisfied (PPD) were measured simultaneously using data loggers. The study revealed that the thermal environment within TCSB is more comfortable than in MBCB as TCSB has lower air temperature, RH, and PPD and longer time in category II thermal comfort compared to MBCB. Factors affecting the indoor thermal comfort differences between the two were identified providing references for architecture design and construction. Findings promote the continued use of existing coral stones as an alternative material to bricks and stones to avoid material wastage and reduce energy consumption, which is necessary for the protection and inheritance of TCSB.

Keywords: Indoor thermal comfort, PPD, Shengtang village of China; Traditional coral stone buildings, Traditional village.

1. Introduction

1.1. Energy consumption and thermal comfort

The global energy demand is increasing because of the world's population expansion [1]. Aqilah et al. [2] highlighted that residential electricity consumption accounts for about one-third of the world's total electricity consumption. As the population and incomes increase, air conditioning has become increasingly popular, especially in warm and hot climate areas. Almost 20% of the total electricity consumption in buildings is used for air conditioning to locate a favourable temperature for indoor thermal comfort, and this demand is increasing greatly [3, 4]. Indoor thermal comfort affects space users' well-being and the energy consumption of a building [5, 6].

1.2. Thermal comfort and the sustainable indoor living environment

PM2.5, PM10, temperature, relative humidity, wind speed, and carbon dioxide concentrations are the key indicators of indoor thermal comfort, and they are also the key factors affecting indoor air quality [7]. In other words, thermal comfort is a reflection of indoor air quality. Considering humans spend more than 90 percent of their time indoors, indoor air quality has a significant impact on environmental health risks [8, 9]. As a result, indoor thermal comfort has a significant impact on the health and well-being of the occupants, as well as the sustainability of the indoor living environment. The comparative empirical analysis between traditional coral stone buildings (TCSB) and modern brick concrete buildings (MBCB) is done through a quantitative method to evidence and prove which type of building will perform better in thermal comfort and is a much better sustainable indoor living environment. If TCSB outperforms MBCB in terms of thermal comfort, it would be easier to persuade the villages to maintain their tradition and inherit TCSB as a heritage. This may contribute to the protection and inheritance of traditional villages.

1.3. The traditional Chinese village (Shengtang village) of Weizhou Island

Weizhou Island is located on the sea surface of Beibu Gulf, south of Beihai City, Guangxi, China. The island is about 6 kilometres long from north to south, about 5 kilometres wide from east to west, with a land area of 26.88 square kilometres, and the geographical location is Longitude of 109°05′ - 109°13′ E and Latitude of 20°54′ - 21°05′ N. It is the youngest volcanic island in China. Shengtang village, located in the northeast of Weizhou Island, is an island village with more than 150 years of history and is most famous for its tourist attractions on the island is the unique coral stone traditional architecture. This village was recognized as the Chinese National Traditional Village in 2019 [10]. The term traditional village in China refers to a protected village that is considered a heritage. The TCSBs village has one of the limited traditional buildings on Weizhou Island, reflecting its traditional and unique architectural characteristics in China. As the core element of traditional villages, TCSB should be protected in these traditional villages. At present, 90% of the houses in the village are TCSB. With the rapid development of tourism on Weizhou Island, many of these traditional houses have been rented to tourism companies to be converted into B & B hotels and inns.

With income from renting traditional houses and a rise in villagers' income, some have built MBCB, leaving many of the existing coral stones mined before 2000 idle and wasted. The TCSBs are warm in winter and cool in summer [10]. The villagers reported that the thermal comfort of MBCB is not as good as TCSB. However, there is still a lack of quantitative data to verify that TCSB is cool in summer and if the thermal comfort of TCSB is better than of MBCB as claimed by the villagers. Thus, the outcomes of the study on the thermal comfort of TCSB and MBCB will help determine if the villagers are willing to continue living in TCSB based on energy consumption, maintenance, transformation, and sustainability of TCSB. Because of Weizhou Island's relatively hot climate, it is required to increase indoor thermal comfort using air conditioning and fans for more than six months of the year, putting a high demand on energy usage. Weizhou Island relies on its electrical generation, resulting in insufficient supply. Furthermore, other resources and public facilities, such as power and gas, are not connected to the mainland. The continuous use of TCSB will greatly reduce the consumption of new building materials, energy, and land resources, thus reducing the negative impact on the environment.

