Chapter 33
Indoor Air Quality Regulation Through the Usage of Eco-Efficient Plasters

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33.1 Introduction

The current use of the Earth resources has led to a development level on Western society that is now considered to be not sustainable. Noticeable environmental disruptions clearly indicate that, unless urgent measures are to be taken, human beings will have considerable difficulties for adapting to its global habitat. These environmental disruptions, mainly caused by anthropogenic activity, comprise climate changes, non-balanced ecosystems, shortage of mineral resources and diminution of soil fertility. It is expected that environmental pressure will tend to be increased in the forthcoming years, as problems related to pollution and shortage of resources are currently being aggravated by population increase. Also, the majority of manufacturing activities will be increasingly located in urban areas.

In 1994, the International Council for Building (CIB) defined sustainable construction as "the creation and responsible management of a healthy built environment, based on the efficient use of resources and ecological principles" (Kibert 2005). In what regards buildings, Agenda 21 for Sustainable Building (UN 1992) has identified the improvement of environmental parameters and the re-engineering of the

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building process, including sustainable development, as one of the major challenges for the building sector. Sustainable (or eco-efficient) building appears as the response of building industry to the aim of achieving global sustainability. It is also expected that built environment will be as healthy and eco-friendly as possible, thus contributing to an improved indoor air quality. As a result of many issues related to energy, environment, ecology, as well as economics, building with earth materials can be considered as an alternative. Globally, building techniques using earth are currently being revived, and the Portuguese situation is not an exception. In several regions, building with earth is largely used as it uses indigenous materials, incorporates low energy and, thus, is economic. This also results in other advantages in what regards sustainability: earth as a building material is natural, non-toxic, ecological, recyclable and with low embodied energy cost, being non-combustible and contributing for increased thermal and acoustic performances (Gomes et al. 2018). However, in less developed countries, earth building is, nowadays, associated with low-quality construction when no other materials are available. Nevertheless, this situation is bound to be altered if the previously mentioned advantages will be considered. Experimental tests, currently underway on this subject, could act as good examples to change this attitude.

Also, the level of indoor air pollutants is, frequently, much higher than exterior ambient air. Therefore, it is important to understand the type and concentrations of indoor air pollutants and also to develop materials that are able to absorb these pollutants, thus reducing its concentration in the indoor environment, simultaneously being able to contribute to balancing temperature and relative humidity. This paper intends to divulge the preliminary work being developed within the INDEED project, on the effect of eco-efficient plasters on indoor air quality. Within the scope of this project, earth-based mortars will be developed and tested to assess its effect on the air quality of indoor environments.

33.2 Ecologic Sustainability—Indoor Air Quality

It should be noticed that buildings also contribute to degradation of the environment as they are responsible for 50% of fossil fuel consumption and 50% of greenhouse gas emissions (Smith 2005). According to the UN Programme for the Environment (SBCI 2009), buildings, at world scale, are responsible for:

1. 25–40% of energy consumption and 30–40% of carbon dioxide (CO_2) emissions;
2. in what concerns natural resources, they are responsible for: materials and extracted minerals—30%; water—20%; surface use—10%.

Gustavsson and Joelsson (2010) in the 3rd Report on Assessment of Climate Change, claim that, in Europe, the residential sector is accountable for a major part of the primary use of energy, thus generating CO_2 emissions and a negative environmental impact. In order to have an environmental sustainable building, it is important to assess the environmental impact throughout its whole life cycle. Building techniques should be optimised according to this aim, considering, in particular, operational aspects, maintenance and end of life. Certain priorities have to be taken into consideration during the preliminary project stages, including low consumption of non-renewable materials, low production of wastes and pollutants, the use of eco-efficient materials, protection of water resources, achieving a healthy and friendly indoor environment, assessment of the efficiency of adopted solutions, cost reduction during the life cycle and optimised techniques involving construction and maintenance. The interaction between the building and its surroundings is also a very important issue. The life cycle of a building is, in fact, a balance between costs and resources: ecological, social, human and energetic. The life cycle starts with the selection of materials to be used in its construction, the construction and operational phases, until its demolishing and comprises even the waste management, as well as all operational, utilisation, maintenance and rehabilitation consumptions. Along these phases, all resulting environmental impacts must be assessed in order to allow for newer solutions to be provided. The operational phase plays a very significant part of the life cycle assessment of a building in what concerns its energy consumption. For a housing or office building, the primary energy consumption is about 150–400 and 250–550 kWh/m^2 year, respectively, whereas 80–90% correspond to the operational phase, and only 10–20% are related with other life cycle phases (Ramesh et al. 2010). Several studies indicated that, for buildings located in moderated to cold climate regions, the major energy consumption occurs in the operational phase (Winther and Hestnes 1999; Scheuer et al. 2003; Gustavsson and Joelsson 2010).

