Journal of Construction in Developing Countries, 19(1), 69–91, 2014

Indoor Air Quality in Adaptively Reused Heritage Buildings at a UNESCO World Heritage Site, Penang, Malaysia

*Rani Prihatmanti[1] and Azizi Bahauddin[2]

Abstract: This study investigated the Indoor Air Quality (IAQ) level in heritage buildings that have been adaptively reused as office buildings. These buildings are located within the vicinity of the UNESCO World Heritage Site in George Town, Penang. The aim of this study was to determine the IAQ level in the designated buildings using thermal monitoring and chemical and microbial tests. Mixed methods were used in this cross-sectional study to achieve the objectives. The IAQ tests variables were the temperature, relative humidity, air velocity, airborne pollutants (Particle Matter 10 [PM_{10}], carbon monoxide, carbon dioxide and formaldehyde), total bacteria count and total fungal count. These variables were adopted from the Industry Code of Practice on Indoor Air Quality, Department of Occupational Health Malaysia and the Malaysian Green Building Index–Non Residential Existing Building (NREB) rating tool. The measurements show that the IAQ level in the identified buildings was unacceptable within the standards stipulated. Dampness stains and mould were present in all buildings due to high humidity and moisture levels. It can be concluded that the IAQ level was due to inappropriate adaptive reuse practices, the occupants' activities and maintenance irregularities.

Keywords: Indoor Air Quality, Adaptive reuse, Heritage building, UNESCO

INTRODUCTION

In George Town, there are a number of heritage buildings that require preservation to prolong their lifespan. Some of these buildings are designated as national monuments by the Antiquities Act of 1976 based on their cultural significance and historic value. After being listed as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) in 2008, George Town is required to conserve all its heritage buildings. The conservation practices must adhere to the conservation principles that maximise retention and minimise intervention to retain their heritage significance (Australia International Council on Monuments and Site [ICOMOS], 1999; Worthing and Bond, 2008). The buildings located within the vicinity of the World Heritage Site have been adaptively reused for similar or different functions. Adaptive reuse is a conservation method that allows altering a building to suit a new or different usage. According to Bullen (2007) and Yung and Chan (2012), adaptive reuse is an effective way to improve sustainability by reducing the use of materials, transportation and energy, decreasing pollution and lowering carbon emissions. Moreover, altering an existing building for new uses could reduce costs compared to demolishing and rebuilding a new building. However, adaptive reuse can create several problems related to the indoor environmental quality, including the quality of the indoor air. Indoor Air Quality (IAQ) can be defined as the acceptable level of indoor air quality for which there are no known contaminants at harmful concentrations as determined by cognisant authorities and with which

[1]Department of Interior Architecture, Ciputra University, Surabaya, INDONESIA
[2]School of Housing, Building and Planning, Universiti Sains Malaysia, Pulau Pinang, MALAYSIA
*Corresponding author: rani.prihatmanti@ciputra.ac.id

a substantial majority (80% or more) of the people exposed do not express dissatisfaction (American Society of Heating, Refrigerating and Air Conditioning Engineers [ASHRAE] Standard 62, 2003). IAQ is currently a major issue for the built environment as well as businesses, tenants, building managers and employers and it directly impacts the building occupants' health, well-being, productivity and comfort during their occupancy period (Pilatowicz, 1995). The importance of IAQ is indicated by its inclusion as one of the major parameters for green building assessments worldwide, including the Leadership in Energy and Environmental Design (LEED), GBTool, Green Building Index (GBI) Malaysia, Building Research Establishment Environmental Assessment Method (BREEAM), Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) and the Green Mark Singapore tools. IAQ is one of the Indoor Environmental Quality parameters established by the Green Building Index (GBI) Malaysia.

The heritage buildings in George Town that have been adaptively reused as offices are also at risk for poor air quality. They were built based on the local climate by maximising passive design methods. However, as the climate changes, the building responses are variable, particularly the thermal conditions inside the buildings. These changes are known to create threats to heritage properties and occupants (Ahmad, 2004; Adams, 2007). Malaysians spend the majority of their time working indoors, which makes them vulnerable to hazardous indoor air pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde (HCHO or CH_2O) and other Volatile Organic Compounds (VOCs) during their working hours. These conditions may be more severe in air conditioned buildings where there is less air exchange inside the building, a condition that could directly affect the occupants' health and well-being. Therefore, the aim of this study was to determine the IAQ level in the identified buildings. The findings of this investigation provide valuable data for occupant comfort and well-being inside office spaces and for the study of heritage conservation in George Town.

Literature Review

Adaptive reuse of heritage buildings

According to UNESCO (1972), a heritage building can be defined as a legacy from a past man-made environment that represents cultural history and should be preserved for the next generation. Conserving heritage buildings helps to explain the past and contribute to future generations and it provides a sense of continuity and belonging to the place where people live. In Malaysia, buildings designated as heritage buildings are believed to be more than 50 years of age and should be preserved, protected and enhanced to prevent them from being lost forever (Malaysia National Heritage Act, 2005). However, the conditions of the heritage buildings in Malaysia are at risk from defects due to conservation knowledge inadequacy and high repair and maintenance costs (Ahmad, 1994; Kamarul et al., 2007).

As stated in the International Council on Monuments and Sites (ICOMOS) Burra Charter and the Malaysia National Heritage Act (Act 645), one possible method for conserving a heritage building is by adaptively reusing it. According to Dolnick and Davidson (1999, in Bullen [2007]), adaptive reuse is rehabilitating or renovating heritage buildings or structures for any uses other than the present uses.

