

Materials Selection for Improved Indoor Air Quality in Residential Buildings: a Pre-occupancy Assessment

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Fig 1: IAQ assessment in residential buildings

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1. DESIGN SAFE, COMFORTABLE AND HEALTHY ENVIRONMENT
 2. NEW GOVERNANCE APPROACH AND NEW REGULATIONS
 3. NEW TECHNIQUES AND HIGH PERFORMANCE PRODUCTS

Research summary

Materials selection and design decisions are factors that determine the quality of the built-environment. Construction materials contribute to the emission of indoor air pollutants, which exposes occupants to multiple pollutants simultaneously. Since human health and safety are two core values in sustainable development, acceptable Indoor Air Quality (IAQ) standards should be defined. In Egypt, defining benchmarks is necessary to help alleviate the adverse health effects due to these emissions. The goal of this work is to investigate the impact of the built environment, namely, construction materials on IAQ. This will be carried out by quantifying air pollution levels in a steady state, controlled environment and by examining the effect of source control in the reduction or elimination of pollutants. IAQ is monitored in nine locations at the preoccupancy stage and an evaluation scheme (IAQ index) is designed and applied to compare the quality of air in the tested rooms. The monitored parameters include particulate matter (PM 2.5, PM 10), Volatile Organic Compounds (VOCs), Formaldehyde (HCHO), Ammonia (NH₃) and Radon Gas while observing indoor and outdoor temperature and relative humidity. The indoor air pollution levels indicated by the proposed index have shown poor air quality immediately after the completion of construction, however, it improves in locations monitored 6 to 12 months after construction. The period after construction, age of the building and type of construction materials affect the indoor pollution levels. The results indicate that IAQ in residential buildings can improve with proper selection of materials during design stages, applying assessment tools and specifying proper standards for hot, arid climates.

Keywords: Indoor Air Quality, Construction Materials, Residential buildings, IAQ index.

1. Introduction

The US Environmental Protection Agency (EPA) designated indoor air pollution among the top five environmental risks to public health, and specified source control as the most effective and cost efficient strategy to “eliminate individual sources of pollutants or reduce their emission” (EPA, 2013). The design of residential buildings in Egypt is mainly influenced by cost, aesthetics and function. Therefore, developing relevant criteria that could assist in the decision making process should be based on monitoring the built environment, with the aim of enhancing the indoor environmental quality especially the IAQ. Ultimately, setting criteria and applying standards would help alleviate adverse health effects that are caused by uninformed decisions, with respect to materials selection. Previous studies conducted in Egypt focused on measuring exposure levels during the post occupancy stage, however, further investigation is needed to monitor the IAQ levels in vacant buildings to identify the effect of design and materials alone, independent from other user activities and to define appropriate source control strategies. The review of current studies, carried out in other countries with similar characteristics, demonstrated that indoor pollutants generated by construction materials are high in the first six months after construction, some of which decrease with time and others which can be diluted using further treatments (Yu, 2013; Missia, 2010). A previous study revealed that some types of volatile organic compounds (VOCs) could diminish with the application of decomposing agents (Kim, 2008).

2. Research objectives

1. Identifying potential indoor pollutants, their sources and health effects due to short term and long term exposure.
2. Identifying acceptable benchmarks for each pollutant.
3. Formulating a suitable framework including an assessment method (IAQ index) for buildings during the preoccupancy phase.

2.1 Indoor Air Quality Parameters

The sources of indoor pollutants vary from one building to another. Factors contributing to indoor air pollution include outdoor sources introduced to indoor environments by infiltration and indoor sources emitted by building materials, furnishings and user activities (Hansen, 1991). Different types of VOCs are emitted by coatings and flooring materials. Formaldehyde, which is classified as a carcinogen, is present in residential buildings (Khoder, 2006; Saarela, 2003 ; Yu, 2013). Other contaminants associated with the application of materials include ammonia, radon gas and particulate matter. Former studies have focused on monitoring one or two of these parameters, however, it is important to develop a comprehensive method for the exposure assessment of multiple contaminants.