During the last decades, both active and passive strategies have been explored in the project of buildings with low energy consumption (Chwieduk 2003; Guy and Farmer 2001). The passive approach concerns a very concise and careful approach in what regards project development strategy, utilising bioclimatic concepts, such as geometry and solar orientation, which play important roles in terms of capture, storage and further distribution of solar and wind energy, instead of focusing on building maintenance (Sadineni et al. 2011; Loonen et al. 2013). To perform a project in a bioclimatic way consists in analysing the building bearing in mind the specific climatic features in the location, as well as the environmental features and the use of natural resources available in the region, in order to attain the maximum energy efficiency and also a friendly indoor environment.

Nowadays, benefiting from mentality change, there is the necessity to develop healthy and friendly environments, as much as possible incorporating positive inputs for indoor air quality. Bearing these considerations in mind, a rammed earth wall was built in 1993 in the Feldkirch hospital in Austria. This wall acts as a climatic regulator and, simultaneously, creates some contrast with the aesthetics of the reception hall of the hospital. As previously mentioned, a healthy indoor environment must be a priority for sustainable construction. The indoor air quality depends mainly of (EPA CPSC 1995; Bonn 2006): pollutant emissions inside buildings derived from building materials and furniture, carpets, insulation degradation, combustion process, chemicals used in hygiene and cleaning activities, air-conditioning systems and bioeffluents; infiltration of external air pollutants, such as radon, ozone, carbon

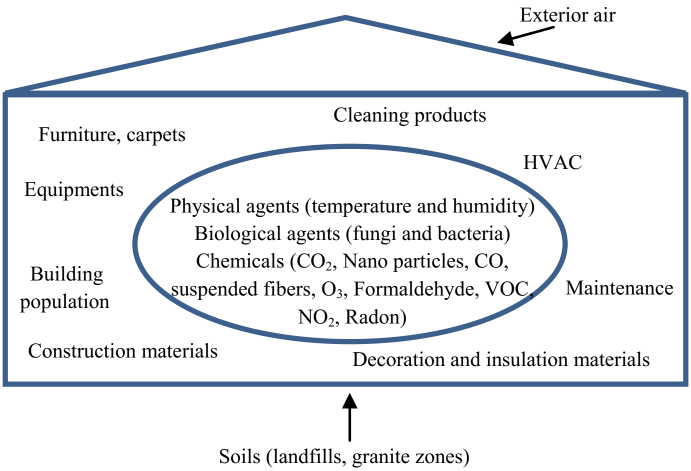

Fig. 33.1 Representation of the parameters affecting the indoor air quality in buildings (adapted from ADENE et al. 2009)

monoxide and pesticides; accumulation of pollutants inside building due to low or no ventilation.

According to ADENE et al. (2009), the major contributors for low indoor air quality are the climatisation like heating, ventilation, and air conditioning (HVAC), and also the building population. The concentration of local pollutants depends from (EPA CPSC 1995; Bonn 2006): the emission rate; air renovations; specific characteristics of the rooms (geometrical dimensions, types of furniture and coatings), as well as its occupancy. Figure 33.1 shows the main parameters affecting indoor air quality.

Natural ventilation was used because of the bioclimatic architecture until air-conditioning systems appeared. The use of natural ventilation is one of the basic principles of sustainable architecture, or good architecture, after all wind is a natural, free and renewable resource. The proper use of this source brings several advantages to the buildings, maintaining the internal quality of the air through the constant exchange—deliver fresh air into buildings, creating healthy and comfortable environments, also reducing the energy expenses, mainly the decrease of the use of air conditioning that is one of the main consumers of energy.

As a consequence of increased energy and its cost, natural ventilation has become an increasingly attractive method for reducing energy use and cost rather than the more prevailing approach of using mechanical ventilation. This change in behaviour has led to an increase in air quality, maintaining a healthy, comfortable and productive indoor climate. According to the National Renewable Energy Laboratory in the USA is possible to save 10–30% of total energy consumption in favourable climates and buildings types, using natural ventilation as an alternative to air-conditioning plants (Walker 2016).