1.4. Building materials of TCSB

TCSB, located on Weizhou Island, is built using coral stones. The coral stones of Weizhou Island are stones secreted, fused, compacted, and petrified by coral insects in the sea. Coral stone brick is cut and chiselled from coral stones. Coral stone brick is 400 mm thick, which is thicker and larger than ordinary brick (112 mm) with many small holes. It is a ventilated and breathable stone brick. It has the characteristics of being warm in winter and cool in summer and can assist in regulating humidity and temperature [10]. It is a local building material loved by Islanders. Coral stones are local materials, and it reflects certain natural conditions and social and historical backgrounds. It has the characteristics of "originating from the sea, being natural, and not polluting the earth.”

The development of local coral stone architecture is a natural and time-consuming process that has resulted in a cultural treasure and a witness to human civilization. The island's persistent sea breeze, high intensity, and high salinity have strong corrosive effects on buildings. Coral stones are used to adapt to this natural marine environment. About 150 years ago, the villagers mined coral stones and transported them home in ox carts to their yards. After several years, when there were enough coral stones, they built their houses with them. At that time, due to the inconvenient transportation, the relatively poor economy, and limited materials, they could not afford to buy red bricks. As a result, the construction of coral stone buildings has been a lengthy process.

The houses built using coral stones were economical and durable, with the added benefit of being warm in the winter and cool in the summer. However, mining coral stones has seriously damaged the coral growth environment, resulting in reducing of coral species and the degradation of coral reef resources. The state has endorsed laws and regulations to prohibit illegal mining and destruction of coral reefs, leading to a shortage of coral stone materials in 2000.

Meanwhile, Beihai Municipal People's government issued a notice to reinforce the protection and management of coral resources to protect the sea environment, and the mining of coral reefs was prohibited after 2000 [10, 11], however, there are many coral stones in the villagers’ yards, which can be used as building materials (as shown in Fig. 1). Rupp et al. [12] stressed that using coral stones in structural systems of the traditional buildings was developed as the wisdom of climatic and cultural responses along the Coast of the Red Sea.

Some researchers believed knowledge and mastery of the physical and chemical phenomena of coral stone buildings are the basis for the conservation process and proposed to preserve historic coastal settlements through an optimal equilibrium with natural environment assets as the architecture of heritage buildings with coral limestone on the coast of East Africa suffers from a severe decay today [13, 14]. Liu and Huang [15] proposed a liveable vernacular architectural design for Weizhou island, considering the design concept and technology of traditional coral stone buildings. There is currently limited literature on coral stone architecture, with most of it focusing on the preservation of coral stone architectural heritage, the artistic value and renewal design of coral stone architecture, residential courtyard design, and the design transformation of coral stone buildings [16, 17].

Fig. 1. Existing coral stone brick in the courtyard.

2. Methods

Physical factors influencing thermal comfort include air temperature, ventilation, airflow, atmospheric pressure, humidity, clothing, natural lighting, and others. [10, 18, 19]. Indoor air temperature is the most important variable in controlling indoor thermal comfort. Indoor air temperature has a significant and direct impact on indoor thermal comfort [19]. Thus, it is commonly used to assess the indoor thermal comfort of residential buildings [20]. In hot and humid climates, the influence of relative humidity on indoor thermal comfort is obvious and should be considered [21, 22]. The International Organization for Standardization (ISO) has adopted PMV research results from Professor Po Fanger of the Danish Institute of technology to formulate the ISO7730 standard - "moderate thermal environment - Determination of Predicted Mean Vote (PMV) and PPD indicators and determination of thermal comfort conditions." Based on this standard and the ASHRAE evaluation method for indoor air quality in the United States, PPD is used to express people's indoor thermal comfort. Air temperature and relative humidity are the main variables of thermal environment comfort.

According to the "evaluation standard for the indoor thermal environment in civil buildings" issued by the National Standards of the People's Republic of China (GB/T 50785-2012), the thermal environment is divided into three categories. They are ①category I: 90% of the crowd is satisfied with the thermal environment; ②category II: 75% of the crowd is satisfied with the thermal environment;

③category III: less than 75% of the crowd is satisfied with the thermal environment. The overall evaluation index of the thermal environment is PPD and PMV are as follows: ① category I with PPD less than 10% and PMV between -0.5 and 0.5; ② category II with PPD between 10% and 25% and PMV between -1 and -0.5 or 0.5 and 1.0; ③ category III with PPD more than 25% and PMV less than -1 and greater than 1.

