Field Study of Summer Thermal Performance of the School Buildings in Avondale College

(Report for Jasmax, 30/11/2020)

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1. Background and Introduction

According to the New Zealand Ministry of Education, in New Zealand, there are 14637 school buildings built from pre-1940s to 1990s (see Figure 1). There could be a significant number of New Zealand school classrooms without sufficient insulation in their envelopes and with single glazing windows. Auckland has a temperate climate, with comfortable warm, dry summers and mild, wet winters. High relative humidity during the Auckland winter is a major issue for building indoor health conditions. An Auckland school building usually does not need air condition for cooling during the summer (window ventilation and ceiling fan) only need space heating during the winter. School building thermal design should more focus on winter thermal performance and indoor health conditions.

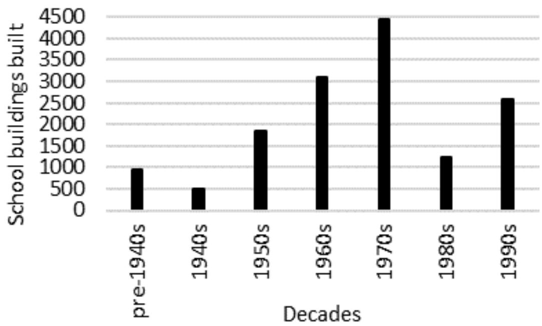


Figure 1. Number of school buildings built from pre-1940s to 1990s in New Zealand

There are about 425 schools in Auckland (New Zealand Ministry of Education). Most Auckland schools have a number of low-rise, isolated buildings (Figure 2) with lightweight structure and envelopes. In 90% of Auckland schools, each isolated building has four or fewer classrooms, and in 50% of the city's schools each isolate building has only one or two classrooms (Figure 3). For these types of school buildings with a big ratio of building surface to volume, the thermal performance of building envelope becomes the most important design factor for indoor thermal and health conditions.

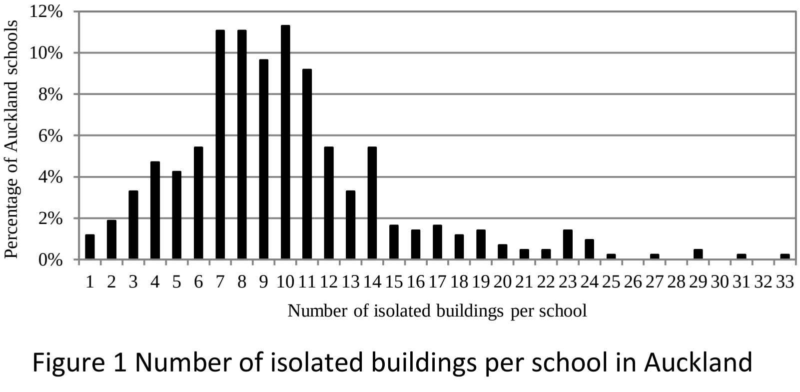


Figure 1 Number of isolated buildings per school in Auckland

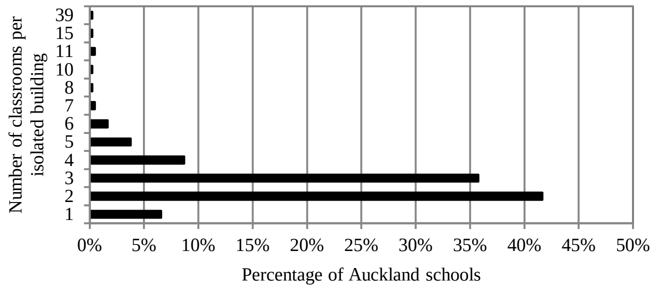


Figure 2 Number of classrooms per isolated school building in Auckland

Auckland has a temperate climate with comfortable warm, dry summers and mild, wet winters. An Auckland school building normally does not need air condition for cooling during the summer (window ventilation and ceiling fan) only need space heating during the winter. High relative humidity during the Auckland winter is a major issue for building indoor health conditions. School building thermal design should more focus on winter thermal performance and indoor health conditions. From 2010 to 2014 the redevelopment of Avondale College represented one of the most significant school rebuilding programs in New Zealand's history. The project provides the school's 2750 students with 92 new and refurbished teaching and resource spaces. It is the first time that Thermomass precast concrete insulated panels have been used as the main structure and building envelope of a new two-storey school building (New Maths Block) in New Zealand; which won Monte Craven Architectural Building Award (New Zealand Concrete Society). The previous study uses field study data of indoor microclimate to compare and evaluate indoor thermal and health conditions of classrooms in the school buildings with or without thermal mass in their building envelopes and structures (Su, 2017). The following two classrooms were used for the previous study:

- A heavyweight classroom in the middle and second floor of the New Maths Block, which has a thermal mass in its envelope (Thermomass insulated precast panels for N, S, W walls) and structure (precast concrete structure);
- A lightweight classroom in the middle of the one-storey retrofitted school building, which has no thermal mass in its envelope (Fundamax high pressure laminate cladding for the walls) and structure (timber structure).

According to the previous field study data, a school building with thermal mass in its envelope and structure has significantly better winter indoor thermal and health conditions than a school building with a similar insulation level (NZS, 2007; NZS 2009), but without thermal mass in its envelope and structure. During the winter night, with or without impacts of space heating and sun, indoor mean air temperatures of the "heavyweight" classroom are higher the "lightweight" classroom, especially for the early morning and night time. The thermal mass effect of the "heavyweight" classroom can contribute 2.8°C to increasing indoor mean air temperature when the building envelope has a similar insulation level during the wintertime. During the winter months and the winter school hours, the "heavyweight" classroom has significantly more time than the "lightweight" classroom when indoor air temperatures are greater than or equal to the indoor minimum air temperatures (16°C, 18°C and 20°C) required by national and international standards for occupants' thermal comfort and health. During the winter months and the winter school hours, the "heavyweight" classroom has significantly more time than the "lightweight" classroom when indoor relative humidity is maintained between 40% and 60%, which can minimize the indoor indirect health effects. The "heavyweight" classroom has significantly less winter time and school hours than the "lightweight" classroom when indoor relative humidity is greater than or equal to 60%, 70%, 75% and 80%. As indoor indirect health effects such as bacteria, viruses, fungi, mites, respiratory infections, allergic rhinitis, asthma, etc. decrease associated with decreasing indoor relative humidity, a school building with thermal mass in its envelope and structure has better indoor health conditions than the school building without thermal mass in its envelope and structure in a climate with a cold, wet winter.

