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An optoelectronic sensor for the monitoring of mould growth in concealed spaces

Eric Savory[a,*], Jayshri Sabarinathan[b], Anna Sauer[b], James A. Scott[c,d]

[a] Department of Mechanical and Materials Engineering, University of Western Ontario, 1151 Richmond Street, London, Ontario N6A 5B9, Canada
[b] Department of Electrical and Computer Engineering, University of Western Ontario, 1151 Richmond Street, London, Ontario N6A 5B9, Canada
[c] Dalla Lana School of Public Health, University of Toronto, 223 College Street, Toronto, Ontario M5T 1R4, Canada
[d] Sporometrics Inc., 219 Dufferin St Suite 20-C, Toronto, Ontario M6K 1Y9, Canada

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ABSTRACT

The growth of mould in the indoor environment is an important contributor to the development and exacerbation of atopic disease, and potentially poses other health risks. Moreover, the detection and elimination of mould have resulted in massive remedial expenditures, often without clear engineering knowledge of the nature of the moisture events that led to the damage, especially for residential light wood-frame construction. Relatively little research has considered such failure of the building enclosure as a starting point for developing practical, evidence-based construction practices to improve building performance. One research limitation concerns the use of invasive or destructive testing as the sole means to monitor mould growth in concealed assemblies, such as wall cavities, making it difficult or impossible to conduct time-course experiments to assess the performance of different materials and designs. The present paper concerns the development and testing of a new optoelectronic sensor capable of non-invasive monitoring of mould growth in concealed spaces in real-time by measuring changes in light reflectance from the sensor's active element, a membrane impregnated with mould spores. It builds upon an earlier concept [1] in which mould-impregnated cellophane coupons were attached to building surfaces, then removed and examined periodically for growth by microscopy. The new device incorporates computer-controlled measurement of mould growth, in response to the environmental conditions and, thus, functions as a remote sensor. Although primarily intended for research use, the device has the potential to be used as a post-remediation monitoring device to provide early-warning of any re-occurrence of mould growth.

1. Introduction

Indoor mould has long been recognized to pose a risk to human health, particularly in the development and exacerbation of allergy and asthma [2]. From a population health standpoint, indoor mould is increasingly viewed as an important health-relevant exposure in residential housing [3].

Without exception, the growth of mould in the built environment is always mediated by superfluous moisture. In the most straight-forward of situations, moisture can be introduced through catastrophic failure of the building enclosure (i.e., building envelope), as was the case with homes in areas of the southeastern US affected by Hurricane Katrina in 2005. By contrast, far more subtle forms of water incursion are responsible for the vast majority of mould damage in housing. While these may relate to failures of mechanical systems, such as plumbing leaks, or egregious conditions of use and lifestyle, most are the result of relatively minor failures of the building enclosure, manifesting either as breaches that permit the direct penetration of water (e.g., cracked caulking joints, damaged flashing, etc.), or as inadequate thermal management (e.g., thermal bridges produced by framing materials or mechanical penetrations, insufficient insulation, gaps in caulking seals or vapour retarding membranes, etc.), resulting in the inappropriate accumulation of moisture by adsorption and condensation. In some cases, design failures arising from efforts to improve energy efficiency have had the unintended effect of trapping moisture. Regardless of the moisture source, once wetted, most organically-based building materials rapidly become colonized with mould in varying degrees according to their susceptibility.

Some aspects of the indoor mould problem have received considerable attention. In particular, there has been much study of mould-related health effects from both epidemiological and pathophysiological perspectives (reviewed in Refs. [3–5]). Likewise, there exists a growing body of literature on methods and approaches to the investigation of buildings and their remediation

* Corresponding author. Tel.: +1 519 661 2111x88256; fax: +1 519 661 3020.
E-mail address: esavory@eng.uwo.ca (E. Savory).

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(reviewed in Refs. [6,7]). However, there has been relatively little parallel effort to advance the understanding of the contribution of construction practices, architectural and design and building materials to the susceptibility of buildings to mould. These knowledge gaps have been reinforced, in part, by the historical reliance of the construction industry on codes of practice derived from received wisdom and intuition rather than objective evidence. This trend has become further entrenched by the many challenges presented by the study of mould in relation to construction. For example, air and moisture leakage through the building enclosure is rarely a straight-forward phenomenon and cannot easily be adequately modelled using partial wall assemblies. As a further complication, while it is possible to measure temperature, air leakage and moisture in concealed spaces by non-invasive techniques, the evaluation of mould growth typically requires invasive sampling, such as periodic inspection through introduced penetrations, or destructive sampling in which the mould condition is only evaluated at the conclusion of an experiment. Although invasive sampling has the advantage of allowing for the assessment of growth over time in relation to other measured factors, it does so at the risk of modifying the growth conditions themselves.