The methods employed in the study are in two parts (as shown in Fig. 2). First is selecting the site and case study of houses to ensure similarity in architecture, front-faced orientation, and dissimilarity in construction materials and roof. The study involved two houses, they are TCSB constructed using coral stones, and the other house is MBCB constructed using concrete and red sintered brick. The second part is the field measurement of specific parameters using data loggers in selected case study houses, which was used to examine the effect of thermal comfort of different case study houses.

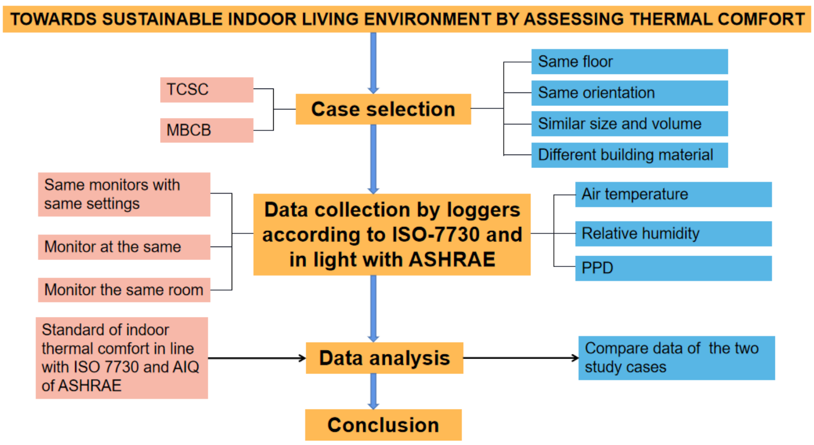

Fig. 2. Methodology framework.

2.1. Study site location and climate

This study was carried out in Shengtang village (latitude 21°2′47″N, longitude 109°6′24″E), Weizhou Island, China. Shengtang is a low-density village with exclusive single courtyard buildings. There are no high-rise buildings and industrial production in the village. Moreover, Weizhou Island is a small town with low density. It is 21 nautical miles away from the city (Beihai) and it is not affected by the greenhouse effect. The climate of this area is a subtropical monsoon, with no winter in four seasons and no hot summer in summer. The annual average temperature is 22.6°C, the annual average monthly maximum temperature is 28.2℃ (July), the annual average monthly minimum temperature is 15.0℃ (January), the extreme maximum temperature is 35.4℃, and the extreme minimum temperature is 2.4℃. The average sunshine time is 6.2 hours, the annual total radiation is 128.22 kcal/cm^2, and the annual average relative humidity is 81.7%. The annual average wind speed is 3.2 m/s, the annual average number of intense wind days is 38.3, and there are two years where the average was affected by typhoons within three years [11].

2.2. Selected case study houses

The selected case study houses are single-family buildings of 2-storey. The house selection aimed to choose a building with a similar construction in the same location, and both selected houses faced the northeast direction (as shown in Fig. 3). However, the selected houses are dissimilar in the use of building materials. The interior and exterior walls of TCSBs are constructed using coral stones, and MBCBs are constructed using reinforced concrete and red sintered brick.

Fig. 3. Case study houses (TCSB on the left and MBCB on the right).

The two case study houses are constructed according to the planning approval and acceptance of the local authorities. Both houses are modest and have few ornaments. The TCSB has a locally fired tiled pitched roof, while the MBCB has a flat concrete roof. The wall of TCSB is 400 mm thick, while the wall of the newly built house is 240 mm thick. The building materials and the thermal properties of the two case study houses are described in Table 1.

Table 1. Thermal properties of building materials of the case study houses.

Building material	Heat transfer coefficient (W/m^2. K)
External wall 220 mm brick wall with 10 mm thick cement mortar plastering on both sides (MBCB)	1.74
External wall 400 mm coral stone wall without no external plastering (TCSB)	0.30
Stainless steel metal door with 2 mm thick (Both TCSB and MBCB)	5.0
Window Single glazing 3 mm thick (Both TCSB and MBCB)	6.40
Fired tiled pitched roof (TCSB)	0.50
Concrete flat roof (MBCB)	0.71

2.3. Data measuring

The indoor thermal comfort and air quality data loggers were used to measure the data of the two selected case study houses simultaneously for five consecutive days from July 14 to July 18. The study was conducted in July, the hottest month of the year in this region.

