Development of a unique full-scale real-fire façade testing facility at IIT Gandhinagar

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Most modern buildings incorporate a façade system to conform to green building regulations. Several common façade systems utilize composite panels made of combustible materials and can significantly enhance the fire risk, as shown by many recent building fires. This study presents the development of a full-scale research facility at IIT Gandhinagar to better understand the behaviour of real fires involving façade systems. Such a facility will facilitate scientific studies pertaining to façade fires and help in improving fire safety of such buildings.

Keywords: Façade testing facility, green building regulations, leap frog effect, real-fire behaviour.

MANY modern commercial and residential buildings around the world utilize a façade system (curtain wall system or building envelop) to achieve better energy efficiency, reduce water and air infiltration, and improve aesthetics. Such green building technologies will have a major role in the upcoming 'smart cities' that have been recently announced by the Government of India. Many common façade systems utilize combustible materials such as aluminium composite panels (ACP) and medium/high-density fibre boards (MDF/HDF) which can become easy vehicles for the rapid spread of fire[1–3]. This inherent fire hazard of such façade materials has been exposed in several building fires in the past. The most recent major façade fire took place on 14 June 2017 in the Grenfell tower at London. The fire had initiated inside a room on the fourth floor and engulfed the whole building within no time. The entire façade of the building that utilized ACP, installed in 2015 at a cost of 12 million GBP, was burnt and caused severe injuries and many casualties apart from a significant economic setback and potential structural damage. Notable recent fires in India involving façade systems include those at AMRI Hospital (Kolkata, 2011), Lotus Business Park (Mumbai, 2014), a LED packaging office (Noida, 2017), a textile showroom (Chennai, 2017) and an office complex (Kolkata, 2017).

Façade systems in all such installations are usually certified for their fire performance using certain testing standards. These range from small-scale (e.g. NFPA 255, 259, 268; ASTM E84; UL 723; BS 476) to full-scale tests (e.g. ISO 13785; BS 8414; DIN 4102; NFPA 285; SP FIRE 105; CAN/ULC S134; GB/T 29416; ANSI FM 4880). Given the scale and intensity of recent façade fires involving such fire-rated materials, it is evident that the existing testing standards and fire ratings are not completely applicable in real-fire scenarios encountered by buildings. This disconnect between testing methods and the actual performance of façade systems during a fire is due to the lack of understanding of the basic fire spread behaviour and new materials being used in building envelopes. This has also been acknowledged in a recent report from the Fire Protection Research Foundation, USA[4], which aimed at studying all the available façade testing standards.

Recognizing this major gap in fire performance of façade systems, a full-scale real-fire façade testing facility has been developed at IIT Gandhinagar (IITGN) in collaboration with Underwriters Laboratories (UL). This facility involved construction of a G + 2-storey steel-frame building with three independent compartments at each level. There are three compartments of plan dimensions 10′ × 20′ at each level. A dog-legged stairwell comprising 23 steps is housed in a separate compartment isolated from all the three test compartments. The significance of such a test structure lies in similarities in the fire-spread mechanisms and overall façade behaviour in these full-scale tests and actual fires (Figure 1). Such a facility will enable realistic characterization and assessment of façade fire behaviour and is expected to bridge the gap between current testing standards and real-life fire performance of façade systems. It will also play an important role in developing detailed fire safety guidelines, specifically to the Indian context which presently do not exist. Given the significant increase in the number of buildings that use a façade system, studies pertaining to fire spread, egress and fire-fighting operations, that can be conducted at this facility, will play a key role in reducing loss of lives and property in future fire incidents.

The developed facility utilizes a steel load-bearing frame with eight columns (ISMB 600), two primary beams (ISMB 400) and nine secondary beams (ISMB 400) for each storey (Figure 2 *a*). Figure 2 *b* shows a construction snapshot of the structural frame. The beam and column joints are connected with connector plates through flexible end-plate connections. The eight steel columns are fixed to concrete pedestals at base level through ten high-strength friction grip (HSFG) M-30 foundation bolts with 20 mm thick column base plate.

Since this structure is primarily to be used to study fully developed room fires and their interaction with the

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Figure 1. ***a–c***, Fire incidents; ***a***, at Address hotel, Dubai; ***b***, at a textile showroom, in Chennai; ***c***, at a factory building, in Noida. ***d***, Test fire at the IITGN-UL experimental facility.