Ventilation is required to remove odours from human physiological activity, tobacco use, domestic activities such as food preparation, the need for aeration to combustion appliances. In order for the environment to be adequate for people to remain, the air must be permanently renewed in order to avoid the formation and accumulation of substances that create an unhealthy environment for the occupants, even when the outside temperature forces the windows to be closed.

The easiest and least expensive way of ventilation and cooling of dwellings is undoubtedly by wind. Natural cross-ventilation is one of the most widely used techniques in buildings and is used in different opening spans in an environment, whether in opposite or adjacent elements. It is necessary to identify the predominant wind of the region (frequency, direction and speed), since the natural ventilation can cause discomfort and unwanted cooling if not analysed properly. The important thing is to allow fresh air to enter, either by opening aperture near the floor, windows, doors, pushing hot air to another part with opening like patio, ceiling, skylight, cast element, wind towers or ventilation tiles in the covers.

Effective ventilation allows good thermal comfort and adequate fresh air levels in the compartments. The solution is the correct location of the building, the strategic location of the spans and its adequate design, with little or no mechanical ventilation. Openings in the building or dwelling must be provided that work permanently and without obstruction. These openings may regulate the renewal of the air, but in no case should they inhibit ventilation.

Nowadays, around 50% of the world population lives in major towns, and people spend 85–90% of their time inside buildings (considering house, work and leisure activities). Therefore, they are greatly affected by these environments (EU—Joint Research Centre 2003). Thus, it is possible to derive a cause–effect relationship between housing conditions and the health of inhabitants, which calls for the increase of sustainable building.

Stieb et al. (2003) pointed out the need for monitoring pollutant concentration levels in all micro-environments. In fact, the concentration of certain pollutants inside buildings is, sometimes, higher than outside. Indoor air has several pollutants such as NO_2, SO_2, CO_2, CO, particulate and micro-organisms, as well as bacteria living in foamy materials or transmitted by moisture inside buildings. Volatile organic compounds (VOC) can also be found. These compounds are highly volatile compounds, mainly aromatics, easily oxidisable in air and heat reactive, which are present in paints, solvents, foamy materials and phenolic products. In indoor environments, products containing VOCs can last about a year to be completely eliminated, as its degradation is usually 100 times slower inside buildings. This happens with synthetic paints containing VOCs. Most common VOCs include formaldehyde, xylene, benzene and toluene. Formaldehyde is a toxic compound that is usually found in indoor environments released from materials such as phenolic adhesives used in the production of agglomerated wood panels (OSB—oriented strand board, MDF—medium-density fibreboard), paints and wood coatings and carpets made of synthetic fibres. Also, a high CO_2 level usually appears in highly populated indoor environments such as classrooms, hospital waiting rooms, sports pavilions. CO_2 in ambient air is usually 400 ppm, while in indoor environments could reach 600–800 ppm, which is mainly due to human breathing. Therefore, the reduction of CO_2 levels in highly populated environment is quite important as CO_2 levels could rise up to 1000 ppm, or more, resulting in symptoms such as headaches, sleepy states and loss of attention. Gomes et al. (2007) pointed out that the knowledge on the real concentrations of specific pollutants, such as VOCs, inside buildings, as well as the knowledge of its health effects on human beings is essential to derive specific protection measures for building occupants. Therefore, there is a considerable need to perform indoor air quality measurements and assess the level of toxic compounds release by coating materials, in order to achieve a better indoor air quality.

The effects of pollutants on human health can be classified as (ADENE et al. 2009): nuisance effects—smells (after 5–60 min of exposure), irritation reactions of eyes, throat, mouth and nose; acute effects—immediate; prolonged effects—allergic or infectious reactions, lung cancer.

Table 33.1 sums up the main sources and effects of the most important pollutants affecting indoor air quality. According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), indoor air quality is acceptable if: toxic concentration levels for pollutants are not exceeded; more than 80% of people exposed to a certain indoor air quality feel comfortable.