Non-invasive monitoring of mould growth in concealed spaces has been attempted with mixed success using radar [8]. However, a promising biosensor was developed using mould itself as a proxy [1]. Spores of *Eurotium herbariorum* (chosen because this species grows under a wide range of moisture conditions), together with nutrients, were placed on a piece of undeveloped and fixed, vapour-permeable photographic film. This was covered with a second segment of film (to prevent the inocula from dispersing into the test environment) and placed in a 35 mm photographic slide holder. Each slide could then be affixed to a test surface and removed at periodic intervals for visual and microscopic assessment of growth. Using this device in an apartment building [9], they derived a numerical "fungal index", defined as the sensor's response as a function of exposure time. The response of this index showed strong agreement with temperature and relative humidity measurements (correlation coefficient $= 0.91$, $p = 0.01$) [10].

Although inexpensive and elegant in its simplicity, Abe's "fungus detector" [1] has several drawbacks. Firstly, the slides must be manually removed from the test environment, examined and then replaced. Secondly, where the positioning of the sensors does not coincide with natural openings, artificial penetrations must be introduced, potentially altering the microenvironmental conditions. The reliance on manual observation is labour-intensive, introduces the potential for subjectivity, and provides data only at selected time-points.

To overcome these deficiencies, the present work has adapted Abe's concept by developing a remote sensor. The new sensor consists of a permeable, hydrophilic membrane inoculated with mould spores that is affixed to a test surface over which a miniaturized optoelectronic illumination and sensing device is positioned (Fig. 1). The reflectance characteristics of the membrane can then be measured at user-defined intervals to determine the time of onset of mould growth. Multiple sensors can be embedded in a wall at pre-selected positions during construction. These sensors can then be monitored remotely over time without the need for manual intervention.

The initial prototype development work was presented previously [11]. Here the final version of the sensor is described, together with details concerning its operation and performance and results from laboratory bench-tests and in-wall installations in a test building. It should be noted that the sensor components were chosen to be as inexpensive as possible in order to allow economic construction of multiple sensors.

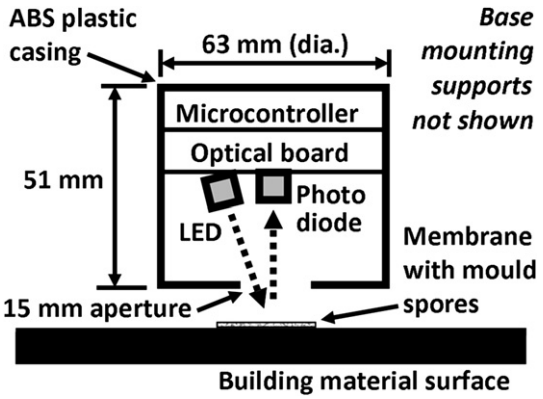

Fig. 1. Conceptual drawing of the sensor.

2. Materials and methods

2.1. Preparation of mould-inoculated membranes

The active element of the device consists of a 25 mm diameter, 0.8 μm pore-size mixed cellulose esters membrane (MCEM, Millipore, Billerica, Massachusetts) inoculated with spores of *Cladosporium sphaerospermum*. This species was selected because it is a common indoor environmental contaminant occurring on a range of materials under relatively low water-activity conditions as a consequence of leakage or condensation. Also, its cells are highly melanized, facilitating the monitoring of its growth by light reflectance [12].

C. sphaerospermum was grown for 7–14 days at room temperature on modified Leonian's agar medium [13]. At the end of this period the Petri plates were flooded with sterile distilled water, and the colony surfaces were gently scraped using a sterile disposable 10 μL bacteriological loop. The suspension was filtered through multiple layers of sterile cheesecloth in a thistle tube funnel to remove large mycelial fragments. The concentration of the resulting spore suspension was enumerated using a haemocytometer and adjusted to approximately 200 cells mL^{-1} by the addition of sterile distilled water. From this stock, a spore suspension was prepared by adding 3500 spores to a sterile broth consisting of 0.8% peptone, 2.5 mM glucose, 5.0 mM NH_4NO_3, 1.6 μM $CuSO_4 \cdot 5H_2O$ and 32.0 μM $ZnSO_4 \cdot 7H_2O$ in distilled water in a total volume of 50 mL. Each suspension was mixed by vortexing and applied immediately to an MCEM aseptically by vacuum filtration. Membranes prepared in this manner were dried aseptically under ambient conditions and stored in darkness until use.

During the development phase of this work, sterilized birch tongue depressors were used to simulate test surfaces. Membranes were adhered to the tongue depressor using an adhesive consisting of sterile molten 2% agarose. The tongue depressors were inserted in sterile 50 mL conical bottom centrifuge tubes into which 2–3 mL of sterile water had been placed, such that the wood was not in direct contact with the water. A series of membranes were prepared in this manner and incubated under ambient conditions for 8 days. Membranes were harvested at 1-day intervals and dried to arrest further growth. An uninoculated membrane treated only with nutrient solution was used as a negative control.

2.2. Optical components

Prior to the selection of a light source, the reflectance characteristics of the set of test membranes described above were evaluated. These assays were conducted using a white LED, placed so its