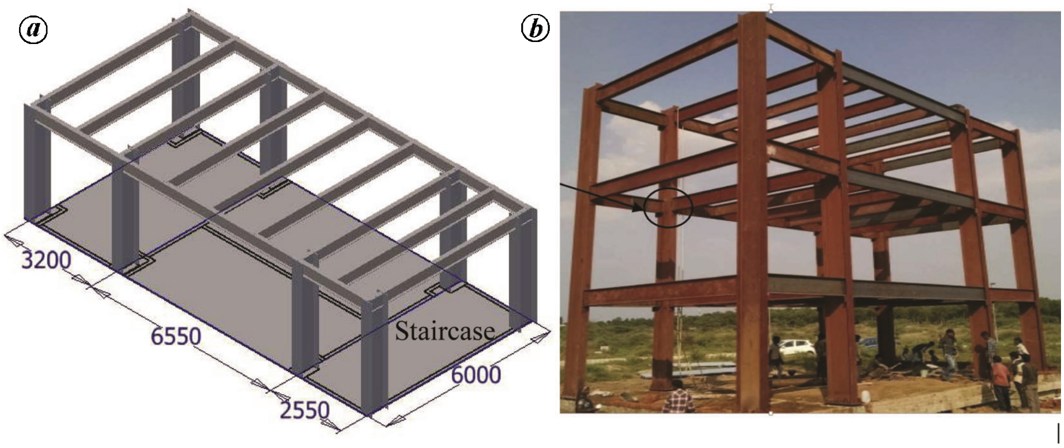

Figure 2. ***a***, Schematic of structural columns and beams for ground floor. Same layout is used for all floors. ***b***, Construction of steel structural frame for the test facility.

façade system, it is necessary to provide adequate fire protection to the structural system. The key purpose of fire protection is to prevent any damage to the main structural system so that multiple façade fire tests can be conducted. For fire protection, each column is enclosed in 115 mm (one brick) thick masonry chamber. These masonry enclosures are expected to provide a fire rating of more than 4 h according to IS 1642:1989 (ref. 5). An air gap is also provisioned between the steel columns and masonry protection to further enhance the efficacy of the fire protection system. Masonry walls are also utilized to partition the three fire compartments at each floor. Since the maximum duration of a test is not designed to exceed 1 h, these masonry fire partitions are adequate. Figure 3 *a* shows a schematic of the masonry protection and compartmentation, while Figure 3 *b* shows a construction snapshot. Figure 4 *a* shows a detailed schematic of the masonry fire protection provided for columns.

A 20 mm thick cement plaster (1 : 6) is also provided as additional protection to all the masonry walls. The plaster can experience significant spalling during fire tests and usually needs to be refurbished after each test. However, such an approach of using masonry as the main fire protection has been found to be economical instead of the conventional fire protection approaches based on commercially available rated fibre boards.

The deck slab at all floor levels is provided with 1 mm thick trapezoidal decking sheet (made of steel with yield strength of 250 MPa) overlaid with 75 mm of M25 grade concrete. The composite decking action is achieved through fasteners in the form of SDS screws of size 18 × 25 mm at a spacing of 300 mm c/c through the decking sheet onto the beams. The concrete incorporates an anti-cracking mesh consisting of 8 mm diameter Fe500 wires (Y8) at 230 mm c/c.

Fire protection of beams and deck slab is more involved. Providing a material like masonry for fire protection is challenging due to (a) its heavy weight and (b) difficulty in installation. A two-layer system of board protection, based on locally available materials, has been developed for fire protection of beams and deck slab. First, a layer of 12 mm thick plaster of Paris (POP) boards is used to cover the base of the deck slab (Figure 5), and all sides of flange and web of the beams