The study site is Shengtang village, located in the climatic zone of Weizhou Island. According to the weather forecast data of the Beihai Meteorological Bureau, the maximum outdoor air temperature was 34℃, and the minimum temperature was 27℃ during the study period. It was sunny during the five days of study, with sunrise at 6:10 and sunset at 19:29. The measurements were recorded from 08:00 to 18:00 every day, and the measurement interval was 2 minutes. The average maximum temperature and relative humidity during the study period were calculated from the daily data and used in data analysis. The hand-held infrared thermometer was used to measure the outer surface temperature of the roof of the two case study houses. The measuring period was 08:00-18:00, with an interval of 2 hours. For the two case study houses, the monitoring of climate parameters is as follows.

2.3.1. Indoor air temperature, relative humidity, PPD, and other indoor thermal comfort parameters monitoring

According to the ISO 7730 standard, the cold and warm feeling grade of most people is determined through a subjective feeling experiment that comprehensively considers six factors: human activity degree, clothing thermal resistance (clothing condition), air temperature, air humidity, and average radiation temperature. This study result forms the basis for the subsequent monitoring of Ta, RH, PPD, and other related thermal comfort parameters. The indoor thermal comfort and air quality tester can measure the above parameters simultaneously [10]. The JT-IAQ-50 indoor thermal comfort and air quality tester can measure PM2.5, PM10, air temperature (*Ta*), black ball temperature (*Tg*), natural wet bulb temperature (*TNW*), relative humidity (*RH*), breeze speed (*Va*), CO_2 concentration, mean thermal sensation index (PMV), percentage of dissatisfied (*PPD*), no solar radiation indoors or outdoors (*WBGTin*), outdoor solar radiation (*WBGT*), instantaneous sound pressure level (*SPL*), thermal radiation (*TR*) illumination (*Lux*), Volatile Organic Compound (*VOC*) and dew point. The JT-IAQ-50 indoor thermal comfort and air quality tester is placed in the middle of the living room, 1.5m above the ground, to measure the indoor Ta, RH, and PPD. On both sides of the living room are bedrooms, which are not affected by the external heat source, humidity, and dryness. There are no ponds, plants, or tall buildings that shelter the houses. During the monitoring period, the number of people living in TCSB and MBCB was not more than three. During the monitoring process, the door was open without air conditioning and an electric fan.

2.3.2. Roof surface temperature monitoring

TCSB has sintered tile sloped roof, and MBCB has a concrete roof. The roof of the two houses is exposed to the sun during the day, not sheltered by plants or buildings. FLUKE-F62 max infrared thermometer was used to measure the surface temperature in the middle of the roof.

3. Results

3.1. Indoor air temperature (*Ta*)

The measured data of indoor air temperature of two houses for five consecutive days were sorted and calculated to obtain the average maximum temperature, as shown in Fig. 4. Based on the measurements, the maximum air temperature of TCSB was 33.49 ℃ on July 15; the lowest air temperature was 30.74 ℃ on July 18. The highest recorded air temperature in MBCB was 34.25 ℃ on July 15, and the lowest air temperature was 31.31 ℃ on July 18. The difference between the two case study houses' highest and lowest air temperatures are 2.75 ℃ and 2.94 ℃, respectively.

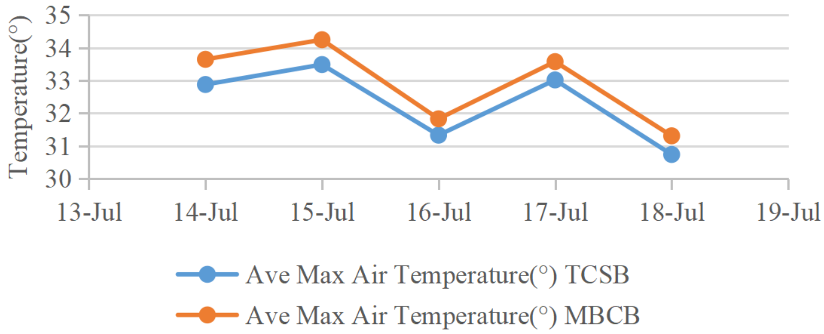

Fig. 4. Comparison of average max Ta between the two study cases.