2.2 Available Standards

Several world organizations have developed IAQ standards including the World Health Organization (WHO) and the European Collaborative Union. Other standards by the EPA and the American Society for Heating, refrigeration and Air-conditioning Engineers (ASHRAE), the Finnish Society of Indoor Air Quality and Climate (FiSIAQ) in Finland, Health Canada in Canada as well as organizations in China specify allowable exposure limits. However there are discrepancies in most of the

specified standards. Related to the standards, Green building rating systems such as Leadership in Energy and Environmental Design (LEED) specify exposure limits for IAQ assessment as a route to fulfill part of the indoor environmental quality evaluation process assigning points to good practice work at the design, construction and post occupancy building stages. Other standards specified by the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) are common for work environments. In Egypt, the housing design and planning building codes have addressed several Indoor Environmental Quality (IEQ) factors and specified acceptable thermal comfort limits, however, limited information is available in form of a IAQ standards or guidelines. The purpose of this study is to advance these guidelines by offering an IAQ index to define the appropriate benchmarks and aid in the decision-making process. The following criteria were adopted to identify applicable benchmarks in Egypt (**Table 1**):

1. National standards supersede.

2. ASHRAE standards were used as a reference, where national standards are not available.
3. Other national standards taking the most stringent limits.
4. If none apply, occupational standards based on 8-hour exposure limits were adopted.

2.2 IAQ index development

An IAQ index is an assessment tool designed to help identify problem areas and guide the materials selection process. Previous indices were based on the assessment of IEQ parameters including day lighting, acoustics, thermal comfort (Marino, 2012); whereas, only few have incorporated IAQ parameters (Demetrios, 2004). These indices were often used in post occupancy assessment, therefore are not designed for the evaluation of vacant buildings. In this study, the index is formulated by calculating a score based on the measured value for each pollutant. For each factor, the relevant weight is calculated using the common Analytical Hierarchy Process (AHP). The final weighted score is scaled, defining acceptable, poor and non-acceptable environments.

Table 1: Indoor air pollutants, their sources and effects on human health

Pollutant	Health Effect	Building Material Sources	Benchmark	Source
1. Volatile Organic Compounds (VOC)	ENT irritations and respiratory tract lesions, some types are carcinogenic	Rubber flooring, adhesives, particleboard and plywood, paints and coatings	500 $\mu\text{g}/\text{m}^3$	LEED
2. Formaldehyde HCHO	Nausea, fatigue ENT and skin irritations, carcinogen	Plywood, particleboard, insulation materials, paints	27 ppb	ASHRAE & LEED
3. Radon	Lung Cancer	Soil and building materials (marble, granite, bricks, ceramic tiles)	4 pCi	EPA
4. Ammonia NH_3	ENT irritation; aggravation of chronic respiratory diseases	Concrete and Floor Structures	43 ppb	FiSIAQ
5. PM 2.5	Cancer	Carpeting	15 $\mu\text{g}/\text{m}^3$	ASHRAE & LEED
6. PM 10	Allergic Symptoms	Gypsum board & concrete	50 $\mu\text{g}/\text{m}^3$	ASHRAE & LEED

3. Research Method



Fig 2: Experimental setup in test room

First, the current study identifies potential pollutant sources (construction and finishing materials) and factors that contribute to IAQ. Next, the levels of contaminants were measured in residential buildings, in Egypt; nine locations were selected and evaluated based on eight-hour monitoring and air sampling, at steady state and in a controlled environment. Finally, the measured factors were introduced into the designed index formulating an assessment tool for built environments.

3.1 Data Collection

The study was carried out during the months of January and February where the recorded outdoor temperature ranges from 8 to 25 ° C and ambient RH ranged from 15.8 to 68%. The study was conducted in nine locations; five of which were monitored 6 to 12 months after the completion of construction work and four during the final stage of construction. Different material compositions were applied to evaluate the contribution of each type of material to the indoor contaminants. In the absence of a clear classification of materials available in the market, samples of mainstream materials were selected and applied using

common construction practices. The wall structure was built using commonly used red bricks (25 cm thick), plaster was then applied and followed by one layer of coating (primer) and one layer of paint coating for interior wall finishing. For floor finishes, ceramic tiles, marble, porcelain and parquet were used in the study. Eight parameters were monitored using data loggers and air-sampling devices, placed at a height of 1.2 m in the center of the room. HCHO was collected in a 0.05% aqueous solution of *3-methyl 2-benzothiazolone hydrazone hydrochloride* (MBTH), while ammonia was collected in a 0.005M sulphuric acid solution. Radon Gas was monitored using a Corentium Digital Radon Monitor, particulate matter using metone model 831 and data loggers for recording indoor and outdoor temperature and relative humidity (HOBO UX100-023 and Extech RHT20). VOCs were measured using carbon-based adsorbents (OSHA). The collected samples were analyzed using a gas chromatograph.