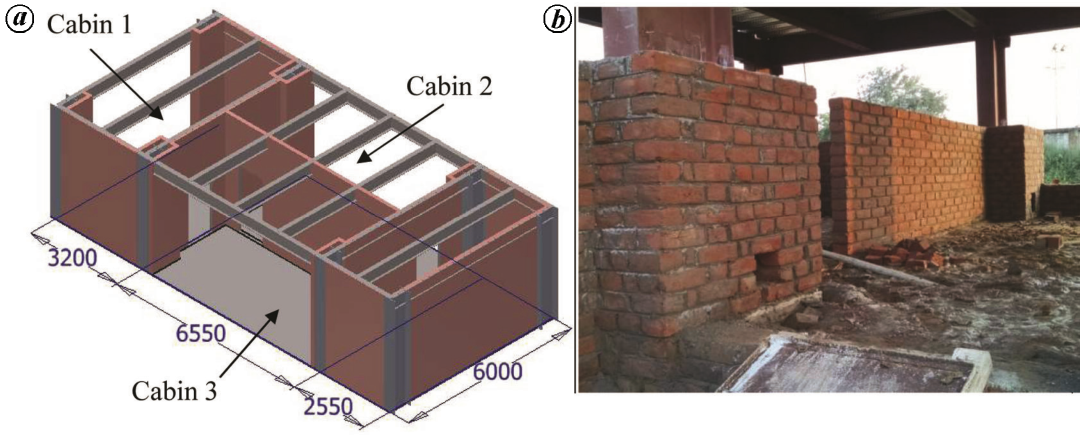

Figure 3. ***a***, Schematic of masonry protection for columns and partition walls. ***b***, Construction of masonry work. Openings are kept in each masonry enclosure to facilitate instrumentation.

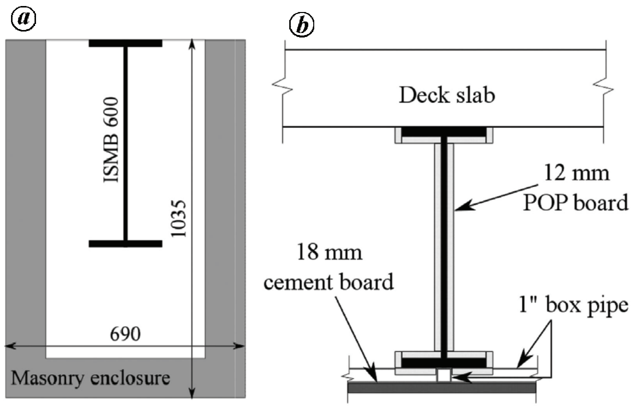

Figure 4. ***a***, Detailed schematic of masonry protection for steel column. ***b***, Detailed schematic of fire protection for steel girders.

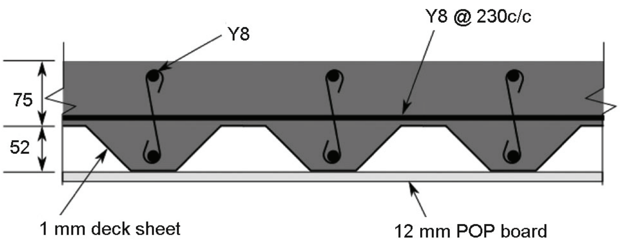

Figure 5. Schematic of construction and fire protection of deck slab.

(Figure 4 *b*). The gaps are sealed with POP paste. Next, a layer of 18 mm thick cement boards is provided as false ceiling, attached to the structural beams through 1″ mild steel (MS) square pipes (Figure 4 *b*). The cement boards are fixed to the MS pipes with SDS type 1″ screws provided at 8″ c/c distance. It is to be noted that the spacing of these screws plays a crucial role in the efficacy of the cement boards. It is also essential to seal all the gaps with POP (or equivalent material). As mentioned earlier, such a design of fire protection system with locally available materials is more economical when compared to the use of commercially available rated fibre boards.

For such fire protection installations, IS 1642:1989 (ref. 5) mentions that a board of thickness 12.7 mm will provide 30 min of fire rating. However, there is no discussion on the installation requirements. Given that the size of these boards is relatively large (typically 8′ × 4′), if the installation is not performed adequately, they cannot provide the rated fire performance. For instance, in one of the full-scale tests performed at the facility, where the boards were fixed with screws at a spacing of 20″, major failure of cement board protection was observed 25 min after fire ignition, which caused permanent thermal deformation of a small portion of the deck slab.

Fire doors (1.5 h UL-rated) are provided to allow passage between different fire compartments. These are single swing steel stiffened doors (stiffeners provided at 4 in spacing) of 16 gauge galvanized steel incorporating single point latches. The thickness of each door is 46 mm. Cavities of the door are filled with mineral wool to prevent transmission of smoke and hot gases during the tests. All door leaves are provided with vision panels of 100 square inch wired glass.