3.2. Indoor relative humidity (RH)

The measured indoor relative humidity (RH) of two case study houses for five consecutive days was analysed and calculated, and the relative humidity was averaged (as shown in Fig. 5). The measured data for the five days are as follows: (1) the average relative humidity of TCSB was between 71.88% to 80.81%; (2) the highest measured RH was 80.81% on July 18; (3) the lowest measured RH was 71.88%, with a difference of 8.93% between the highest and the lowest value. The relative humidity of MBCB was between 69.03% to 76.98%. The highest RH of 76.98% was recorded on July 14, while the lowest RH was 69.03% on July 17, with a difference of 7.95%. Findings show that the relative humidity of TCSB is higher than that of MBCB, which is significant in reducing indoor temperature and improving thermal comfort.

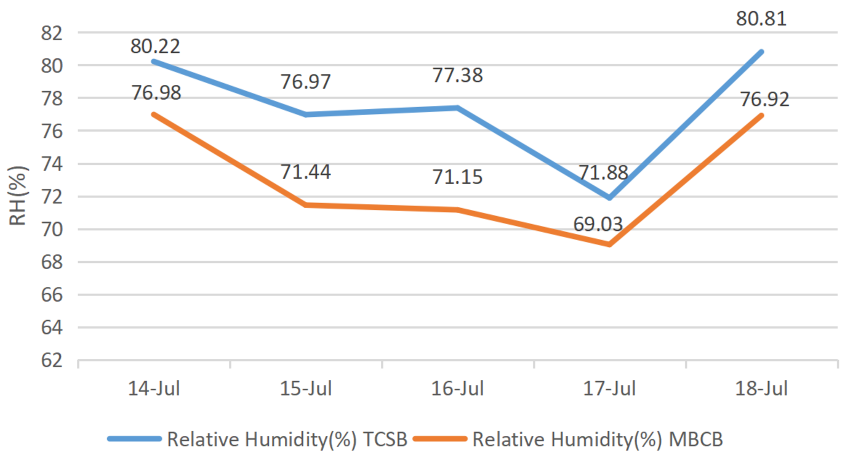

Fig. 5. Comparison of average RH between the two study cases.

3.3. Predicted percentage of dissatisfied (PPD)

From monitoring the two houses for five consecutive days, the daily average PPD value was between 48.64 and 84.49 (as shown in Fig. 6). This falls into thermal comfort category III, in which the crowd dissatisfaction with the thermal environment is higher than 25%. The minimum value is 48.64, which appeared in TCSB on July 16, and the maximum value is 84.49, which appeared in MBCB on July 17. During these five days, the lowest and highest instantaneous PPD value was 12.5 and 99.1, respectively.

In the continuous monitoring from 8:00 to 18:00 every day, the proportion of PPD value was less than or equal to 25 (thermal environment Level II and above) (as shown in Figs. 6 and 7), of which the maximum was 6.97%, reported in TCSB on July 18; the minimum value was 0, appeared in MBCB on July 15 and TCSB and MBCB on July 17, respectively. These data illustrate that the average PPD of TCSB is less than that of MBCB, and the minimum value of the difference is 1.74, whilst the maximum value is 19.39. From 8:00 to 18:00, the proportion of TCSB reaching category II or above is higher than that of MBCB, and the maximum and minimum differences are 0 and 1.43, respectively.

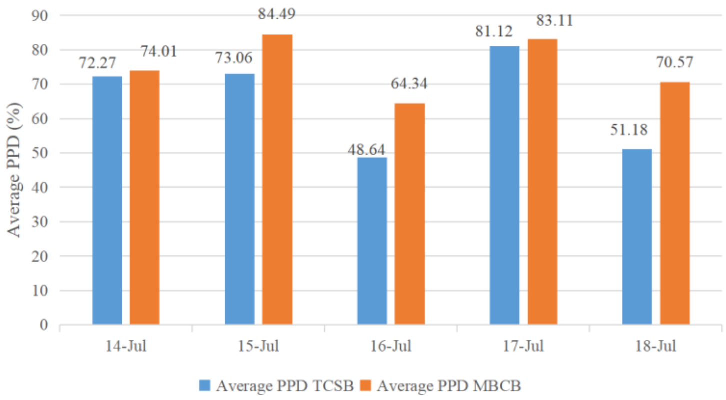

Fig. 6. Comparison of average PPD between the two study cases.