The materials and technologies used in a building are typically selected in accordance with the project of the building, its availability and commonly used practices in the construction site. They should fulfil the needs of society development and the user, nevertheless minimising its environmental impact. In order to control the negative environmental impact, great attention should be devoted to minimisation of greenhouse gases emissions. Therefore, the production processes for obtaining of building materials should also minimise these emissions, which also requires accurate research on the energy consumption and greenhouse gas emissions related to the production processes themselves. To minimise all energy spent in building construction, which is the net sum of all energy needed to assemble a building, extraction of raw materials, manufacture, transportation, construction process, operation and maintenance, demolition and recycling after this shelf life (Sartori and Hestnes 2007), it is, thus, important to construct buildings having a high recycling potential. Thormark (2006) mentions that a very important amount of energy can be saved by reusing construction materials. In fact, it is not enough to conclude that a certain material is recyclable, but all processes related to its valorisation should be accounted for. In order to reduce the total consumption of energy in buildings as a hole, particular attention should be given to the selection of materials and the operations related to its end of life.

Earth construction can be an effective alternative to certain problems in what concerns sustainability and indoor air quality. As previously mentioned, the use of earth as construction material brings several advantages such as: earth is a natural and eco-efficient material; earth is non-toxic and can improve air quality; earth is ecological, producing very low wastes, as it is reusable; earth is non-polluting, as there implies only low CO_2 levels during processing; earth is a low cost material, in what concerns extraction because it is frequently obtained as a waste in construction sites, thus reducing costs and energy for transportation, and for processing. Furthermore,

Table 33.1 Major sources and effects on human health from pollutants affecting indoor air quality (APA 2009; DGEG, APA and ADENE 2009)

Pollutant: CO (Carbon monoxide)	
Sources	Health effects
Combustion processes (heating, stoves, fireplaces), exhaust gases from vehicles. Tobacco smoke	Carboxyhemoglobinemia (hinders oxygen absorption) Headaches, nausea, dizziness Effects on nervous and cardiovascular systems
Pollutant: CO_2 (Carbon dioxide)	
Occupants (sweat, respiration, stomach and intestines). Tobacco smoke	Effects on nervous and cardiovascular systems Headaches, Dores de cabeça, eye and throat irritation Dizziness, asthma
Pollutant: HCHO (Formaldehyde)	
Disinfectants, pesticides Wood preservers, construction materials, insulation foams, furniture, textiles, adhesives, paints, glues, solvents, resins. Tobacco smoke	Eye, throat and skin irritation Respiratory problems Dizziness Headaches
Pollutant: VOC (volatile organic compounds)	
Paint, solvents, adhesives, resins and varnishes, construction materials, agglomerated cork, furniture, cleaning products, disinfectants, deodorants, fragrances, insecticides, pesticides, fungicides, tobacco smoke, proximity to gas filling stations	Smells Allergy symptoms Headaches, nausea, dizziness Leukaemia Lung and skin cancer Throat and nose dryness, eye irritation
Pollutant: O_3 (Ozone)	
Photocopy machines LASER printers Cleaning activities Photochemical reactions Water disinfectant	Respiratory problems, allergic reactions, asthma Eye irritation, headaches Lung oedema for prolonged pain repeated exposure Mouth and throat dryness Cough
Pollutant: PM_{10} (Particle)	
Combustion processes, tobacco smoke Occupants AVAC systems Paper	Respiratory problems, cough, sneezes Eye irritation, asthma, allergies Dryness of skin and nose Professional diseases (metals)

(continued)

Table 33.1 (continued)

Pollutant: Bactérias, fungos e *legionella*	
Sistema AVAC systems, construction materials, textiles (carpets), pollens, wet construction areas, occupants (bacteria), hair, and insect droppings, still waters (Legionella and fungi)	Allergies—rhinitis, sinus, asthma Infections—tuberculosis, pneumonia, criptococose Irritation—eyes, nose, throat and skin (fungi) Headache, fever Legionary diseases and Pontiac fever—*Legionella*
Pollutant: Radon	
Construction materials, soil from granitic regions	Increases risk of lung cancer
Pollutant: C_6H_6 (Benzene)	
Wood-derived products Tobacco smoke	Cancer
Pollutant: NO_2 (Nitrogen dioxide)	
Combustion process	Respiratory problems, chronic bronchitis Irritation of eyes, throat, cough and dizziness
Pollutant: Naphthalene	
Tobacco smoke Naphthalene	Eye irritation Respiratory irritation

during the operational phase of the building their utilisation may bring advantages such as contribution towards comfort improvement by the regulation of thermal and hygrometric equilibrium.