The facility is provided with an external fire hydrant system to enable efficient fire fighting as and when necessary. Underground mains are laid 1 m below the ground level. Hydrant stand post (single) with nominal pipe size 75 mm made of MS and having 80 mm flanged inlet and outlet, mouthed with standard 63 mm size hydrant valve is installed at a distance of 3 m from the face of the building. Fire brigade inlet having gunmetal body with three gunmetal male instantaneous inlets of size 63 mm (with non-return valve) and 100 mm size flanged outlet is connected to the dry riser piping. Fire brigade inlet body is also provided with drain valve. Internal hydrants are provided inside the building near the exit staircase area at each floor. One hose-reel arrangement is provided at every internal hydrant location. Galvanized iron pipes conforming to IS: 1239 (ref. 6) are used for the hydrant system.

The facility has been designed to simulate two types of typical fire spread behaviour observed in buildings that use a façade system: external spread and internal spread (Figure 6). The former mechanism often proceeds through the so-called leap-frog effect. Two faces of the test structure have the capability to simulate external spread mechanism while one face has been designed to simulate internal spread mechanism. Figure 7 provides typical details of façade installation.

Extensive instrumentation is provided within the test structure to facilitate the measurement of relevant quantities during the fire tests. Five types of data are collected during each test: structural and air temperatures (using *K*-type thermocouples), strain levels in structural beams, out-of-plane deformation of masonry partition walls (using linear variable differential transformer (LVDT)), video footage of each compartment, and temperature profile of the entire façade face (using infrared imaging camera).

Except for the infrared imaging camera, which is operated from outside the building, all other sensors are

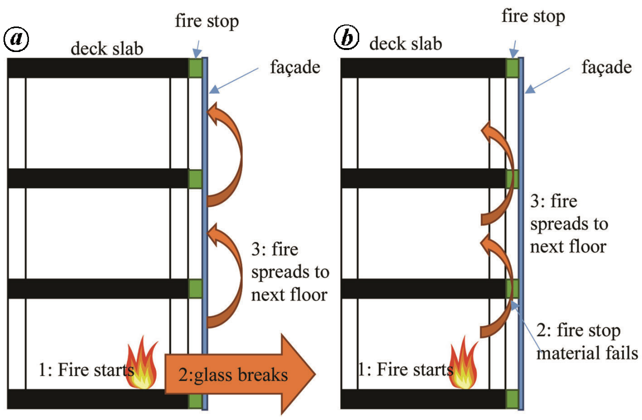

Figure 6. Fire spread mechanisms in façade systems. ***a***, External spread mechanism (faces 1 and 2). ***b***, Internal spread mechanism (face 3).

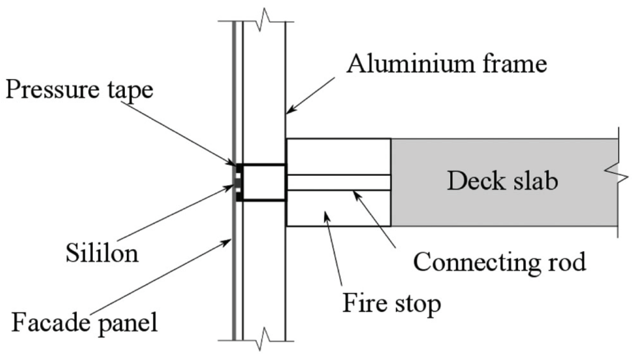

Figure 7. Installation details of façade panels and fire stop through aluminium frame.

installed in the test structure before each fire test. Embedded ducts (1″ pipes in slabs, 2 × 1″ pipes in walls and ground) are provided to safeguard the wiring of instrumentation from fire during the tests. All the wires from sensors to the data acquisition system (DAQ) are passed through these ducts. Figure 8 shows the plan layout of these ducts at each floor level.

A 128-channel PXIe-based DAQ system from National Instruments is used for acquiring all the sensor data. Video camera data are acquired separately through a digital video recorder. During a fire test, a safe perimeter of about 10 m is necessary to avoid injuries. However, if the DAQ is placed outside the test structure, the length of the sensor wires can become very large and there are chances of data corruption due to attenuation. Thus, the DAQ is placed inside the test structure, though in a different cabin (e.g. if cabin 1 is to be put on fire, DAQ is kept in cabin 2). During the tests, the DAQ is operated remotely through a desktop computer installed in the control room situated about 30 m away from the test structure. The DAQ is connected to the controlling computer through an Ethernet cable.