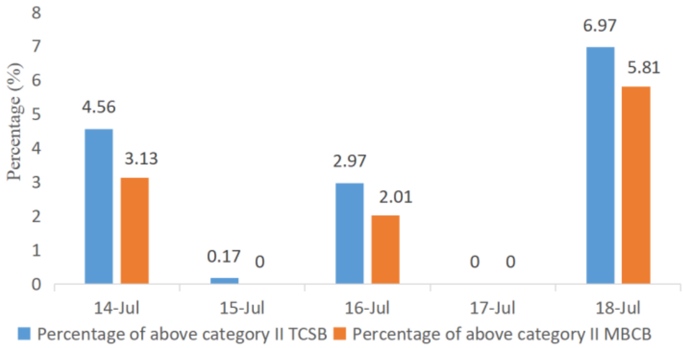

Fig. 7. Percentage of above category II thermal environment of study cases.

3.4. Roof surface temperature

The hand-held infrared thermometer was used to measure the roof surface temperature of the two houses at the interval of two hours. The maximum recorded temperature of the roof surface of TCSB was 40.3℃, while the minimum is 27.4℃. The maximum recorded temperature of MBCB was 45.5℃, and the minimum was 28.3℃. The highest temperature was recorded on the roof surface of MBCB, which was 5.2℃ higher than the highest temperature of TCSB, and the lowest temperature was recorded on TCSB's roof, which is 0.9℃ lower than that of MBCB. It can be concluded that the roof surface temperature of TCSB is lower than that of MBCB, ranging between 1.94℃ to 3.37℃ (as shown in Fig. 8).

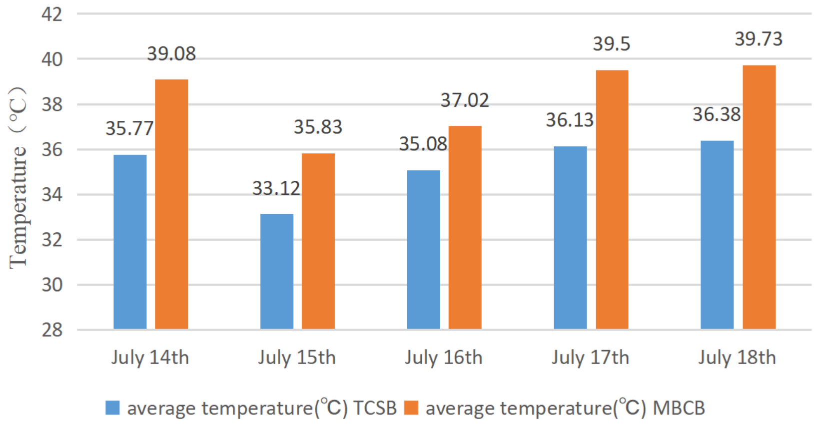

Fig. 8. Comparison of the average roof surface temperature of study cases.

4. Findings and Discussions

The continuously measured data illustrates the difference between the indoor thermal comfort of MBCB and TCSB. The average indoor air temperature of TCSB is lower than that of MBCB, while the average indoor relative humidity of TCSB is higher than that of MBCB. From the PPD monitoring data, it can be concluded that the daily PPD falls into category III, which is uncomfortable. However, in terms of the proportion of PPD above category II, TCSB is slightly higher than MBCB. If the monitored PPD extends to category II or above, the occupants will be comfortable, and there is no need to adjust the indoor thermal comfort using mechanical equipment. In other words, saving energy. When PPD falls into categories III and IV, the human body feels uncomfortable, and mechanical equipment is needed to improve indoor thermal comfort. Based on the data, it is found that the cumulative time of conducive indoor thermal comfort on July 14 is the longest at 19 minutes, and the cumulative time difference of PPD above category II in the two Case Study houses is 8.58 minutes. Each monitored houses have two floors and three rooms on each floor, with a total of 6 rooms. If each room is equipped with 1.5HP air conditioners to improve thermal comfort, the energy consumed by TCSB would be 0.215 kWh less than MBCB. Thus, the whole house can save 1.287 kWh of electric energy. The comparison of electric energy consumption during the monitoring period is shown in Table 2.