This field study investigates and compares summer thermal performances and indoor thermal conditions of the school buildings with or without thermal mass in their structures, envelopes and partitions. According to the monthly mean temperature (19.7 °C) of the hottest months (February) in Auckland (see Table 1), the neutral temperature (Tn) during the hottest summer month is 21.7 °C (Tn = 17.6 + 0.31 × To.av =17.6 + 0.31×19.7 = 23.7 °C), summer comfort zone for the local people is 21.7 °C to 25.7 °C (the summer comfort zone: Tn - 2 °C to Tn + 2 °C). The monthly mean maximum temperatures during the summer are in the comfort zone, but the sun radiations during the summer months are quite high. The original research question is whether or not a school building with thermal mass in its building structure and envelope can negatively impact the summer indoor thermal conditions (e.g. indoor overheat problem), under the local summer conditions with the comfortable temperatures and the high solar radiations.

The first-time field study of summer thermal performances of school buildings with or without thermal mass in their structures, envelopes and partitions were carried out during the summer from 2016 to 2017 in Avondale College. As a number of important data loggers were damaged by the students, the inadequate data cannot be used for the comparison analysis. The second-time field study of summer thermal performance of school building was carried out during the summer from 14 December 2017 to 12 March 2018. There are total 12 classrooms (A15, A18, A21, A24, A32, A35, A39, A44, D8, D9, D16, D21) with different building structure and envelopes in Avondale College used for this field study. The data logger adjacent to the ceiling in the classroom A18 is damaged or did not work properly (the temperature data are extremely low). Only the data adjacent to the floor is available for the classroom A18. The data analysis excluded classroom A18. Table 2 shows the building materials of the 11 classrooms used for this study (PCIS precast concrete insulated structure, TS timber structure, LCP laminate cladding panel, BV break veneer, TPP Thermomass precast panel, TW timber weatherboard, FCS floor concrete slab, HF hardwood floorboard, PCCP precast concrete cladding panel).

Table 1 Auckland climate data from NIWA

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max Temp. (°C)	23.1	23.7	22.4	20.1	17.7	15.5	14.7	15.1	16.5	17.8	19.5	21.6
Min Temp. (°C)	15.2	15.8	14.4	12.1	10.3	8.1	7.1	7.5	8.9	10.4	12.0	14.0
Average Temp. (°C)	19.1	19.7	18.4	16.1	14.0	11.8	10.9	11.3	12.7	14.1	15.7	17.8
RH at 9am (%)	79.3	79.8	80.3	83.0	85.8	89.8	88.9	86.2	81.3	78.5	77.2	77.6
Radiation (Mj/m2)	22.7	19.5	15.9	11.5	8.1	6.5	7.2	9.9	13.7	17.4	20.7	22.2
Wet Days	8.0	7.1	8.4	10.6	12.0	14.8	16.0	14.9	12.8	12.0	10.3	9.3
Sun hours (h)	228.8	194.9	189.2	157.3	139.8	110.3	128.1	142.9	148.6	178.1	188.1	197.2
Rainfall (mm)	73.3	66.1	87.3	99.4	112.6	126.4	145.1	118.4	105.1	100.2	85.8	92.8

Table 2 Building materials of the 11 classrooms

Classroom	A15	A32	A35	A21	A39	A24	A44	D16	D21	D8	D9
Level	Dow.	Ups.	Ups.	Dow.	Ups.	Dow.	Ups	Dows.	Ups.	Ground	Ground
Position	Mid.	Mid.	West	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.
Structure	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	TS	TS
N Wall	BV	LCP	BV	BV	LCP	TPP	TPP	TPP	TPP	LCP	LCP
S Wall	TPP	TPP	TW	BV	TW	LCP	LCP	LCP	LCP	LCP	LCP
Floor	FCS	FCS	FCS	FCS	FCS	FCS	FCS	FCS	FCS	HF	HF
Partition	LCP	LCP	LCP	LCP	LCP	LCP	LCP	PCCP	PCCP	LCP	LCP

2. Research Method

The field study of the indoor microclimate of a number of classrooms with different building structures and envelopes were carried out during the summer months from 14 December 2017 to 12 March 2018 in Avondale College. Indoor air temperatures and relative humidity near the ceiling and the floor of the 12 classrooms and outdoor air temperature and relative humidity under the eaves of the roofs (6 test points) were continuously measured at 15-minute intervals 24 hours a day by HOBO temperature and relative humidity (RH) loggers during the summer months from 14 December 2017 to 12 March 2018. About 539,136 indoor and outdoor temperature and relative humidity data are collected for this study. All field study data of air temperatures of indoor and outdoor have been converted into percentages of summer time related to different ranges of indoor air temperature. The study used percentages of summer time when indoor air temperatures are greater than or equal to 20°C, 21°C, 22°C°C, 23°C, 24°C, 25°C, 26°C, 27°C, 28°C, 29°C, 30°C and 31°C to compare indoor thermal conditions of the classrooms with or without thermal mass in their building structures, envelopes and partitions. The study also investigates and compares the variations and the differences in hourly mean temperatures in the classrooms with or without thermal mass in their building structures, envelopes and partitions. All field study data of air temperatures of indoor and outdoor were converted into hourly mean air temperature during the summer.

Indoor surface temperature impacts indoor thermal comfort. During the summer, indoor surface temperatures must be cool enough to avoid occupant discomfort due to excessive radiative heat gain from the warm indoor surfaces (NRCC, 2010). The difference between the indoor surface and indoor mean air temperature must be smaller than 4°C to maintain the indoor thermal comfort during the summer. Indoor surface temperatures of the ceiling, floor, walls and windows of a number of classrooms with or without thermal mass in with or without mass in their building structures, envelopes and partitions were measured from 11am to 3pm on a number of summer days during the weekends (without students) under different weather conditions (sunny day, overcast day, raining day) by a FLIR E4 Infrared Camera (the emissivity of the FLIR E4 Infrared Camera was set up according to the particular indoor surface material). Indoor surface temperature data of the four classrooms D8, D9, D16 and D21 with and without opening windows and using ceiling fans are used for the comparison study in this report. Meanwhile, indoor wet bulb temperature, dry bulb temperature, globe temperature, wet bulb globe temperature WBGT (indoor) and heat index / Humidex at seating height of the classrooms were measured by 3M QUES Temp 36 Thermal Environmental Heat Stress Monitor on the desk in the middle of the classroom. Indoor air movements at the seating height were measured by TSI Hot Wire Anemometer when the windows were opened, and the ceiling fans were used. Mean Radiant Temperature (MRT), the Predicted Mean Vote (PMV) and the predicted percentage of dissatisfied PPD were calculated according to the field study data, the sensation according to the ASHRAE thermal sense scale (ASHRAE, 2013).