Among all the sensors, thermocouples are the most important ones that not only give temperature conditions within the fire compartment, but are also utilized to monitor the temperature of structural beams and columns. Knowledge of structural temperature during a fire test is crucial to assess the functioning of the fire protection system and determine whether a test must be stopped so that the structural system is not damaged. Video footage is important to perform fire and smoke spread studies in the initial stages of fire. Once the room is full of smoke, the video captures are completely obscured. Since video cameras are not installed in a fire-protected enclosure, they also melt when the size of the fire becomes substantial. However, they do relay the necessary smoke obscuration details before failing. Infrared camera data yield the surface temperature profile of the entire façade face, which is not possible through thermocouples. In future, it is planned to include installation of heat flux sensors during fire tests to directly assess the levels of heat flux experienced during the tests. Installation of such sensors is challenging because of their limited operating temperatures, due to which they need to be water-cooled at all times.

It is expected that the information presented here will enable development of more such facilities for characterization of façade behaviour during fire. Such studies are quintessential to developing in-depth scientific understanding of behaviour of façade installations in real fires. Once such issues are well understood, better building codes and standards can be formulated. In the Indian context, where no such standards exist, commissioning of more such facilities will pave the way for their development, thereby improving the safety of such buildings.

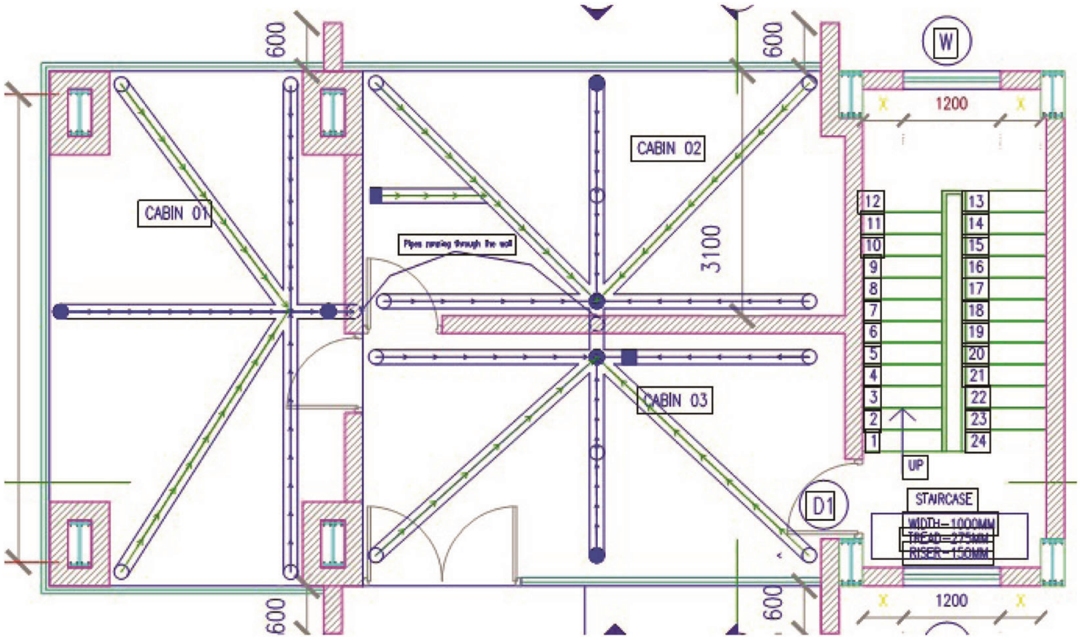

Figure 8. Layout of ducts for wiring of instrumentation at each floor level. Filled and open circles near the walls indicate ducts of walls used for instrumentation.