Table 2. Building power consumption between TCSB and MBCB.

Date	PPD above category II （%）		The difference between the two （%）	Cumulative time difference above category II in PPD (minutes)	The difference in electric energy consumption of one room （kWh）	The difference in electric energy consumption of the whole building （kWh）
	TCSB	MBCB				
July 14	4.56	3.13	1.43	8.58	0.2145	1.287
July 15	0.17	0	0.17	1.02	0.0255	0.153
July 16	2.97	2.01	0.96	5.76	0.144	0.864
July 17	0	0	0	0	0	0
July 18	6.97	5.81	1.16	6.96	0.174	1.044

The measured data and analysis for five consecutive days in summer with high temperatures demonstrate that the indoor thermal comfort of TCSB is better than that of MBCB. This finding corroborates the qualitative research conclusion of other studies [23-26] confirming that traditional rural residential buildings perform well in terms of thermal comfort and climate adaptability and reducing solar gain. This study result proves the rationality for the continuation of TCSB. To achieve better thermal comfort and the purpose of saving building energy consumption, the remaining coral stones on Weizhou Island can potentially be used as building materials in the new buildings. Additionally, materials with the same or better thermal properties insulation, and other physical properties of coral stones can be produced in other areas to construct new buildings. Since this study only monitored the indoor thermal comfort of TCSB and MBCB during the hottest period in summer with high temperatures, there is a need for comparative measurement of indoor thermal comfort throughout the year.

5. Conclusions and Recommendations

From the above data measurement and analysis, the research shows that the indoor thermal comfort of TCSB is slightly better than that of MBCB. The average indoor air temperature difference between the two case study buildings is 0.5-0.77 ℃. From the perspective of air conditioning for improving indoor thermal comfort, TCSB can reduce the energy consumption for air conditioning and refrigeration by an average of 0.67kWh/day/building with two floors with an area of $80m^2$. The relatively hot months in Weizhou Island are from May to October, which needs air conditioning for suitable thermal comfort. A similar building to TCSB can potentially reduce energy consumption by approximately 21kWh/month and 120kWh/year.

For Weizhou Island (tourism and ecological island), which has many TCSB with unique characteristics, the protection and continuous use of TCSB have great significance. The surface temperature of the traditional sloped roof of TCSB is lower than that of the flat roof of MBCB, and the temperature difference is 0.9-5.2℃, indicating that TCSB performs better than MBCB in terms of roof thermal insulation. It can provide references for future design and construction of energy-efficient residential buildings.

Unlike other cultural heritage protection, the protection of architectural heritage in traditional villages requires villagers to continue living in them, preserve local craftsmanship and traditional architecture unique to Weizhou Island and inherit them to the next generation. Since the construction of TCSB has a long history and the indoor facilities and equipment are relatively simple, it is necessary to upgrade and transform the TCSB of Shengtang traditional village without changing the unique traditional architecture. In terms of thermal comfort, it can be improved by using green roofs for better ventilation, indoor cooling, and energy consumption [27], insulative walls [28], application of building shading technology in hot summer [29], vertical green facades [30] and vegetation shading without changing the traditional style.

Furthermore, in terms of life convenience and enhanced living standards, it can improve residents' satisfaction using ornaments [21], the addition of modern furniture and household appliances, and access to convenient public facilities provided by the governments. Therefore, the villagers living in TCSB can be more comfortable and confident in their culture. This will contribute to realizing the inheritance, and sustainable use of traditional buildings. Additionally, it will also contribute to the protection and sustainable development of the traditional villages and the construction of the ecological tourism island of Weizhou Island in the long run.

Acknowledgment

This paper is produced within the 2020 basic scientific research ability improvement project for young and middle-aged teachers in colleges and universities in Guangxi: "the urban renewal design and ecological restoration Project Research on the protection and renewal of old neighbourhoods based on the concept of ‘urban double repair’"(No.2020ky60015) financed by the Guangxi Education Department of China, and scientific research and innovation team project “Guangxi local architecture research and innovation team (2018LSTD03) funded by Liuzhou Institute of Technology, China. The authors are grateful to Ai Xiangren and Zeng Chuyi for their assistance with measuring data.

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