Furthermore, adaptive reuse is a process to retain as much of the existing building as possible while upgrading its performance to suit modern standards and changing users' requirements. This option is beneficial for attracting developers who have transparent economic, environmental and social benefits as an aim in sustainable development (Bullen, 2007; Yung and Chan, 2012). By revitalising heritage buildings, the expectation is to bring back memories and to revitalise the vicinity. Newly vacant buildings are more likely to be reused than constantly vacant buildings, which impacts the adaptive reuse value of a designated building; the timeline is an important factor of the adaptive reuse potential (ARP) (Ball [1999] in Langston et al. [2008]). Kincaid (2002) described three types of possible adaptation in heritage buildings: adaptation for the same use plus ancillary uses, adaptation for mixed classes of use and adaptation for a totally new class of use. All these changes must be compatible with the new use. Moreover, the adaptation practices should involve the least amount of physical intervention, which could eliminate the embodied heritage significance and its authenticity. The practice of minimum intervention also applies to the building fabric and all actions in place, such as additions, new buildings and changes in use (ICOMOS, 1999; Worthing and Bond, 2008). In this context, the identified buildings in this research are considered as adaptively reused buildings.

Indoor Air Quality (IAQ) in office buildings

As stated previously, the preservation of heritage buildings is strongly encouraged to extend the lifespan of the buildings with the least amount of intervention. Being occupied is the simplest way to maintain the economic, social and environmental viability of a building. The occupants' activities, information technology, global competition, environmental concerns, new organisational structures, flexible employment arrangements and a variety of working practices have caused existing buildings to change to suit the occupants' demands, particularly in interior spaces (Kincaid, 2002). In the past, heritage buildings were purposely built to adapt to the local climate. To ensure occupant comfort, Mechanical Ventilation and Air Conditioning (MVAC) systems were installed. Unknowingly, these changes have resulted in negative impacts to the quality of indoor air by trapping pollutants. Pollution is consistently two to five times greater indoors than outdoors and indoor pollutant levels are often 100 times greater than outdoor levels (Pilatowicz, 1995; Environmental Protection Agency [EPA], 1997; Hess-Kosa, 2002). To meet occupant demands, office environments are provided with a variety of furnishings and equipment. However, these furnishings and equipment are likely to emit harmful indoor contaminants, as stated in Table 1. The occupants themselves are included as one of the pollutant sources. The EPA (1997) states that particles of dust, dirt or other substances may be drawn into a building from outside or from the activities inside the building. In indoor spaces, the primary source of CO_2 is from the human respiratory system, especially in overpopulated rooms, confined space or high activity areas (Hess-Kosa, 2002).

Table 1. Possible Contaminant in an Office Environment

Possible Contaminant Sources	Pollutant Type
Paint, glue, plastic, wood preserver, air freshener, cleaning solution, dry cleaning solution, perfume, solvent, resin, plastic foam	Organic gases, vapours, VOC (xylene, toluene, perchloroethylene, benzene, styrene, 1,1,1-trichloroethane, methyl ethyl ketone, alcohol)
Paints, glue, Environmental Tobacco Smoke (ETS), acid hardening lacquer, processed wood product	Formaldehyde (Urea formaldehyde: UF and phenol-formaldehyde: PF), other aldehydes
Plastic, wallpaper, vinyl tile	Phthalates, Poly Vinyl Chloride (PVC), Styrene
Impregnated wood	Fluorides
Occupants, unvented combustions	CO_2
Paints	Lead (Pb), mercury, amino
Copy machines, electronic cleaners	Ozone (O_3), VOCs, SVOCs
Papers, textiles	Organic dust
Acoustic ceilings, insulations, gypsum board	Man-Made Mineral Fibres (MMMF), calcium sulphate
Outdoor dirt, building materials	Inorganic dust, lead
Disinfectant	Alcohol, quarternary ammonium compound (QAC), phenol
Pesticide	Chlordane, aldrin, diedrin, heptachlor
Dust mites, moulds, danders, plants, occupants	Biological dust, metabolic product of microorganisms

Source: Maroni, Seifert and Lindvall (1995); Mendler and Odell (2000); Destaillats et al. (2008); Doren (2008)

According to Apte, Fisk and Daisey (2000) (as cited in Syazwan et al., 2009), the concentration of CO_2 in old buildings is higher due to the poor ventilation rate. A study by Syazwan et al. (2009) shows that the concentrations of indoor air pollutants, including CO, CO_2, Total Volatile Organic Compound/TVOC, Particulate Matter/PM_{10} and $PM_{2.5}$, are also significantly higher in older buildings than in newer buildings. CO and CO_2 are known to be strongly related to ventilation inadequacy. Therefore, CO_2 is a key parameter for assessing IAQ and ventilation efficiency. In addition to CO and CO_2, VOCs and Semi Volatile Organic Compounds (SVOCs) are also common indoor pollutants emitted from furniture, finishes, office stationery, mould and many other sources. Another important indoor contaminant commonly detected in office environments is particulate matter. According to the definition, "particles are solid or liquid substances that are light enough to suspend in the air" (EPA, 1997). Smaller particles have a greater chance of being inhaled and deposited in the human respiratory system. Particles, which are easily inhaled, are generally less than 10 µm (PM_{10}). A study by Destaillats et al. (2008) found that ultrafine particles and VOCs were emitted by laser printers and copiers that are operated during office hours. Printers and copiers are known to emit more VOCs, particularly toluene, styrene, benzene and alkyl benzene, than computers. However, computers are long-term sources of

VOCs and SVOCs. These chemicals can also be emitted by paper during printing and copying (Wolkoff et al. [1993] in Destaillats et al. [2008]).

Thermal comfort factors, mainly air temperature and humidity, are categorised as the physical indoor air and are crucial in the prevalence of Sick Building Syndrome (SBS) (Syazwan et al., 2009). A low air velocity indicates insufficient ventilation and a low air exchange rate in an indoor space. An insufficient ventilation rate and exposure to indoor contaminants could negatively impact the health of a building's occupants and contribute to Sick Building Syndrome (SBS), Building Related Illness (BRI) and Multiple Chemical Sensitivities (MCS). Based on previous research, SBS is a critical issue in Malaysia due to the installation of MVAC systems and maintenance irregularities associated with them. These factors result in an increase in the indoor air pollutant level (Syazwan et al., 2009). Further, SBS is more commonly found in mechanically ventilated buildings (Hummelgaard et al., 2007; Syazwan et al., 2009). Increasing the ventilation rate per person could significantly reduce the prevalence of SBS. The symptoms of SBS are generally non-specific and predominantly occur as (1) sensory irritation of the upper respiratory system (eyes, nose and throat), (2) neurotoxic or general health problems, (3) skin irritation, (4) non-specific hypersensitivity reactions and (5) odour and taste sensations (Godish, 2000; Syazwan et al., 2009).