3. Data Analysis

3.1 Indoor thermal conditions of the classrooms without students during the school holidays

Table 3 shows indoor temperatures and percentages of summer time related to different temperature ranges of the 11 classrooms during the school summer holidays from 14/12/2017 to 30/01/2018 (without students). During the school holidays, the classrooms' windows and doors were closed (without the impact of natural ventilation), and the ceiling fans were off (without mechanical ventilation). With the same concrete structure, the mean indoor temperature (25.1°C) of the upstairs classrooms A32, A35, A39, A44 and D21 was 0.7°C higher than the mean indoor temperature (24.4°C) of the downstairs classrooms A15, A21, A24 and D16. The mean indoor temperature (25.1°C) of the two single-storey classrooms D8 and D9 without thermal mass in their building structures, envelopes and partitions was close to the upstairs classrooms A32, A35, A39, A44 and D21 with thermal mass in their building structures and 0.7°C higher than the downstairs classrooms A15, A21, A24 and D16 with thermal mass in their building structures. The mean indoor temperature (25.1°C) of the two single-storey classrooms D8 and D9 without thermal mass in their building structures, envelopes and partitions was 1.1°C higher the classrooms D16 and D21 with thermal mass in their building structures, building envelopes and partitions (see Table 3).

Except for the difference of indoor mean temperatures, there are two major differences in indoor thermal conditions between the classrooms with or without thermal mass in their building structures, envelopes and partitions. One is the fluctuations in indoor temperatures. Another is the percentages of summer time associated with the different ranges of indoor temperatures, especially for high temperature ranges (see Table 3). The fluctuations (11.3°C to 11.4°C) of indoor temperatures of the classrooms D8 and D9 without thermal mass in their building structures, envelopes and partitions were significantly larger than the fluctuations (5.2°C to 8.1°C) of the classrooms A15, A32, A35, A21, A39, A24, A44, D16 and D21 with thermal mass in their structure, and with or without thermal mass in their building envelopes (see Table 3 and Figure 1). As the building envelope and structure of the classrooms D8 and D9 without thermal mass, indoor space can be quickly heated by the sun heat gain and the raising outdoor temperatures during the daytime and cooled down by the decreasing outdoor temperature during the night time. Adding thermal mass in the building structure and envelope of a school building can reduce the fluctuation of indoor temperatures during the summer.

Table 3 Percentages of summer time related to different temperature ranges and indoor temperatures of the 11 classrooms without students during the summer school holidays

Classroom	**A15**	**A32**	**A35**	**A21**	**A39**	**A24**	**A44**	**D16**	**D21**	**D8**	**D9**	**Outdoor**
Level	Dow.	Ups.	Ups.	Dow.	Ups.	Dow.	Ups	Dows.	Ups.	Ground	Ground	
Position	Mid.	Mid.	West	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.	
Structure	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	TS	TS	
N Wall	BV	LCP	BV	BV	LCP	TPP	TPP	TPP	TPP	LCP	LCP	
S Wall	TPP	TPP	TW	BV	TW	LCP	LCP	LCP	LCP	LCP	LCP	
Floor	FCS	FCS	FCS	FCS	FCS	FCS	FCS	FCS	FCS	HF	HF	
Partition	LCP	LCP	LCP	LCP	LCP	LCP	LCP	PCCP	PCCP	LCP	LCP	
≥20 C°	100%	100%	100%	100%	100%	100%	100%	100%	100%	99%	99%	87%
≥21 C°	100%	100%	99%	100%	100%	100%	100%	100%	100%	97%	97%	74%
≥22 C°	99%	99%	97%	100%	100%	99%	100%	94%	98%	90%	91%	58%
≥23 C°	91%	94%	87%	98%	97%	92%	100%	60%	87%	78%	79%	41%
≥24 C°	67%	78%	67%	74%	81%	77%	96%	25%	62%	65%	66%	29%
≥25 C°	37%	52%	44%	44%	56%	44%	69%	8%	34%	49%	51%	19%
≥26 C°	14%	28%	22%	20%	31%	11%	34%	0%	15%	34%	36%	12%
≥27 C°	2%	10%	9%	7%	13%	2%	13%	0%	5%	20%	22%	7%
≥28 C°	0%	2%	2%	1%	4%	0%	2%	0%	0%	12%	12%	3%
≥29 C°	0%	0%	0%	0%	0%	0%	0%	0%	0%	5%	6%	1%
≥30 C°	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.3%	0.7%	0.3%
Mean T (C°)	24.6	25.3	24.8	24.9	25.3	24.8	25.6	23.4	24.5	25.0	25.1	22.7
STDEV (C°)	1.2	1.4	1.6	1.2	1.4	1.1	1.1	1.0	1.4	2.3	2.3	2.6
Max T (C°)	27.6	28.7	28.6	28.4	28.8	27.8	28.5	26.1	27.8	30.3	30.6	31.3
Min T (C°)	21.3	21.3	20.5	22.3	21.8	20.7	23.4	20.9	20.8	19.0	19.1	16.2
Fluctuation (C°)	6.2	7.4	8.1	6.1	7.0	7.1	5.1	5.2	7.0	11.3	11.4	15.1

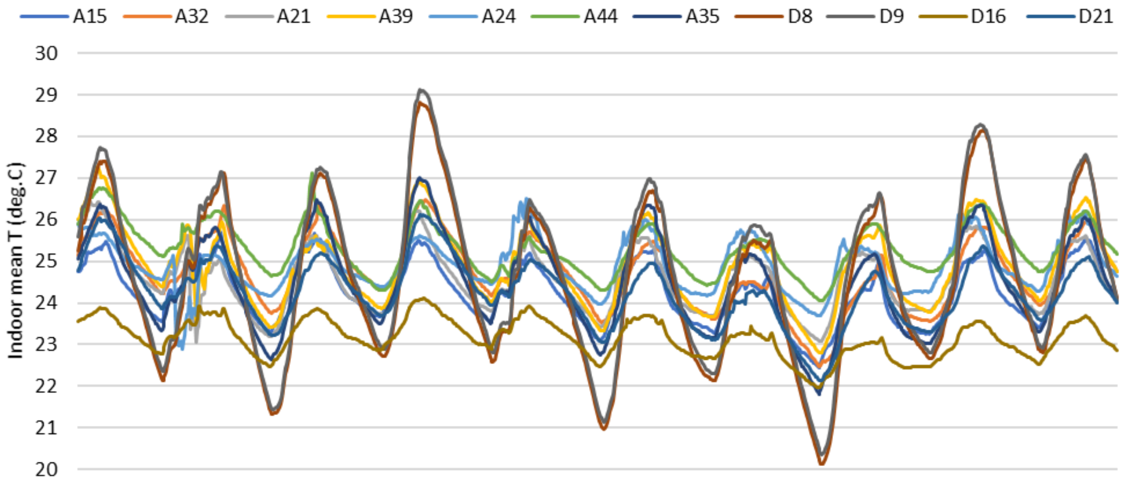


Figure 1 Partial indoor temperatures of the 11 classrooms

The large fluctuation of indoor temperatures of the classrooms can result in very high indoor temperatures during the summer daytime, which can negatively impact indoor thermal comfort. When indoor mean temperatures were higher than 26°C, 27°C, 28°C, 29°C and 30°C, the percentages of time of the classrooms D8 and D9 without thermal mass in their building structures, envelopes and partitions were significantly higher than the classrooms A15, A32, A35, A21, A39, A24, A44, D16 and D21 with thermal mass in their structure and with or without thermal mass in their building envelopes (see Table 3). The indoor mean temperatures of the D16 and D21 with thermal mass in their building structures, envelopes and partitions were clearly lower than the classrooms A15, A32, A24 and A44 without thermal mass in their building structures and envelopes and without thermal mass in their partitions When indoor mean temperatures were higher than 26°C, 27°C, 28°C, 29°C and 30°C, the percentages of summer time of the D16 and D21 classrooms were also clearly lower than the A15, A32, A24 and A44 classrooms A15, A32, A24 and A44 (see Table 3). Adding some thermal mass in partitions of the classrooms can positively impact indoor thermal conditions during the summer.