- 1: Particulate Matter Monitor Met one 831
- 2: Air pump & charcoal tube
- 3: NH₃ and HCHO impingers
- 4: Extech RHT20 (indoor data logger)
- 5: Corentium Digital Radon Monitor

Fig 3: Measurement and air monitoring devices

4. Results and design potential

Table 2: Rating of studied locations

Parameters	Indoor Measurements								
	S1	S2	S3	S4	S5	R1	R2	R3	R4
HCHO	10.00	15.47	13.84	10.00	5.70	24.85	67.30	32.57	15.47
Radon	1.02	2.02	0.20	0.80	0.08	1.51	1.28	0.55	0.11
PM 2.5	17.24	8.11	6.93	7.48	26.42	15.20	20.76	35.55	54.45
PM 10	41.86	27.86	26.96	18.64	74.28	75.23	94.27	99.05	198.7
Ammonia	—	64.46	37.24	—	42.27	51.69	41.60	28.38	18.65
VOCs	160.53	396.29	17.80	—	—	69.89	179.70	175.07	142.34
Temp	14.70	15.80	14.90	15.20	19.40	16.30	14.17	17.55	17.60
Humidity	61.00	48.60	54.90	68.30	47.30	55.83	69.17	71.50	55.75
Index	1	1	1	1	2	3	4	4	1



- 1: Acceptable
- 2: Needs Improvement
- 3: Poor
- 4: Unacceptable

Table 2 presents the data for the monitored rooms and the calculated index for each location. The measured concentrations of air pollutants revealed that PM, VOCs, HCHO, NH₃ and radon gas are present at different concentrations in the monitored locations. The concentrations of these pollutants exceeded the benchmark for the locations tested immediately after construction (highlighted in red). The application of materials in these studies demonstrated that the concentration of HCHO and NH₃ increased with the application of primer (the first wall coating used to provide a smooth surface). Furthermore, when coatings were applied, PM 2.5 and PM 10 levels were reduced by 25% from the original reading. This suggests that suspended particulates are trapped in the coating. In locations monitored after six months of construction (S1 to S5), PM 2.5 and PM 10 were recorded at lower concentrations compared to spaces monitored immediately

after the completion of construction (R1 to R4). A positive correlation was observed between PM 2.5 and PM 10 concentrations and the age of the building ($r=0.57$ and 0.52), therefore S5 which was constructed 25 years before conducting the study showed a rating of 2 on the index, due to higher levels of PM 2.5 and PM10. On the other hand, the time since the finishing was applied showed a strong negative correlation ($r=-0.71$, -0.88) with PM 2.5 and PM 10 respectively, indicating that during the first 12 months after renovation the concentration of suspended particulate is expected to decrease as they become adsorbed on the surfaces. As the age of the building increases, the concentration starts increasing with time. Rooms (R1 to R4) were monitored during the application of flooring and wall finishing compositions. Therefore, their ratings are from 2 to 4 reflecting poor or unacceptable conditions, with the exception of room 4 where more favorable materials were applied.

5. Future implementation

The following are suggestions to overcome the limitations of the study in future work;

- Monitor IAQ in each location for longer time periods; after the completion of construction work to define changes in emission rates and the time needed to maintain desirable IAQ.
- Apply the same study during different seasons to test the effect of climatic changes.
- Test a wider range of materials is essential to confirm the results and patterns of the contaminants generated at each stage of application.
- Investigate new material options including decomposing agents (Kim, 2008), materials with hygroscopic properties as well as dust repellent coatings.

Figure 6 demonstrates a proposed framework, which could be adopted for material assessment from the design stage to building operation.

- First, the screening of products is essential especially for formaldehyde and ammonia, to classify products into categories A, B and C, where A is where the test results are acceptable for high cost products, B is for recommended economic products and C are rejected.
- On the building level, after completion of construction, the IAQ in different spaces could be tested and the spaces could be graded using the proposed index. This will help associate the defined products (A, B or C) with the grade of each space.

- Following up with building operation is necessary to identify problematic areas, which can be later, used in the improvement of the designed index. For example if the VOC concentration increase after occupancy, their weights should be increased in the designed index.