Heritage buildings in tropical countries are at a high risk of deterioration by microbial agents, such as fungi and bacteria, which are significantly related to moisture content. Based on the study by Ahmad (1994), high moisture levels induce fungal growth, which is known to be one of the most common building defects in heritage buildings (51.9%). Dampness in the building fabric creates visible damp stains and could indicate the emergence of mould, particularly *Aspergillus*, *Penicillium*, *Stachybotrys*, *Altenaria* and *Cladosporium* species, dust mites, mildew and bacteria, which can result in allergic reactions, infectious health outcomes and other adverse health effects. Mould can proliferate in damp fabric at room temperature from airborne fungal spores. Even low water conditions (a_w) are suitable for the growth of microbial agents, such as bacteria and fungi, particularly gram-negative bacteria that is harmful to occupants (Storey et al., 2004; Mudarri and Fisk, 2007; Cabral, 2010). Godish (2000) and Storey et al. (2004) showed that mould can grow given adequate conditions of moisture, nutrition, such as building fabric and furnishings, light, oxygen and temperature.

METHODOLOGY

The main goal of this cross-sectional study was to determine the IAQ levels in the identified buildings based on air quality tests. Five heritage office buildings were chosen for the case study based on feasibility and accessibility to the associated premises. A walk-through inspection and site observation were also conducted to identify visible pollutant sources. To verify the presence of fungal contamination on a surface, swab sampling was performed.

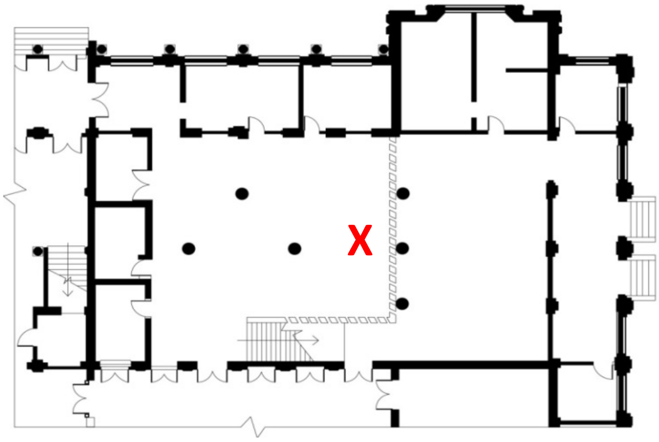
Walk-through Inspection and Site Observation

A walk-through inspection and site observation were performed as a preliminary survey before conducting the IAQ sampling. The observation focused on factors in the surrounding area, including the location, orientation, external pollutants, external water sources and building envelope and factors on the inside of the occupied buildings such as the potential pollutant sources emitted inside the buildings, the building layout after being adaptively reused, the density and activity of occupants, the office equipment used, the presence of indoor vegetation, water features, the position of openings, interior furnishings and furniture, evidence of water damage and the level of custodial care. Characteristics of the MVAC systems, including the type, position, location of the outdoor unit, grilles, diffusers, AHU and the thermostat controller, were also inspected. The observation data were used to support the air sampling results.

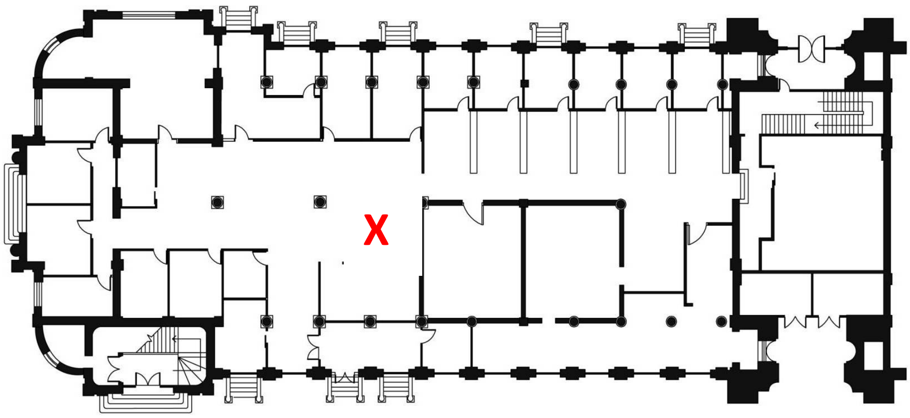
Indoor Air Quality Measurements

The IAQ assessments were conducted according to the guidelines from the Industry Code of Practice on Indoor Air Quality (COP-IAQ), Department of Occupational Safety and Health, Malaysia in 2010, during peak business hours from 9 a.m. to 5 p.m. for a total of eight hours of working time. The peak office hours were chosen as the sampling period because occupants in the respective buildings were actively working during this period. The thermal comfort data logger was set to record the thermal data at a one-minute interval during office hours. This method was also used by Daghigh, Sopian and Moshtagh (2009) to capture the range of the indoor climate during the working hours in a day. The installed probes measured the dry bulb temperature, air velocity and relative humidity. Because this study focused on the IAQ in office buildings, samples were taken in an air conditioned room where occupants' were prone to SBS and other building-related illnesses. Sampling apparatuses were positioned at the centre of the work place at the height of the breathing zone, approximately 110 cm from the floor. The positions of the sampling apparatuses are marked with an X in Figure 1 (a–e).