Figure 2 shows Indoor hourly mean temperatures of the 11 classrooms during the summer without students. Minimum hourly mean temperatures of the 11 classrooms occur at 4:00pm, and maximum hourly mean temperatures of the 11 classrooms occur at 7:00am. The variation of indoor hourly mean temperatures in the classrooms D8 and D9 without thermal mass in their building structure, envelopes and partitions were strongly associated with the variation of outdoor hourly mean temperatures. Indoor hourly mean temperatures in the classrooms D8 and D9 were higher than 26°C during the period of time from 1:00pm to 9:00pm and 27°C during the period of time from 2:00pm to 7:00pm. Because of mass effect, the variations of indoor hourly mean temperatures in other nine classrooms A15, A32, A35, A21, A39, A24, A44, D16 and D21 with thermal mass in their structure were more stable and not strongly associated with the variation of outdoor temperatures. Indoor hourly mean temperatures in the three classrooms A35, A44 and A39 with thermal mass in their structure are slightly higher than 26°C during a relatively short period of time. The hourly mean temperature of the classrooms D16 and D21 with thermal mass in their partitions were relatively lower than the classrooms A15, A32, A24 and A44 without thermal mass in their partitions and with the similar building structure and envelopes (see Figure 3). The indoor hourly mean temperatures of the classrooms D16 and D21 with thermal mass in their building structures, envelopes and partitions could be lower than the outdoor hourly mean temperature for a period of time during the summer school holidays (see Figure 3).

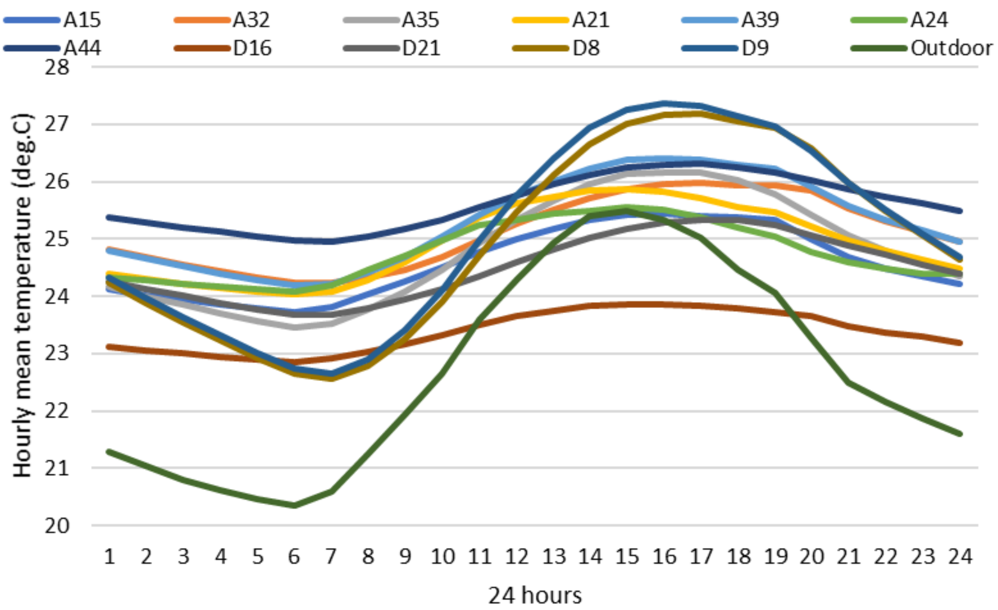


Figure 2 Indoor hourly mean temperatures of the 11 classrooms during the summer school holidays

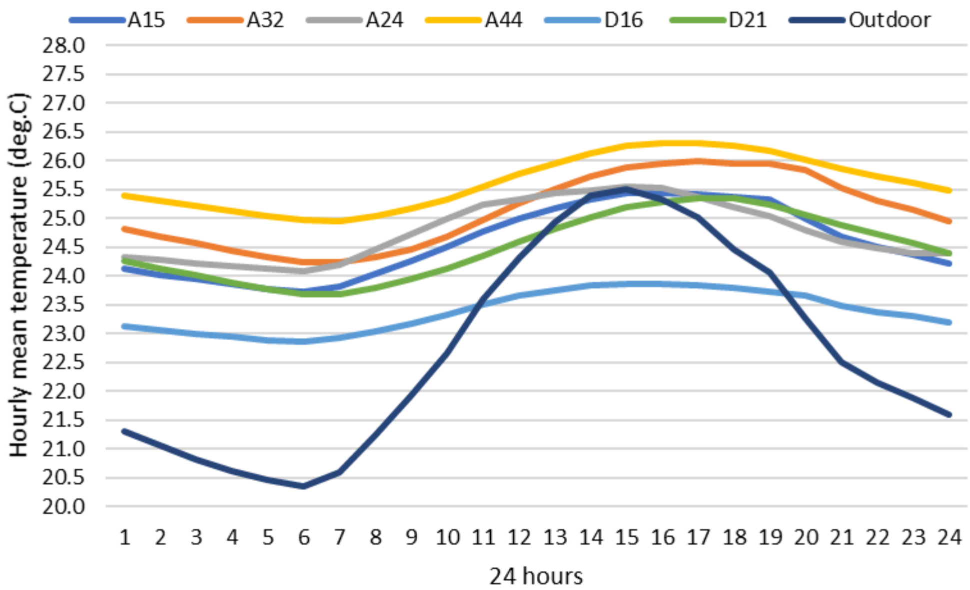


Figure 3 Indoor hourly mean temperatures of the classrooms with different partitions during the summer school holidays

3.2 Indoor thermal conditions of the classrooms with students during the summer school term

Table 4 shows indoor temperatures and percentages of summer time related to different temperature ranges of the ten classrooms during the school summer team from 31/01/2018 to 12/03/2018 (with students). The data loggers in the classroom D16 did not work properly from 10/02/2018. The data analysis excluded classroom D16. The classroom A32 was movie room, and its windows were covered by black paper, which could result in relative higher indoor temperature during the summer school team (school hours with students). The classroom A24 was uniform change room and its ceiling fans were on all the time, which could result in relative lower indoor temperature during the summer school team (school hours with students). The hourly mean temperature of the classrooms D16 and D21 with thermal mass in their partitions are relatively lower than the classrooms A15, A32, A24 and

A44 without thermal mass in their partitions and with similar structure and building envelopes (see Figure 3). During the summer school team, the indoor hourly mean temperatures of the classrooms D8 and D9 were always higher than the outdoor hourly mean temperature.