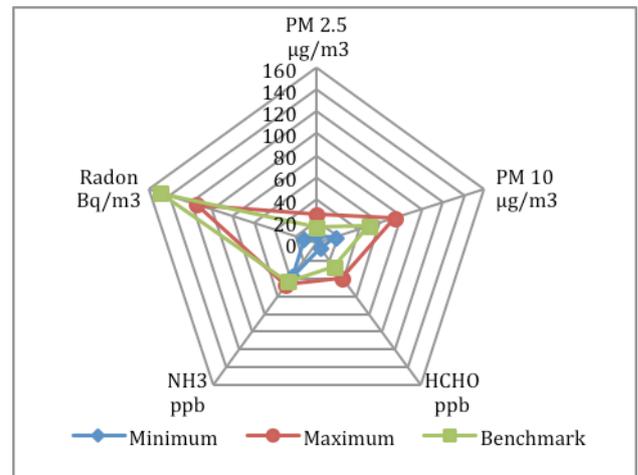


Fig 4: Minimum, maximum and mean concentrations (6 to 12 months after construction)

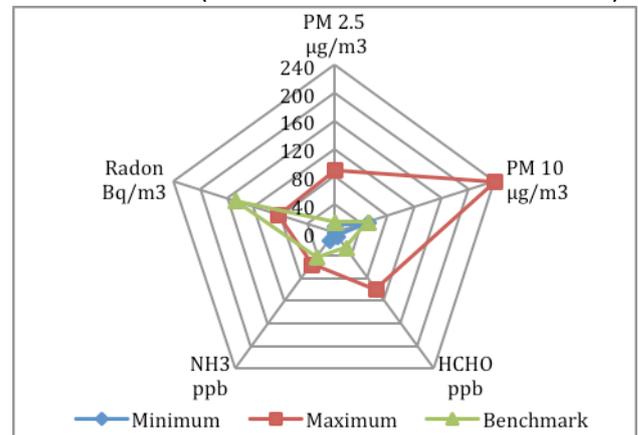


Fig 5: Minimum, maximum and mean concentrations immediately after the completion of construction