Table 1. Detailed timeline of events of the test

Sequential number	Time (min)	Event
1	00:00	Manual ignition through waste papers and accelerators.
2	03:03	Heavy smoke obscuration at ground level. ACP sheets begin to shrink. Maximum temperature at ground floor façade level is about 275°C.
3	06:03	Fire did not spread and temperatures became constant around 250°C for 10 min. Heavy smoke obscuration was observed at first floor level.
4	16:46	ACP sheets fall due to failure of pressure tapes, thus enhancing ventilation. Wooden crib placed in the middle of the compartment catches fire. Maximum temperature at ground level is 400°C.
5	24:50	ACP sheets are charred exposing the inner insulation polymer to fire. Maximum temperature at ground and first floor level has reached about 610° and 115°C respectively.
6	25:03	Major failure of structural fire protection, i.e. cement boards fixed with c/c spacing between bolts of about 20″.
7	26:03	Flames begin to leap out through ventilation opening by leap frog effect. Temperatures at ground level have reached 770°C and at the first floor around 165°C.
8	27 : 08	Flashover occurs during this period and temperature reaches about 800°C, which leads to melting of façade frame at certain locations. Two glass panels fall out intact due to failure of silicon sealant.
9	28 : 10	Burning of inner insulation polymer (polyethylene) of ACP initiates a small secondary fire at ground level. Maximum façade temperature at first floor level is about 400°C.
10	30 : 06	Fire reaches first floor level and chars ACP sheets. Fire spreads vertically upwards through ACP. It could not penetrate inside the compartment.
11	32 : 06	External fire spread reaches the second floor level through ACP sheets.
12	33 : 13	Fire extinguishing begins as it reaches the second floor level.

A full-scale fire test of façade system comprising 60% glass and 40% ACP assembly mounted on one of the faces of the facility was carried out to study fire spread behaviour. Saint Gobain toughened glass of 1200 × 400 mm size and 6 mm thickness, and ALUDECOR AL 45 ACP sheets comprising polyethylene core and similar size with 4 mm thickness were fixed to aluminium framework as described earlier (Figure 7).

Fire scenarios were developed at all three levels of the facility using real office furniture and wooden cribs in accordance with the National Building Code. The fire load energy density at ground, first and second floor levels was 35, 19 and 10 kg/m^2 wood equivalent respectively. Ignition source in the form of gasoline-soaked polyurethane basket of size $0.15 \text{ m} \times 0.15 \text{ m} \times 0.3 \text{ m}$ corresponding to fire load of 21.12 MJ was used. Initial ventilation was provided at ground floor by opening a single glass panel (1200 × 400 mm), whereas no ventilation was provided in the first and second floors. Table 1 shows a brief timeline of events during the test.

During the test it was observed that glass panels failed in intact form instead of cracking and breaking. Post-fire investigations suggested that this was due to failure of silicon sealant and pressure tapes used for fixing the panels. Also, when temperature reached above 680°C, due to melting of aluminium, combustible polyethylene core was exposed to fire and charred. It also initiated secondary fire at the ground-floor level, enhancing the severity of the event. Overall, it can be concluded that the full-scale real-fire test demonstrated visually similar behaviour to some of the recent façade fires, and highlighted the vulnerability of combustible façade panels to fire, in addition to giving insights into possible fire spread and façade failure mechanisms.

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Monitoring of total volatile organic compounds and particulate matter in an indoor environment

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Indoor air pollution in the workplace is considered as one of the most potential environment risks to an occupant’s health. Office employees are exposed to airborne pollutants that include particulate matter (PM), volatile organic compounds (VOCs), gases chemicals and microorganisms originating from indoor and ourdoor sources. Exposure to PM and VOCs is likely to be higher in the workplace than outdoors due to the amount of time people spend in the indoor environment. A weekly monitoring of VOCs and PM with sampling period of 8 h was carried out in an indoor (office) environment in order to evaluate the exposure to pollutant concentration. The sampling was carried out with the help of a Grimm dust monitor and potable VOC monitor for PM and VOCs respectively. The results clearly show that exposure to PM and VOCs is much higher in an office building.

Keywords: Indoor environment, particulate matter, office, volatile organic compounds.

INDOOR air pollution is considered as a critical issue for human health since individuals spend a significant part of the day in indoor environments: offices, schools, colleges, residential and commercial buildings[1]. Office employees spend most of their time inside their office building, where the indoor environment has a direct influence on their performance and productivity as well as their well-being. Therefore, it is important to develop a good and healthy working environment in workplaces[2]. However, indoor air quality (IAQ) has received considerably less attention compared to outdoor air quality until last decade[1]. Poor IAQ can be especially harmful to children, the elderly, and those with cardiovascular and chronic respiratory diseases. In developing countries, the problem of indoor air pollution far outweighs the ambient air pollution[3,4]. Employees are exposed to different pollutants such as particulate matter (PM), volatile organic compounds (VOCs), oxides of nitrogen (NO_x), carbon monoxide (CO), etc. typically attributed to indoor sources as well as infiltration of outdoor air. Several studies have consistently ranked indoor air pollution as an important environmental health problem quality[1–7]. Good IAQ can

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