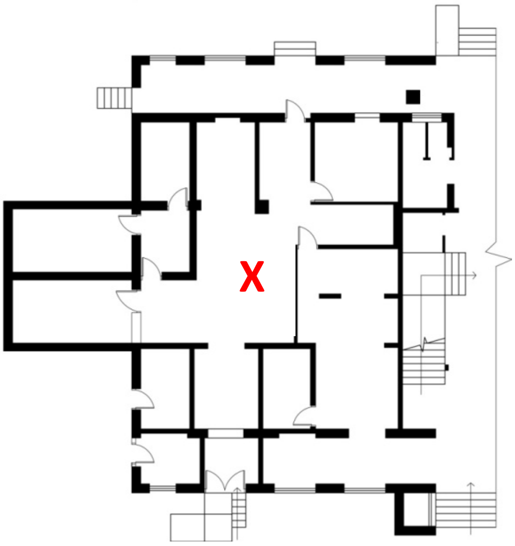
The air sampling variables were divided into three categories: physical, chemical and biological. These variables were adopted from the Industry Code of Practice on Indoor Air Quality (COP-IAQ), Department of Occupational Safety and Health, Malaysia (2010). The measured physical variables were the thermal condition (air temperature, relative humidity and air velocity) and the concentration of particulate matter 10 µm (PM_{10}) or dust. The thermal condition was measured using a BABUC/A data logger with detachable probes. PM_{10} was directly read from an aerosol monitor 8520 Dust Track. The measured chemical variables included CO, CO_2 and formaldehyde. An 8554 TSI Indoor Air Quality meter was used to measure CO and CO_2 and an HAL-HFX 105 Formaldehyde meter was used to measure the concentration of formaldehyde in the identified buildings.



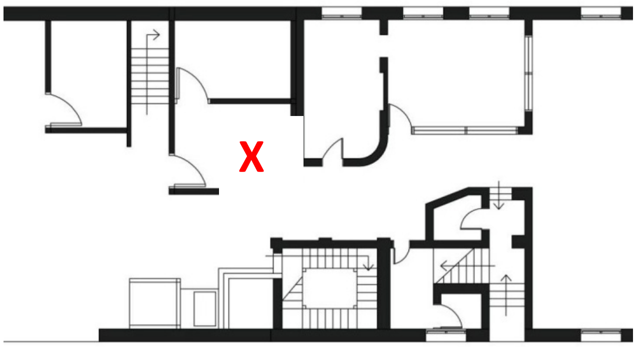
a. The City Hall



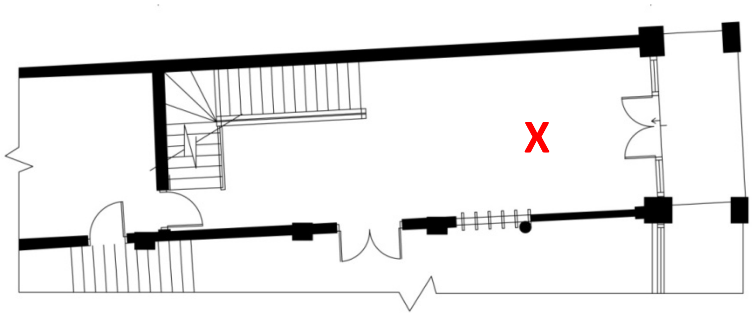
b. The Penang Islamic Religious Department (JHEAIPP)



c. The Penang Immigration Department



d. The Fire Brigade and Rescue Station



e. The George Town World Heritage Incorporated (GTWHI)

Figure 1. Position of the Sampling Apparatuses

To determine the level of biological pollutants, microbial sampling was performed through air sampling and swab testing. An Andersen N-6 single stage air impactor and agar plates were used to withdraw indoor air. This method is widely used to sample viable and culturable mould spores. Malt Extract Agar (MEA) and Potato Dextrose Agar (PDA) were chosen as the growth media due to their ability to isolate, cultivate and enumerate moulds and bacteria. The microbial sampling time depends on the conditions of the indoor environment. For a normal office, the sampling time is three minutes with a flow rate of 16.45 litres of air/minute. Extended sampling times may result in oversampling and a loss of viability. Samples were sealed and incubated at room temperature under artificial lighting for three days. The colonies were quantified 24 hours after sampling until the third day using the standard formula for enumerating airborne colonies on an agar plate. To confirm any unidentified fungal growth, swab sampling was also conducted. Swab sampling, or surface sampling, is a non-destructive technique and the most convenient method for surface sampling of possible microbial contamination because it uses sterilised cotton swabs and agar plates. The instruments were calibrated and pre-tested before the sampling was conducted.

SELECTION OF ADAPTIVE REUSE CASES

There are several heritage buildings in George Town; however, studying all of them is not possible or feasible. Thus, this research was conducted in five buildings within the UNESCO World Heritage Site in George Town. These buildings were chosen based on their similar building materials, MVAC systems, which are more than 50 years of age, communality activities and government agency occupancy (Figure 2 [a–e]). According to the Regulations for Conservation Areas and Heritage Buildings established by the Penang Municipal Council, buildings that are categorised as Category 1 are of exceptional interest and are recognised by the Malaysian Antiquities Act 1976. Therefore, the original character and fabric of these buildings must be maintained and no external or internal changes are allowed. Category 2 buildings are of special interest and should be preserved. Internal alterations and extensions on the sides and rear of these buildings are permissible.

a. City Hall

b. The Penang Islamic Religious Department (JHEAIPP)

c. The Fire Brigade and Rescue Station

d. Penang Immigration Department

e. The George Town World Heritage Incorporated (GTWHI)

Figure 2. The Selected Case Studies

1. The City Hall: Esplanade
   This grand building was constructed between 1900 and 1903 and was a British administrative office. To prevent its abandonment, this building is currently occupied by the Penang Municipal Council. Due to its heritage significance, this building is designated as a national monument by the Antiquities Act of 1982 and as a Category 1 building.

2. The Islamic Religious Department: Beach Street
   This double storey building is located on Beach Street and Downing Street and was erected in 1907 as the last extension of government offices during the period of British settlement. This refurbished building is currently occupied by the Islamic Religious Department. Due to its significance, this neo-classical building is listed as a Category 2 building by the state regulation for heritage building conservation.

3. The Penang Immigration Department: Beach Street
   The Penang Immigration Department was built in 1890 to house the administrative office of the police force that is within the same compound as the Central Police Station. This double storey building is located at the corner of Beach Street and Light Street. Because of its cultural significance, history and antiquity, this neo-classical building is designated by the state government as a Category 2 heritage building.