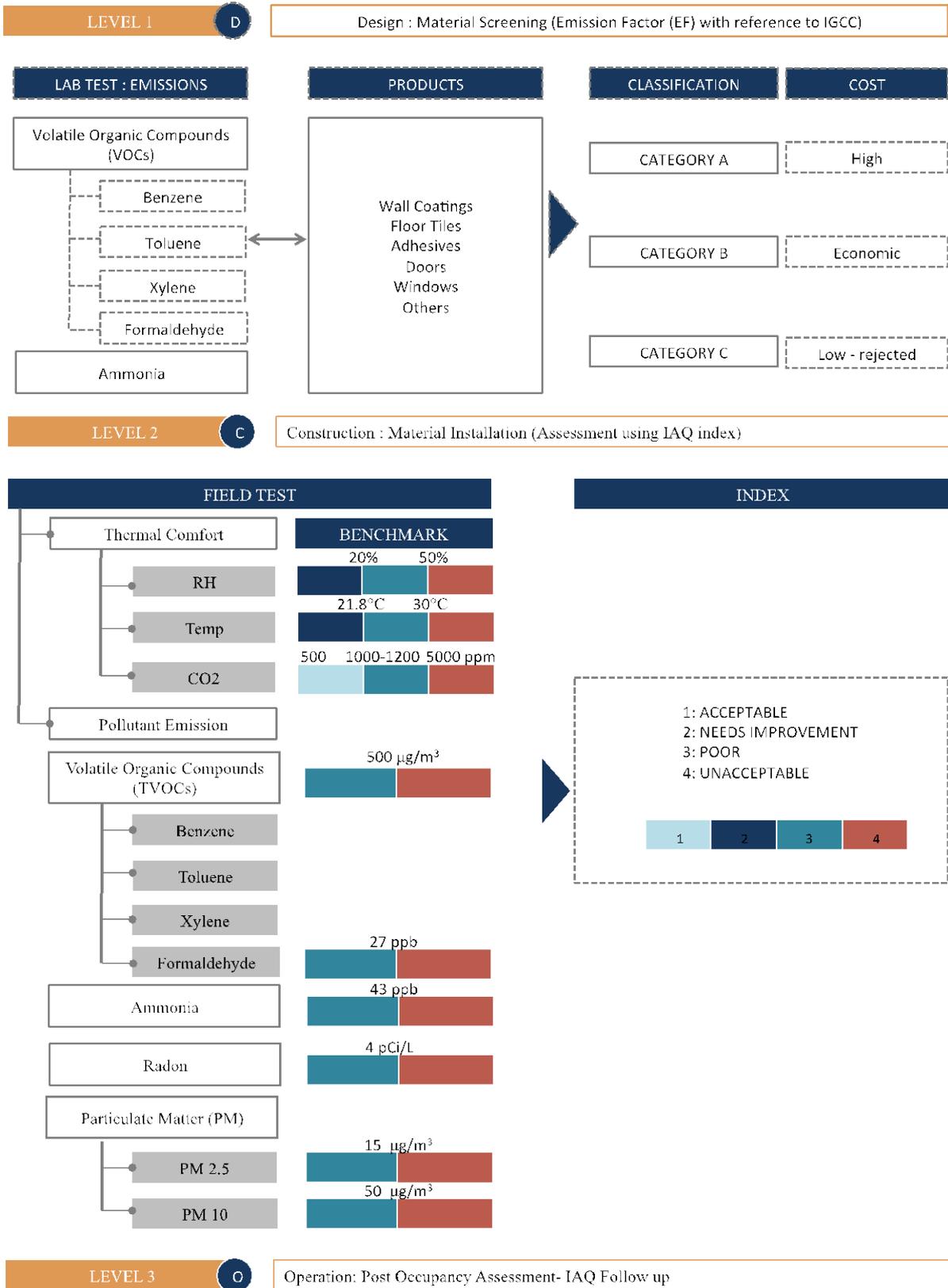


Fig 6: IAQ assessment framework (from design to occupancy)

6. Conclusions

Based on the materials used, environmental conditions and other parameters associated with this study, the IAQ in tested apartments has ranged from level 1 (acceptable) to level 4 (unacceptable), depending on the time since construction as well as the types of materials used. The levels of contaminants remained high during the first few months after completion of construction work. For this reason, it is important to delay occupancy until acceptable IAQ levels are achieved or to eliminate contaminants with the correct selection of materials as a source control strategy.

The development of the framework presented in this paper can be used as a screening system for construction materials, identifying recommended products with lower emissions.

To overcome the limitations of this study, it is recommended to monitor the change in pollutant levels in each space from the start of construction until occupancy by extending the testing time in each space. This is necessary to estimate the time needed to achieve an acceptable IAQ level. Further research is required to resolve these challenges and address the limitations.

7. Acknowledgment

The authors wish to acknowledge that this work was supported by a research grant from the graduate program at the American University in Cairo as well as the contribution of the Egyptian National Research Center for providing technical assistance needed in this study.

8. References

- Demetrios J Moschandreas, & Sait C Sofuoglu. 2004. The indoor environmental index and its relationship with symptoms of office building occupants. *Journal of the Air & Waste Management Association*, 54, 1440.
- EPA, Environmental Protection Agency. 2013. Retrieved May/6, 2015, from <http://www.epa.gov/iaq/is-imprv.html>
- Hansen, S. J. 1991. *Managing indoor air quality*. Lilburn, GA: Fairmont Press.
- Järnström, H., Saarela, K., Kalliokoski, P., & Pasanen, A.-L. 2006. Reference values for indoor air pollutant concentrations in new, residential buildings in Finland. *Atmospheric Environment*, 40, 7178-7191.
- Khoder, M. I. 2006. Formaldehyde and Aromatic Volatile Hydrocarbons in the Indoor Air of Egyptian Office Buildings. *Indoor and Built Environment* 15.4, 379-87.
- Kim, S., Kang, D., Choi, D., Yeo, M., & Kim, K. 2008. Comparison of strategies to improve indoor air quality at the pre-occupancy stage in new apartment buildings. *Building and Environment*, 43(3), 320-328.
- Marino, C., Nucara, A., & Pietrafesa, M. 2012. Proposal of comfort classification indexes suitable for both single environments and whole buildings. *Building and Environment*, 57-67.
- Missia, D. A., Demetriou, E., Michael, N., Tolis, E. I., & Bartzis, J. G. 2010. Indoor exposure from building materials: A field study. *Atmospheric Environment*, 44(35), 4388-4395.
- Saarela, K., & Järnström, H. 2003. Indoor air quality in new residential buildings and behaviour of materials in structures. *Indoor and Built Environment*, 12(4), 243-247.
- Tuomainen, A., Tuomainen, M., Pasanen, A., Jyrki Liesivuori, & Juvonen, P. 2001. Usefulness of the Finnish classification of indoor climate, construction and finishing materials: comparison of indoor climate between two new blocks of flats in Finland. *Atmospheric Environment*, 35(2), 305-313.
- Yu, C. W. F., & Kim, J. T. 2013. Material emissions and indoor simulation. *Indoor and Built Environment*, 22(1), 21-29.