Table 4 Percentages of summer time related to different temperature ranges and indoor temperatures of the 10 classrooms with students during the summer school team (excluding D16)

Classroom	A15	A32	A35	A21	A39	A24	A44	D21	D8	D9	Outdoor
Level	Dow.	Ups.	Ups.	Dow.	Ups.	Dow.	Ups	Ups.	Ground	Ground	
Position	Mid.	Mid.	West	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.	Mid.	
Structure	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	PCIS	TS	TS	
N Wall	BV	LCP	BV	BV	LCP	TPP	TPP	TPP	LCP	LCP	
S Wall	TPP	TPP	TW	BV	TW	LCP	LCP	LCP	LCP	LCP	
Floor	FCS	FCS	FCS	FCS	FCS	FCS	FCS	FCS	HF	HF	
Partition	LCP	LCP	LCP	LCP	LCP	LCP	LCP	PCCP	LCP	LCP	
≥20 C°	100%	100%	100%	100%	100%	100%	100%	100%	99%	99%	83%
≥21 C°	100%	100%	99%	100%	100%	99%	100%	100%	95%	96%	75%
≥22 C°	99%	99%	97%	99%	99%	98%	99%	99%	87%	90%	61%
≥23 C°	93%	97%	86%	99%	97%	95%	98%	91%	77%	80%	41%
≥24 C°	65%	86%	64%	92%	84%	94%	92%	72%	60%	64%	26%
≥25 C°	34%	64%	41%	72%	62%	69%	62%	50%	42%	47%	15%
≥26 C°	10%	43%	19%	45%	37%	35%	36%	25%	29%	34%	8%
≥27 C°	2.1%	17.9%	6.2%	21.0%	13.4%	9.9%	11.7%	8.0%	17.1%	20.8%	3.2%
≥28 C°	0.2%	5.5%	0.8%	7.9%	4.3%	1.0%	2.2%	2.5%	9.5%	11.3%	0.8%
≥29 C°	0.0%	1.0%	0.0%	2.2%	0.4%	0.1%	0.0%	0.2%	3.4%	6.4%	0.3%
≥30 C°	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	2.0%	0.0%
≥31 C°	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%
Mean (C°)	24.5	25.6	24.6	25.9	25.5	25.5	25.5	25.0	24.7	25.0	22.5
STDEV (C°)	1.2	1.5	1.5	1.4	1.4	1.3	1.2	1.5	2.3	2.4	2.4
Max (C°)	28.7	30.0	28.5	30.2	29.8	29.6	28.9	29.3	30.4	31.3	29.9
Min (C°)	20.8	20.7	20.4	20.9	20.8	20.3	20.7	20.7	19.3	19.4	16.7
Fluctuation (C°)	7.9	9.2	8.1	9.3	9.0	9.3	8.2	8.6	11.1	11.9	13.2

During the school hours in the summer school team, the classrooms' windows and doors were likely opened (with natural window ventilation), and the ceiling fans were likely used. The indoor mean temperature of the ten classrooms could be impacted by natural window ventilation (how often the windows were opened during the field study), mechanical ventilation (how often the ceiling fans were used during the field study) and occupants' heat gains (how often the classrooms were used by students). Those impacts can reduce the effectiveness of thermal mass. The fluctuations (7.9°C to 9.3°C) of indoor temperatures of the classrooms A15, A32, A35, A21, A39, A24, A44 and D21 with thermal mass in their structures during the summer school team with students were larger than the fluctuations (5.1°C to 8.1°C) of indoor temperatures during the summer school holidays without students.

The fluctuations of indoor temperatures (8.1°C to 9.3°C) of the classrooms A15, A32, A35, A21, A39, A24, A44 and D21 with thermal mass in their structures during the summer school team with students were still smaller than the fluctuations (11.1°C – 11.9°C) of indoor temperatures of the two classrooms D8 and D9 without thermal mass in their structures. Although the mean indoor temperature (25.3°C) of the classrooms A15, A32, A35, A21, A39, A24, A44 and D21 with thermal mass in their structures were slightly higher than the mean indoor temperature (24.9°C) of the classrooms D8 and D9 without thermal mass in their structures, the percentages of time of the classrooms A15, A32, A35, A21, A39, A24, A44 and D21, when indoor mean temperatures were higher than 26°C, 27°C, 28°C, 29°C, 30°C and 31°C, were generally lower than the classrooms D8 and D9. Generally, the indoor thermal conditions of the classrooms with thermal mass in their structures were better than the classroom D8 and D9 without thermal mass in their structures during the summer school team with students.

Figure 4 shows Indoor hourly mean temperatures of the ten classrooms during the summer without students. The minimum hourly mean temperatures of the 11 classrooms occur at 4:00pm, and the maximum hourly mean temperatures of the 11 classrooms occur at 7:00am. There were significant variations of the hourly mean temperature lines of the ten classrooms during the daytime, which were impacted by the window national ventilation, the ceiling fan mechanical ventilation and the heat gain from students. The fluctuations of hourly mean temperatures in the classroom D8 and D9 without thermal mass were relatively larger than other classrooms with thermal mass. The hourly mean temperatures of the classrooms D16 and D21 with thermal mass in their partitions were relatively lower than the classrooms A15, A32, A24 and A44 without thermal mass in their partitions and with a similar structure and building envelope during the school team (see Figure 5).

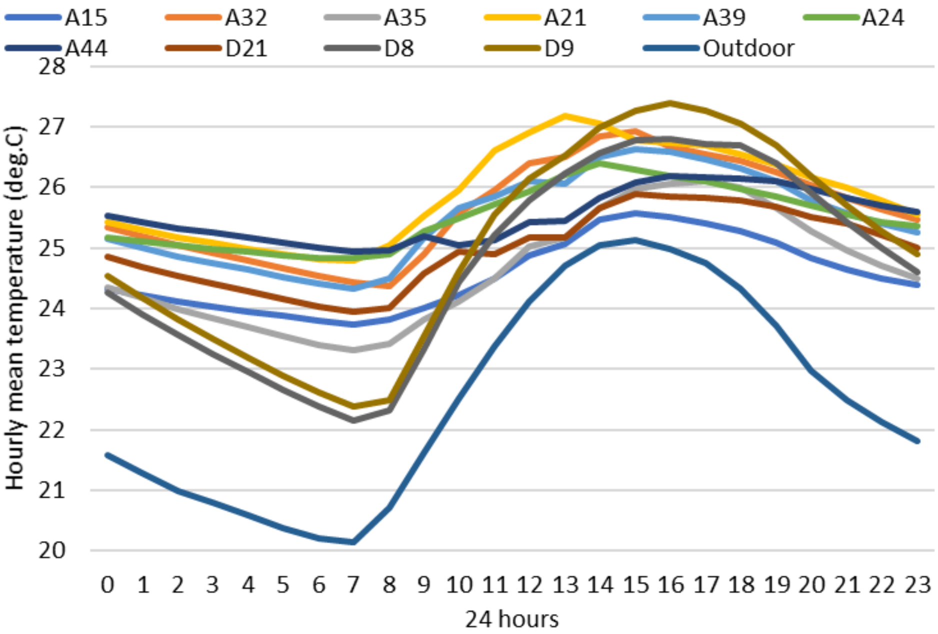


Figure 4 Indoor hourly mean temperatures of the 10 classrooms during the summer school team