4. The Fire Brigade and Rescue Station: Beach Street
   In 1908, the fire fighter's building on Beach Street was constructed. This building is still used for its original purpose and its architecture remains intact to preserve the early streetscape of George Town. Due to its authenticity, cultural significance artistic value, historic value and setting, this building is considered as a national heritage building according to the Antiquities Act of 1976 and as a Category 1 heritage building based on the state regulation for heritage building conservation.

5. The George Town World Heritage Incorporated: Acheh Street
Unlike other buildings, the GTWHI building was originally two double storey shop houses for commercial-cum-residential purposes. It is located at the corner of Acheh Street and Armenian Street. It was built in the 1920s and is listed as a Category 2 heritage building in George Town. Currently, this building is occupied by the heritage management office.

RESULTS AND DISCUSSION

Site Observation

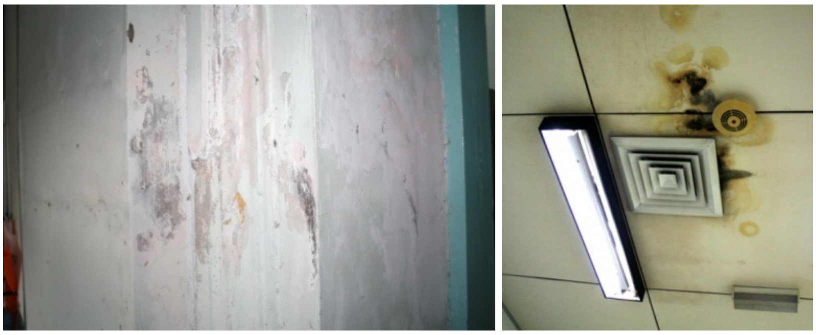
The UNESCO World Heritage Site in George Town is located on the north end of Penang Island. Its location near the sea affects the ground water level and salinity. These conditions put the heritage buildings at risk of deterioration due to moisture problems. Moisture is the greatest enemy of buildings because it can cause dampness in the building envelope and internal walls. Based on the site observations, dampness was prevalent in the identified buildings (Figure 3). Dampness triggers the growth of fungi and other microbial agents that can degrade air quality. Fungal stains were also observed on the building fabric of the identified buildings (Figure 4).

a. Penang Immigration Department

b. City Hall

c. The Penang Islamic Religious Department (JHEAIPP)

Figure 3. Dampness on Building Fabric



a. Penang Immigration Department

b. Fire Brigade and Rescue Station

Figure 4. Visible Fungal Stains

The peeling and crumbled paint also indicated fungal activity. Fungi are highly erosive and they can live under low water activity (a_w) conditions. They are strongly enzymatic and can cause the decay of plaster, lime, paint, stone and mortar in the exterior and interior of a building. They also degrade the organic binders in paints, causing the reduction and loss of paint layers (Sterflinger, 2010).

In this study, peeling paint was noticed in some of the buildings, particularly on the building columns (Figure 5).

a. The George Town World Heritage Incorporated (GTWHI)

b. Penang Immigration Department

Figure 5. Peeling Paint

In addition to dampness and fungal spores, salt crystallisation also contributes to indoor air pollution. Hygroscopic salt, or salt weathering, is commonly related to moisture problems in buildings and it occurs when salt remains intact on a wall after the moisture has evaporated. After time, materials decay by fretting, crumbling and loss of the surface. In this study, salt weathering was observed in almost all of the identified buildings (Figure 6).

a. City Hall

b. The Penang Islamic Religious Department (JHEAIPP)

Figure 6. Salt Crystallisation on Building Fabrics

Another visible pollutant discovered during site observation was dust. It was mostly accumulated in the mechanical ventilation system (air conditioner diffusers and fan blades), on the architectural ornaments such as cornices and mouldings and on open shelves (Figure 7). The classical architectural ornaments act as dust harvesters due to a lack of maintenance in each building. The amount of dust is based on the housekeeping practices in a building. Dust particles in damp spaces may contain harmful biological agents, particularly *Altenaria* and gram-negative bacteria (Cabral, 2010).

a. City Hall

b. The Fire Brigade and Rescue Station

c. The Penang Islamic Religious Department (JHEAIPP)

Figure 7. Accumulated Dust

Another significant observation that could affect the IAQ level was the obstruction of existing openings, windows and doors. Because they are adaptively reused, all of the identified buildings are equipped with MVAC systems and their interior spaces have been altered to meet the occupants' workspace requirements. These changes significantly affect the thermal conditions of air temperature, humidity and air velocity and the pollutant concentrations in the identified buildings. The building defects identified during the walkthrough inspections are tabulated in Table 2.

Table 2. Summary of the Building Defects in the Observed Buildings

Defects Founded	Observed Buildings				
	City Hall	**Islamic Religious Department**	**Fire Brigade and Rescue Station**	**Penang Immigration Department**	**GTWHI**
Dampness on building fabric	✓	✓	✓	✓	–
Visible fungal stains	✓	✓	✓	✓	–
Peeling paints	✓	✓	✓	✓	–
Salt crystallisation	✓	✓	✓	✓	–
Accumulated dusts	✓	✓	✓	✓	✓
Obstructed existing openings	✓	✓	–	–	✓

Notes: ✓ – Obviously detected

Based on Table 2, the City Hall and the JHEAIPP were designated as the poorest buildings in terms of their physical building defects, followed by the Fire Brigade and Rescue Station and the Penang Immigration Department. The GTWHI building was considered to be better than the other buildings. Nonetheless, the interior and exterior of any building must be maintained regularly to ensure that the building is healthy for its occupants and to prevent further deterioration.