In Portugal, there is a strong tradition regarding construction with earth. The main utilised techniques are rammed earth (earth compacted between formworks) and adobe (earth blocks sun dried) (Gomes et al. 2014). The use of these techniques suffered a decay after 1950–60, when more modern techniques using newer construction materials, such as cement, started to be use all over the country. The construction technique using compressed earth blocks started to appear in Portugal during the 1950s, although this technique did not spread because it was by that period that earth construction in Portugal started to decline. However, in the last decades, earth construction started, again, to be used in new buildings and the interest to retrofit and repair old earthen-based buildings also started due to their environmental benefits, contribution for improving indoor air quality, as well as good thermal and acoustic characteristics, as referred before

Ventakarama-Reddy and Kumar (2010) also pointed out other advantages related to rammed earth construction: low energy intensity and low carbon emissions, the recycling feature of the materials, the aspect of being locally available thus reducing transportation costs, flexibility for use in the geometry of buildings, allowing a great variety of finishing's and textures, and also the fact that wall thickness can be easily adjusted, when stabilised rammed earth is used.

33.3 Use of Earth Mortars

Mélia et al. (2014) assessed the energy incorporated when using earth mortars which compared very favourably with other alternatives. One of the most important characteristics of porous building materials is the way they transport and react to the presence of moisture, i.e. their hydric behaviour. This is particularly significant for earth-based materials in which the binder is clay (Gomes et al. 2016). Some authors pointed out that mortars based on clayish earth used in wall plasters can contribute to the improvement of air quality—clay can act as a passive absorption material, thus decreasing ozone concentrations and, therefore, reducing the probability of occurrence of ozone reactions with other materials existing inside buildings (Lima and Faria 2016). However, certain aspects related to the possibility of development of biological agents are also to be accounted for (Santos et al. 2017).

Earth, as a construction material, acts as a protection against major humidity variations, thus contributing to balance relative moisture inside buildings (Minke 2006; Kirsima and Maddison 2009; Liuzzi et al. 2013; Bui et al. 2014; Lima et al. 2016). This capacity is due to the exchange mechanism of water vapour with air: it releases humidity when the air is more dry, absorbing it when it is more humid. This hygroscopic equilibrium depends on factors such as the type of clay, its thickness (Fionn et al. 2017) or the eventual stabilisation obtained by the finishing, that will influence the adsorption velocity and the capacity of water vapour release. It is important to note that these mortars, when organic solvents are not incorporated, do not release toxic organic compounds to the indoor air, as their components are clay and sand. One of the aims of project *INDEED* is to analyse if—and to what extent—earth mortars, when in contact with toxic substances and high carbon dioxide concentrations, are able to reduce smells and the concentration of certain pollutants such as particulate (PM_{10} and $PM_{2.5}$), carbon monoxide, ozone, and volatile organic compounds, such as formaldehyde and BTEX.

It is also important to assess the behaviour of earth mortars in the presence of particulate aerosols as the latter are potential condensation nuclei for micro-organisms such as virus, pollen, bacteria and fungi, mainly as these micro-organisms can be developed and favoured by the presence of high moisture conditions indoor (Lima 2013). As earth plasters can act on the balance between moisture and indoor air, the drive for development of micro-organisms could be greatly reduced.

Therefore, it is paramount to analyse the behaviour of earth mortars when exposed to different pollutants existing in indoor air, as a way to reduce human exposure to aggressive indoor environments, as well as to perform the monitoring of comfort indoor conditions in Portugal. Within INDEED project, five test chambers will be built and pollutants will be injected, namely aerosol particles (PM_{10} and $PM_{2,5}$), carbon dioxide (CO_2), carbon monoxide (CO), ozone (O_3) and volatile organic compounds (VOCs). Inside each test chamber, different earth-based plasters and a cement plaster will be placed, simulating walls and ceiling coatings. The main objective is to collect the air inside the chambers and to determine the changes in pollutants concentrations, as well as temperature and relative humidity. It is expected to be able to quantify the de-pollutant capacity of the earth-based plasters in comparison with the cement-based one.

33.4 Final Considerations

There is currently enough scientific evidence relating complaints and environmental discomfort from building occupants in what regards construction materials used inside buildings. Both the hygienic aspects as well as the toxicological ones have been studied in order to guarantee the existence of pleasant, healthy and comfortable environments. As there is evidence that earth-based mortars have an active and positive effect on the regulation of thermal and hygrometric equilibrium, it is also important to study its behaviour when put into contact with toxic, pollutants and smelly compounds. *INDEED* project aims to quantitatively answer these queries so that a better indoor air quality can be achieved and, as expected, an important contribute to the use of earth plasters may be presented.

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