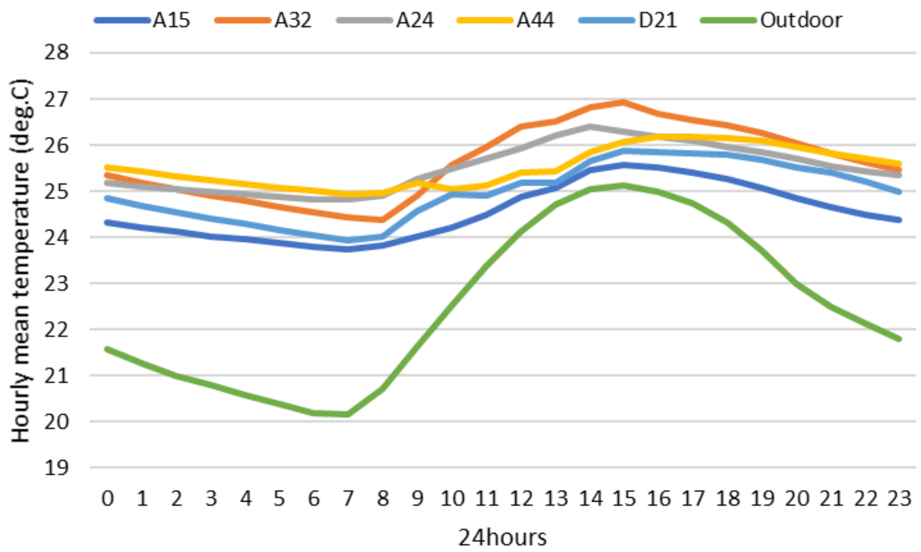
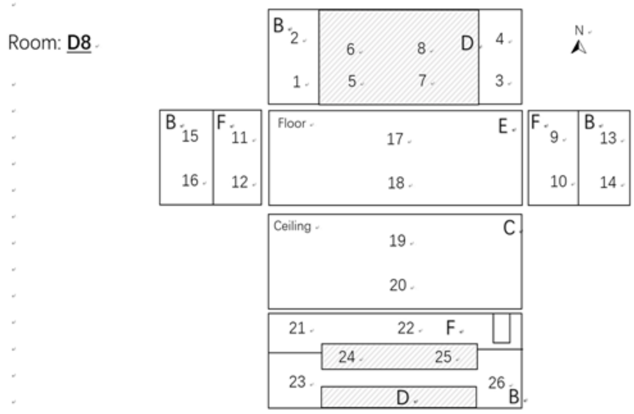


Figure 5 Indoor hourly mean temperatures of the classrooms with different partitions during the summer school team

3.3 Indoor surface temperature and thermal comfort without opening windows and using ceiling fans

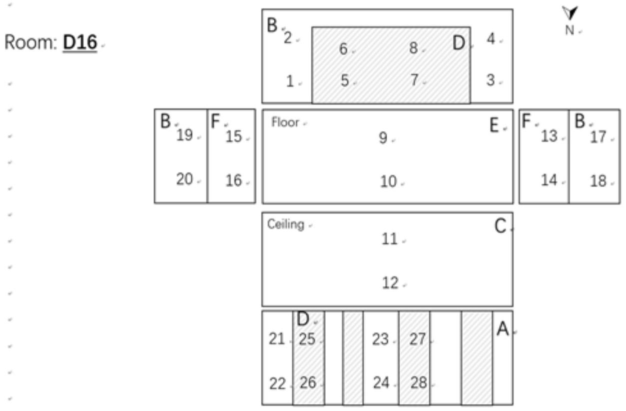
Figure 6, 7 show the testing indoor surface temperature plans for the classrooms D8 and D16. Table 5 shows indoor surface temperatures and the differences between indoor surface temperatures and the indoor air temperatures (Dry T) at the setting height of in the middle of the four classrooms D8, D9, D16 and D21, with or without thermal mass in their building structures, envelopes and partitions, when the windows and doors were closed, and the ceiling fans were not used during the weekends (without students). The differences between the indoor surface temperatures and the air temperature at the seating height (on the desk in the middle of classrooms) were never over 4°C for the different weather conditions. The thermal designs of the four school buildings D8, D9, D16 and D21, can efficiently control indoor surface temperatures to meet the requirement of summer indoor thermal comfort. For all the different weather conditions, when the windows were closed and the ceiling fans were not used, the indoor mean surface temperature of the classrooms D16 and D21 with thermal mass in their building structures, envelopes and partitions were generally lower than the classrooms D8 and D9 without thermal mass in their building structures, envelopes and partitions. The low indoor surface temperatures can positively impact indoor thermal comfort of the classrooms during the summer.



Emissivity

Symbol	A	B	C	D	E	F	G	P	
Material	Precast concrete panel	Painted plaster wall	Calcium silicate board	Door or window glass	Floor carpet	Wall fabric	Wood	Paper	
Σ=	0.97	0.90	0.90	0.85	0.95	0.95	0.85	0.90	

Figure 6 Test points of indoor surface temperature and their emissivity of the D8 classroom



Emissivity

Symbol	A	B	C	D	E	F	G	P	
Material	Precast concrete panel	Painted plaster wall	Calcium silicate board	Door or window glass	Floor carpet	Wall fabric	Wood	Paper	
Σ=	0.97	0.90	0.90	0.85	0.95	0.95	0.85	0.90	

Figure 7 Test points of indoor surface temperature and their emissivity of the D16 classroom

Table 5 Indoor surface temperatures (°C) and the differences between indoor surface temperatures and the air temperatures (Dry T, °C) at the setting height of the 4 classrooms