The Indoor Air Quality Level

The IAQ sampling results show that the air temperature and the humidity recorded during office hours were not fully acceptable based on the benchmark (23 degree Celsius to 26 degree Celsius) for indoor air conditioned offices in Malaysia (Table 3). Both variables tend towards the unacceptable limit. In the City Hall and the Fire Brigade and Rescue Station, the air temperature exceeded the acceptable limit (27.5 degree Celsius to 29.7 degree Celsius and 28.8 degree Celsius to 30.2 degree Celsius) and the air velocity in all studied buildings was similarly low. This condition is mainly caused by the blockage of openings, the presence of full height partitions that obstruct airflow and the occupants' activities. However, measurements from air conditioned rooms will be different from those taken in naturally ventilated rooms. The indoor temperature may be more unacceptable if the air velocity is low. Furthermore, low air velocities may induce the prevalence of building-related illnesses and contribute to the discomfort of occupants.

According to COP-IAQ (2010) the acceptable limit for indoor humidity in the Malaysian climate is 40%–70%. This range was also emphasised by Godish (2000) and a maximum limit for indoor humidity of 70% was stipulated in the Malaysia Green Building Index (2010). Humidity levels above this maximum limit are considered ideal for the growth of mould spores. Moreover, a study conducted by Bayer (1990, in Syazwan et al. [2009]) stated that SBS might occur in indoor spaces with insufficient ventilation as a result of high temperatures and humidity levels. Nevertheless, the physical variables of air quality in a building may fluctuate over time depending on the local climate and the occupants.

Table 3. IAQ Sampling Result

Variables	**Units**	**Buildings**					**Bench-marks**
		City Hall	**JHEAIPP**	**Fire Brigade and Rescue**	**Penang Immigration Department**	**GTWHI**	
Physical							
Temperature	°C	27.5–29.7	24.2–25.9	28.8–30.2	23.6–25.7	24.1–27.5	*23–26*
RH	%	56.2–74.0	59.4–70.1	60.7–71.7	57.1–75.0	51.8–65.7	*40–70*
Air velocity	m/s	0.01–0.17	0.01–0.35	0.01–0.2	0.01–0.17	0.01–0.22	*0.1–0.5*
Chemical							
PM_{10}	mg/m³	0.08	0.04	0.23	0.11	0.12	*0.15*
CO	ppm	0	0	0	0	0	*10*
CO_2	ppm	716	698	549	1,666	586	*1000*
HCHO	ppm	0	0	0.01	0.06	0.01	*0.1*
Microbial							
Total fungal count	cfu/m³	486.8	101.3	628.2	810.5	405.3	*500*
Total bacteria count	cfu/m³	303.9	283.7	263.4	202.6	729.5	*1000C*

Notes: Benchmarks are referring to COP-IAQ 2010 ; C is the ceiling limit and shall not be exceeded at any time

Based on the observation data, dust or PM_{10} was prevalent in all the buildings. Based on the air quality test, PM_{10} was detected at various levels in all the building. However, in the Fire Brigade and Rescue Station, the reading was significantly higher (0.23 mg/m³) than the benchmark (0.15 mg/m³). In the other buildings, the PM_{10} levels were within the acceptable limit. High levels of PM_{10} can be caused by several factors, such as the adjacency of a building to a surrounding road, irregularities in housekeeping practices, occupant activities inside the building, the building size and the airflow speed. However, in the Fire Brigade and Rescue Station, the high level of PM_{10} was mainly due to irregularities in housekeeping practices. The presence of PM_{10} in indoor environments should be taken into account because it can affect the health of a building's occupants. High levels of dust, particularly dust containing organic material, may also affect occupant health by contributing to allergies, asthma and other health disturbances (Storey et al., 2004). PM_{10} is emitted by operating printers, including laser printers, ink-jet printers and all-in-one office machines (Destaillats et al., 2008).

CO, CO_2 and formaldehyde (HCHO) are categorised as chemical indoor pollutants that are commonly found in indoor spaces. CO is a light, colourless and odourless gas that occurs with the incomplete combustion of materials such as kerosene, gasoline, fuel and plastic. Unfortunately, in all the buildings studied, the presence of CO was undetected by the direct reading instrument during the air sampling period mainly due to the sensitivity of the instrument. Like CO, CO_2 is a combustion-generated contaminant that is related to the presence of humans and their respiratory metabolism products. The concentration of CO_2 in indoor spaces increases as the occupant density increases and when there is exposure to outdoor air (Kubba, 2009). The CO_2 test results show that in the Penang Immigration Department, the level of CO_2 exceeded the acceptable limit (1,660 ppm). The presence of high CO_2 level was possibly due to the number of occupants and the poor ventilation rate in the associated building. Based on the air velocity monitoring, the flow of indoor air in the Penang Immigration Department was very low (0.01–0.17 m/s). The last chemical parameter tested was formaldehyde (HCHO), a VOC from the aldehyde group. This chemical is widely used in indoor environments and is a common irritant of the eyes, nose, throat and sinuses at a low concentration of only 0.03 ppm (Godish, 2000; Bingelli, 2006).

Formaldehyde is easily detected in a newly refurbished environment in which the paints and finishes have been recently applied. Because this study was conducted in heritage buildings that are more than 50 years old, formaldehyde was detected in only three buildings: the Fire Brigade and Rescue Station, the GTWHI building and the Penang Immigration Department. The concentration of formaldehyde in the Penang Immigration Department was the highest of all the buildings at 0.06 ppm. Based on observations of the Penang Immigration Department, several potential sources of formaldehyde, including particle board, which was the main desk material, copy machine ink, toner and office stationery., The indoor ventilation rate, the building size and office activities that involve printing and copying also affected the formaldehyde concentration in the designated building. Destaillats et al., (2008) showed that office equipment decreases indoor air quality because it is a source of VOCs, ozone and PM. Formaldehyde is included as one of the VOCs. Moreover, the presence of offices with an open floor plan in the studied building also influenced the indoor air quality. Pollutants accumulate more easily in an enclosed office compared to an office with an open floor plan. However, in the City Hall and the Islamic Religious Department, formaldehyde was undetected. This result is most likely due to the size of the buildings compared to the other three buildings. Because formaldehyde is a volatile chemical at room temperature, detecting this gas in a spacious indoor environment is difficult.

During the site observations, damp stains were discovered on the internal building fabrics. These stains must be verified to determine their ability to harbour microbial growth. Swab tests were performed on the suspected building fabrics and on the air-conditioner diffuser or outlet in all of the identified buildings. The results show that the suspected stains and the air-conditioner outlets were positively contaminated by fungi (mainly *Aspergillus* and *Penicillium*), yeast and bacteria. The presence of microorganisms on the building fabrics and in the air-conditioner units was related to the quantity of bio-aerosols in the air, as indicated by the total fungal counts and the total bacteria counts. The total fungal counts were greater than the acceptable limit for the City Hall, the Penang Immigration Department, the GTWHI building and the Fire Brigade and Rescue Station. The Fire Station showed the greatest amount of airborne fungal spores at 682 cfu/m^3. Fortunately, the airborne bacteria counts were all under the maximum limit. Crook and Burton (2010) reported that although some of buildings may be within the safe level, exposure to biological agents in an indoor space is a significant factor in microbial contamination and could contribute to SBS and other building-related disease.

CONCLUSIONS

George Town is in the midst of preserving its heritage buildings to retain the UNESCO World Heritage Status. Adaptive reuse and occupancy are the most economically, socially and environmentally beneficial ways to use a heritage building. However, alterations to meet modern standards and occupant requirements have adversely impacted the quality of the air inside the heritage buildings in George Town. People spend approximately 90% of their time indoors, which makes them prone to health impairment due to indoor pollutants. This study measured air quality levels in adaptively reused heritage buildings during office hours.

The findings show that the indoor air quality levels in the identified buildings were below acceptable standards. High air temperatures, high humidity levels and damp fabrics accelerate the growth of biological agents, resulting in a large number of airborne spores. The presence of fungi and other microbial agents could be a useful indicator in determining indoor air quality. The inappropriate adaptive reuse of heritage buildings was shown to affect the quality of indoor air, which could lead to health disturbances such as SBS and other building-related illnesses. However, the magnitude of the emissions of any indoor pollutants depends on multiple factors such as inadequate ventilation, pollutant sources, poor maintenance, MVAC installation, water intrusion and occupant activity. To decrease the number of microbial agents, a prompt remediation strategy must be executed to achieve acceptable indoor air quality levels and to prevent SBS.

The studied buildings could be ranked according to their IAQ measurements and assessed based on the similarities of their uses. The Penang Immigration Department had the poorest IAQ in general, followed by the GTWHI building and the Fire Brigade and Rescue station. The Islamic Religious Department had better IAQ test results than the other buildings. The Penang Immigration Department was designated as the building with the poorest IAQ based on defects discovered during the site observation. For example, black mould stains were observed on the ceiling and surrounding the air conditioner diffusers, resulting in an excessive number of fungal colonies. Further, the air velocity rate was the lowest among all the buildings; formaldehyde was detected; and the CO_2 level exceeded the acceptable limit. Thus, it was concluded that the occupants of the Penang Immigration Department were highly prone to suffer from building-related illnesses caused by poor IAQ.

Despite the building defects, such as salt crystallisation, the JHEAIPP had better IAQ levels compared to the other buildings. The PM_{10} and total fungal count levels were the lowest among all the buildings. Furthermore, formaldehyde was not detected. These results were affected by the building size and the ventilation rate. The JHEAIPP was categorised as large building. Although this building is small and densely occupied like the Penang Immigration Department, the ventilation rate must be increased.

The rank order determined from the observations and that based on the IAQ measurements differed in some cases. Thus, it was concluded that the physical condition of a building does not singularly affect IAQ measurements. Many factors can affect the measurements, including a building's size (large, medium or small sized building). Therefore, further research is needed to determine the IAQ of heritage buildings based on building size.

REFERENCES

Adams, J. (2007). Global climate change: Every cultural site at risk? In *Heritage at Risk 2006/2007*. Paris: International Council on Monuments and Site. Available at: http://www.international.icomos.org/risk/world_report/2006-2007/pdf/H@R_2006-2007_50_Special_Focus_GCC_Every_Site_Risk.pdf [Accessed on 12 October 2010].

Ahmad, G. (2004). Understanding common building defects. *The Dilapidation Survey Report*. Available at: http://www.hbp.usm.my/conservation/DilapidationSurvey.htm [Accessed on 18 March 2010].

———. (1994). *Why Buildings Decay*. Paper presented at E & O Hotel, Penang, Malaysia, 11 December. Available at: http://www.hbp.usm.my/conservation/SeminarPaper/DECAY.html [Accessed on 18 March 2010].

American Society of Heating, Refrigerating and Air Conditioning Engineers Inc. (ASHRAE). (2003). *Standard 62: Ventilation for Acceptable Indoor Air Quality*. Atlanta: ASHRAE.

Apte, M.G., Fisk, W.J. and Daisey, J.M. (2000). Indoor carbon dioxide concentrations and SBS in office workers. *Proceedings: Proceedings of Healthy Buildings 2000. Vol. 1*. Available at: http://www.google.com.my/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CB8QFjAA&url=http%3A%2F%2Fsenseair.hemsida.eu%2Fwp-content%2Fuploads%2F2011%2F05%2F6.pdf&ei=YuaoU_LgHYSiugSUr4DwBw&usg=AFQjCNFlR33G3eyLcehQZI7wEfEZBLTdxg&sig2=8vo9yBt43unL09Tla2co8A&bvm=bv.69620078,d.c2E.

Australia International Council on Monuments and Sites (ICOMOS). (1999). The *Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance*. Victoria: Australia ICOMOS Inc.

Ball, R. (1999). Developers, regeneration and sustainability issues in the reuse of vacant industrial buildings. *Building Research and Information*, 27(3): 140–148.

Bayer, C.W. (1990). Maintaining optimum indoor air quality. *Journal of Property Management*, 55: 37–40.

Bingelli, C. (2006). *Building Systems for Interior Designer*. New York: John Wiley and Sons Inc.

Bullen, P.A. (2007). Adaptive reuse and sustainability of commercial buildings. *Facilities*, 25(1): 220–231.

Cabral, J.P.S. (2010). Can we use indoor fungi as bioindicators of Indoor Air Quality?: Historical perspectives and open questions. *Science of the Total Environment*, 408(20): 4285–4295.