Weather	Class.	North	East	West	Floor	Ceiling	South	Average	Dry T	Dif. Ceil/Dry T	Dif. Ind. Surf./Dry T
Sunny	D8	31.8	30.8	30.6	31.0	31.4	30.8	31.0	28.9	2.5	2.1
Sunny	D9	32.1	30.9	30.7	31.0	31.5	30.6	31.1	28.6	2.9	2.5
Sunny	D16	28.9	26.7	27.1	26.6	27.1	27.4	27.3	28.5	-1.4	-1.2
Sunny	D21	29.3	28.6	28.8	28.0	29.0	28.9	28.7	28.1	0.8	0.6
Overcast	D8	29.5	28.2	28.1	28.7	28.7	28.5	28.6	27.4	1.3	0.8
Overcast	D9	30.5	28.5	28.5	29.4	29.5	29.5	29.3	27.7	1.8	1.2
Overcast	D16	28.1	26.4	26.7	26.0	26.9	26.8	26.8	26.8	0.1	2.1
Overcast	D21	29.3	27.0	27.3	26.6	27.1	27.6	27.5	26.9	0.2	2.7
Rainy	D8	26.6	25.8	26.0	25.7	25.9	26.1	26.0	24.9	1.0	1.1
Rainy	D9	28.0	26.2	26.2	27.0	26.1	28.4	27.0	26.7	-0.7	0.3
Rainy	D16	25.4	24.1	24.3	23.9	24.2	24.3	24.3	24.6	-0.5	-0.3
Rainy	D21	28.3	25.6	25.6	25.2	25.7	25.8	26.0	25.0	0.6	1.0

Table 6 shows different indoor temperatures (wet bulb temperature, dry bulb temperature, globe temperature, wet bulb globe temperature (indoor) WBGTi, heat index / humidex H.I. and mean radiation temperature MRT) and thermal comfort conditions (the predicted mean vote PMV, the sensation according to the ASHRAE thermal sense scale and the predicted percentage of dissatisfied PPD) at the seating heights in the middle of the four classrooms D8, D9, D16 and D21, with or without thermal mass in their building structures, envelopes and partitions, when the windows and doors were closed and the ceiling fans were not used under the different weather conditions. To compare indoor thermal conditions between the classrooms with or without thermal mass in their structures and envelopes, not only the mean air temperatures (Dry T) at the seating height in the D16 and D21 classrooms were lower than the D8 and D9 classrooms but also the globe temperature and the mean radiation temperatures (MRT) at the seating height in the D16 and D21 classrooms were lower than the D8 and D9 classrooms for the all different weather conditions (sunny, overcast and rainy). The lower globe temperatures and mean radiation temperature at the seating height in the D16 and D21 classrooms represent the less radiative heat from the indoor surfaces with the lower temperatures (see Table 5). The lower air temperature and the lower mean radiation temperature at the seating height in the D16 and D21 classrooms resulted in the better summer indoor thermal conditions than the D8 and D9 classrooms. The PMV values of the D16 and D21 classrooms were lower than the D8 and D9 classrooms for the different weather conditions (see Table 6). Without impacts of natural window ventilation and mechanical ventilation (not using the ceiling fans), the summer thermal performance of a school building with thermal mass in their thermal mass in its structure and building envelope is better than the conventional school building without thermal mass in its structure and building envelope under the local summer climatic conditions. For the sunny day, the indoor thermal conditions of the four classrooms were not in the comfort zone (slight warm to warm,) and for the overcast days the indoor thermal condition of the D9 classroom was slightly warm, which need adequate ventilation to restore the thermal comfort for the occupants.

Table 6 Indoor different temperatures and the thermal comfort conditions at the seating height in the middle of the 4 classrooms under different weather conditions

Weather	Class.	Wet T	Dry T	Globe	WBGTi	RH	H.I.	MRT	PMV	Sensation	PPD
Sunny	D8	23.7°C	28.9°C	29.8°C	25.5°C	57%	31°C	29.8°C	1.46	Slight warm	49%
Sunny	D9	23.8°C	28.6°C	30.3°C	25.7°C	58%	31°C	30.3°C	1.5	warm	51%
Sunny	D16	23.5°C	28.5°C	27.6°C	24.7°C	56%	30°C	27.6°C	1	Slight warm	26%
Sunny	D21	23.2°C	28.1°C	28.2°C	24.7°C	59%	30°C	28.2°C	1.05	Slight warm	28%
Overcast	D8	22.7°C	27.4°C	28.6°C	24.5°C	58%	28°C	28.6°C	0.97	Neutral	25%
Overcast	D9	22.8°C	27.7°C	28.8°C	24.6°C	57%	29°C	28.8°C	1.05	Slight warm	28%
Overcast	D16	22.9°C	26.8°C	26.8°C	24.1°C	62%	28°C	26.8°C	0.58	Neutral	12%
Overcast	D21	22.7°C	26.9°C	27.4°C	24.1°C	62%	28°C	27.4°C	0.7	Neutral	15%
Rainy	D8	20.2°C	24.9°C	26.2°C	21.9°C	51%	24°C	26.2°C	-0.01	Neutral	5%
Rainy	D9	25.8°C	26.7°C	26.7°C	22.3°C	50%	26°C	26.7°C	0.43	Neutral	9%
Rainy	D16	20.0°C	24.6°C	24.7°C	21.4°C	53%	24°C	24.7°C	-0.3	Neutral	7%
Rainy	D21	19.8°C	25.0°C	25.4°C	21.5°C	51%	24°C	25.4°C	-0.12	Neutral	5%

3.4 Indoor surface temperature and thermal comfort with opening windows and using ceiling fans

The indoor surface temperatures, wet bulb temperature, dry bulb temperature, globe temperature, wet bulb globe temperature (indoor) WBGTi, heat index / humidex H.I. and the air velocity at the seating height in the middle of the classrooms D9 and D21 were measured from 10:20 to 15:30 during a sunny day, when windows are opened and the ceiling fans were on from 8:30. The mean indoor air velocity at the seating height in the middle of the classrooms D9 and D21 was 0.2m/s with a range of 0.1m/s to 0.3m/s, which were used to calculate MRT, PMV and PPD. The metabolic rate for seating people is set at 1 and the clothing level for summer cloth is set at 0.57, which were used to calculate PMV and PPD (Tartarini, Schiavon, Cheung & Hoyt, 2000). Table 7 shows indoor surface temperatures and the differences between indoor surface temperatures and the indoor air temperatures (Dry T) at the setting height of the classrooms D9 and D21. For a sunny day, when the windows were opened and the ceiling fans were used, indoor surface temperatures of the D21 classroom with thermal mass in its building structure, envelope and partition were significantly lower than the classroom D9 without thermal mass in its building structure, envelope and partition (see Table 7).

Table 7 Indoor surface temperatures (°C) and the differences between indoor surface temperatures and the air temperatures (Dry T, °C) at the setting height of the 2 classrooms

Weather	Class.	North	East	West	Floor	Ceiling	South	Average	Dry T	Dif. Ceil/Dry T	Dif. Ind. Surf./Dry T
Sunny	D9	30.0	26.9	27.1	29.4	27.6	28.5	28.2	26.3	1.3	1.9
Sunny	D21	24.9	23.9	23.8	24.2	24.1	23.9	24.1	23.5	0.6	0.6

Table 8 shows the different indoor temperatures (wet bulb temperature, dry bulb temperature, globe temperature, wet bulb globe temperature (indoor) WBGTi, heat index / humidex H.I. and mean radiation temperature MRT) and thermal comfort conditions (the predicted mean vote PMV, the sensation and the predicted percentage of dissatisfied PPD) at the seating heights in the middle of the D9 and D21 classrooms, with or without thermal mass in their building structure, envelope and partition, when the windows and doors were opened and the ceiling fans were used during the sunny day of a weekend in the summer (without students). With ceiling fans mechanical ventilation and window natural ventilation and without the student heat gains, indoor thermal conditions of the classrooms D9 and D21 are neutral or marginal slight cool. The ventilation design with window natural ventilation and ceiling fans mechanical ventilation can efficiently maintain the indoor thermal comfort for the classrooms with and without thermal mass in their building structures, envelopes and partitions during the summer.

To compare indoor thermal conditions between the D9 classrooms and the D21 classroom with or without thermal mass in their structures, envelopes and partitions, indoor air temperature, globe temperature and mean radiation temperature of the D21 were significantly lower than the D9 classroom. There was a clear difference between the PMV value between the D21 classroom and the D9 classroom. Without students' heat gain, the PMV value of D21 (-1.05, marginal slight cool) was clearly lower than the classroom D9 (0.22, neutral) for the summer condition (see Table 8). The indoor thermal conditions of the classroom D21 was cooler than the classroom D9 during a sunny day. A school building with thermal mass in its building structures, envelopes and partitions, with the natural window ventilation and the ceiling fan mechanical ventilation, can provide the better indoor thermal conditions for maintaining the students' thermal comfort during the Auckland summer.

Table 8 Indoor different temperatures and the thermal comfort conditions at the seating height of the classrooms D9 and D21

Weather	Class.	Wet T	Dry T	Globe	WBGTi	RH	H.I.	MRT	PMV	Sensation	PPD
Sunny	D9	19.6°C	26.3°C	27.3°C	21.9°C	46.8%	26.3°C	28.1°C	0.22	Neutral	6%
Sunny	D21	18.3°C	23.5°C	23.7°C	19.9°C	49.2%	23.0°C	23.9°C	-1.07	Slight cool	29%

Discussions and Conclusions

According to the field study data of indoor microclimate of the 11 classrooms in Avondale College during the school summer holidays (without students), when all windows were closed and ceiling were off, the indoor mean temperature of the classrooms D16 and D21 without thermal mass in their structures, building envelopes and partitions was 1.1°C lower than the classrooms D8 and D9 without mass in their structures, building envelopes and partitions, the fluctuations of indoor temperatures of the classrooms D16 and D21 were significantly smaller than the classrooms D16 and D21, and the percentages of time in the classrooms D16 and D21, when the indoor mean temperatures are higher 26°C, 27°C, 28°C, 29°C, and 30°C, are significantly lower than the classrooms D16 and D21. Generally, the summer thermal performance of the school buildings with thermal mass in their structures, envelopes and partitions are better than the conventional school buildings without thermal mass in their structures, envelopes and partitions.

According to the field study data of testing indoor surface temperature and testing indoor thermal conditions at the seating height in the middle of the classrooms, without ceiling fans and window ventilation and without students, the indoor thermal conditions of all the classrooms with or without thermal mass in their structures, envelopes and partitions cannot be maintained within the thermal comfort zone at the seating height. Especially for the sunny day, the indoor thermal conditions of the classrooms D8 and D9 are slightly warm or warm, indoor thermal conditions of the classrooms D16 and D21 are slightly warm. All classrooms do need ventilation (natural ventilation or mechanical ventilation) to restore thermal comfort during the summer.

Without opening window and using a ceiling fan, although the indoor thermal conditions of all the classrooms with or without thermal mass in their structures, envelopes and partitions cannot be maintained within the thermal comfort zone at the seating height, the mean air temperatures, globe temperatures and mean radiation temperatures at the seating height of the classrooms D16 and D21 are clearly lower the classrooms D8 and D9 for the different weather conditions (sunny day, overcast day and rainy day). The summer indoor thermal conditions of a school building with thermal mass in their structures, envelopes and partitions are generally better than the conventional school building without thermal mass in their structures, envelopes and partitions. Not only for the local school buildings but also for a similar size controlled building, such as a library building, an office building, a motel, etc., (without opening windows), using a central air-conditioning system, better indoor thermal conditions of a building with thermal mass in its structure, envelope and partition, could have a positive impact on the energy efficiency for the cooling during the summer.

According to the field study data of indoor microclimate of the ten classrooms in Avondale College during the school team with students, with the impacts of natural window ventilation and mechanical ventilation, the fluctuations of indoor temperatures of the classrooms without thermal mass in their structures, envelopes and partitions were still larger than the fluctuations of indoor temperatures of the classrooms with thermal mass in their structures, building envelopes and partitions. Although the indoor mean temperature (24.9°C) of the classrooms D8 and D9 without thermal mass in their structures was not higher than the indoor mean temperature (25.3°C) of the classrooms A15, A32, A35, A21, A39, A24, A44 and D21 with thermal mass in their structures (with or without thermal mass in their building envelopes and with or without thermal mass in their partition), the percentages of time in the classrooms D8 and D9, when the indoor mean temperatures are higher 26°C, 27°C, 28°C, 29°C, 30°C and 31°C, are generally higher than the classrooms A15, A32, A35, A21, A39, A24, A44 and D21. With the same ventilation design, the indoor thermal conditions of the school buildings with thermal mass are generally better than the conventional school without thermal mass during the summer school team. Not only for the local school buildings but also for other types of free-running buildings with a similar size, using ceiling fans as an only thermal control method, the better summer thermal performance of a building with thermal mass in its structure, envelope and partition, could have a positive impact on indoor thermal comfort during the summer.

According to the field study data of testing indoor surface temperature and testing indoor thermal conditions at the seating height in the middle of the classrooms during the weekends without students, when the ceiling fans were on and the windows were opened, the indoor thermal conditions of the classrooms D9 and D21, with or without thermal mass in their structures, envelopes and partitions, can be maintained within the thermal comfort zone at the seating height for the sunny day, the indoor thermal conditions of the classrooms D9 was neutral and the classroom 21 was marginal slight cool. With natural window ventilation and ceiling fan mechanical ventilation, the thermal design of the school buildings with or without thermal in Avondale College can efficiently maintain indoor thermal comfort for the students during the summer.

According to the field study data, indoor air temperature, globe temperature and mean radiation temperature of the D21 were significantly lower than the D9 classroom. Without students' heat gain, the PMV value of the classroom D21 (-1.05, marginal slight cool) was clearly lower than the D9 (0.22, neutral) for the summer condition. With the natural window ventilation and the ceiling fan mechanical ventilation, a school building with thermal mass in its structures, envelope and partition, can provide better indoor thermal conditions to maintain the students' thermal comfort during the Auckland summer.

Acknowledgement

This work was supported by Jasmax, Nauhria and New Zealand Minister of Education's funding. The authors would like to thank Jerome Partington and Justin Evatt, who gave us help and support for the field studies.

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