Crook, B. and Burton, N. (2010). Indoor moulds, Sick Building Syndrome and building related illness. *Fungal Biology Reviews*, 24:106–113.

Daghigh, R., Sopian, K. and Moshtagh, J. (2009). Thermal comfort in naturally ventilated office under varied opening arrangements: Objective and subjective approach. *European Journal of Scientific Research*, 26(2): 260–276.

Department of Occupational Safety and Health. (2010). *Code of practice on Indoor Air Quality 2010.* Malaysia: Ministry of Human Resources. Available at: http://www.dosh.gov.my/doshV2/index.php?option=com_contentandview=articleandid=284%3Aindustry-code-of-practice-on-indoor-air-quality2010andcatid=38%3Aslideshowandlang=en [Accessed on 27 February 2011].

Destaillats, H., Maddalena, R.L., Singer, B.C., Hodgson, A.T. and McKone, T.E. (2008). Indoor pollutants emitted by office equipment: A review of reported data and information needs. *Atmospheric Environment*, 42(7): 1371–1388.

Dolnick, F. and Davidson, M. (eds.) (1999). A glossary of zoning, development and planning. *Terms, Planning and Advisory Service Reports Number 491/492*. Chicago: American Planning Association.

Doren, J. (2008). *Indoor Air Pollution: A Toxic and Hidden Threat to the Safety of Our Homes*. Colorado: Phantom Creek Publishing.

Godish, T. (2000). *Indoor Environmental Quality.* Florida: CRC Press.

Hess-Kosa, K. (2002). *Indoor Air Quality: Sampling Methodologies*. Florida: Lewis Publishers.

Hummelgaard, J., Juhl, P., Sœbjörnsson, K.O., Clausen, G. and Toftum, J. (2007). Indoor Air Quality and occupant satisfaction in five mechanically and four naturally ventilated open-plan office buildings. *Building and Environment*, 42(12): 4051–4058.

Kamarul S.K., Lilawati A.W., Ahmad, G. and Saipol B.A.K. (2007). *Understanding common building defects.* Paper presented at the *International Conference on Built Environment in Developing Countries*, Universiti Sains Malaysia, Pulau Pinang, 3–4 December. Available at: http://buildingconservation.blogspot.com/2007/12/understanding-common-building-defects.html [Accessed on 14 March 2011].

Kincaid, D. (2002). *Adapting Buildings for Changing Uses: Guidelines for Change of Use Refurbishment.* London: Spon Press.

Kubba, S. (2009). *LEED Practices, Certification and Accreditation Handbook.* Burlington, MA: Elsevier Inc.

Langston, C., Wong, F.K.W., Hui, E.C.M. and Shen, L-Y. (2008). Strategic assessment of building adaptive reuse opportunities in Hong Kong. *Building and Environment*, 43(10): 1709–1718.

Malaysia Green Building Confederation. (2010). *Malaysia Green Building Index*. Available at: http://www.greenbuildingindex.org/ [Accessed on 24 March 2010].

Maroni, M., Seifert, B. and Lindvall, T. (eds.) (1995). *Building Design for Good Indoor Air Quality*. Amsterdam: Elsevier Science B.V. Retrieved from http://www.buildingecology.com [Accessed 2 January 2009].

Mendler, S. and Odell, W. (2000). *The HOK Guidebook to Sustainable Design*. Canada: John Wiley and Sons, Inc.

Mudarri, D. and Fisk, W.J. (2007). Public health and economic impact of dampness and mould. *Indoor Air Journal*, 17(3): 226–235. Available at: http://www.heritagebuildings.com/green-buildings.html [Accessed on 7 March 2011].

Pilatowicz, G. (1995). *Eco-Interior: A Guide to Environmentally Conscious Interior Design*. New York: John Wiley and Sons Inc.

Sterflinger, K. (2010). Fungi: Their role in deterioration of cultural heritage. *Fungal Biology Reviews*, 24(1/2): 47–55.

Storey, E., Dangman, K.H., Schenck, P., DeBernardo, R.L., Yang, C.S., Bracker, A. and Hodgson, M.J. (2004). *Guidance for Clinicians on the Recognition and Management of Health Effects Related to Mold Exposure and Moisture Indoors*. Farmington, CT: University of Connecticut Health Center.

Syazwan, A.I., Juliana, J., Norhafizalina, O., Azman, Z.A. and Kamaruzaman, J. (2009). Indoor air quality and sick building syndrome in Malaysian buildings. *Global Journal of Health Science*, 1(2): 126–135. Available at: http://ccsenet.org/journal/index.php/gjhs/article/viewFile/3946-3482 [Accessed on 15 June 2010].

United Nations Educational, Scientific and Cultural Organisations (UNESCO). (1972). Paper presented at the *7th Session at General Conference, Convention Concerning the Protection of the World Cultural and Natural Heritage*. New York: United Nations. Available at: http://whc.unesco.org/archive/convention-en.pdf [Accessed on 15 November 2010].

United States Environmental Protection Agency. (1997). *An Office Building Occupants' Guide to Indoor Air Quality*. Available at: http://www.epa.gov/iedweb00/pubs/occupgd.html [Accessed on 22 October 2008].

Wolkoff, P., Wilkins, C.K., Clausen, P.A. and Larsen, K. (1993). Comparison of volatile organic compounds from processed paper and toners from office copiers and printers: Methods, emission rates and modeled concentrations. *Indoor Air*, 3(2): 113–123.

Worthing, D. and Bond, S. (2008). *Managing Built Heritage: The Role of Cultural Significance*. Oxford: Blackwell Publishing.

Yung, E.H.K. and Chan, E.H.W. (2012). Implementation challenges to the adaptive reuse of heritage buildings: Towards the goals of sustainable, low carbon cities. *Habitat International*, 36(3): 352–361. Available at: http://ac.els-cdn.com/S0197397511000877/1-s2.0-S0197397511000877main.pdf?_tid=c2df649c34bc695eab60b73c4d6cc4e5andacdnat=1340170044_c8872481ca326805712785f686f0d8cc [Accessed on 20 June 2012].