Construction and Building Materials 147 (2017) 352–361

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Influence of internal relative humidity and mix design of radiation shielding concrete on air permeability index

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HIGHLIGHTS

- A procedure of specimen preparation of homogeneous RH a desired value was proposed.
- API of shielding concrete in oven dry state and at a specific, stabilized RH was determined.
- Linear relationship between API and concrete RH in range of 2% to 99% was found.
- The influence of the type of aggregate for shielding concrete on API value was determined.

ARTICLE INFO

Article history:
Received 5 February 2017
Received in revised form 22 April 2017
Accepted 23 April 2017
Available online 28 April 2017

Keywords:
Autoclam air permeability
Relative humidity
Heavyweight aggregate
Barite
Magnetite
Serpentine
Radiation shielding concrete
Slag cement

ABSTRACT

The permeation properties of concrete are strongly influenced by the degree of saturation of capillary pores. Test results of the Autoclam air permeability index (API) of radiation shielding concrete are presented. Concrete specimens were made with CEM I and CEM III/A cements and special aggregates for radiation shielding: crushed barite, magnetite, serpentine and amphibolite. Two procedures of accelerated drying with simultaneous measurement of moisture distribution in the specimens were proposed. The specimens were tested at different RH levels from a fully saturated state to an oven dried state. The linear relationship between the API and RH was obtained. Effects of heavyweight and hydrogen-bearing aggregates on air permeability index were revealed.

1. Introduction

The essential criteria for concrete mix design for shielding structures of nuclear power plants include both shielding against ionizing radiation, mechanical and physical properties and also durability under severe environmental conditions [1,2]. Criteria for the selection of concrete components are related to plant operation conditions, especially neutron and gamma radiation, and also elevated temperature, which is cyclically variable in relation to the reactor fuel cycles. Moreover, concrete in load-bearing shielding structures should meet the requirements of strength, elasticity and impermeability to liquids and gases – also in emergency conditions [3–5]. The impermeability of concrete with regards to potentially contaminated air and water (due to e.g. the leaking of a reactor's cooling system) is one of the basic indicators of the functional suitability of a biological shield [6]. Low permeability also prevents against the penetration of harmful substances into concrete, which could lead to the corrosion of steel reinforcement or the destruction of concrete, as in e.g. spent fuel pools. The assessment of the permeability of concrete should take place in environmental conditions that are representative of the place of its usage.

Shielding concrete is prepared using special components, which are selected due to their neutron and gamma radiation shielding properties. Heavy aggregates such as barite, magnetite and hematite, which contain elements with a high atomic number, provide effective shielding for the γ radiation. For protection against neutron radiation, aggregates that contain elements with a low atomic number, a large amount of bound water and also boron in

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http://dx.doi.org/10.1016/j.conbuildmat.2017.04.177
0950-0618/

their composition are the most effective [7,8]. Special aggregates, ASTM C637 [9], generally made of soft rocks, are sometimes characterized by unfavourable gradation and a high content of dust that cause an increase of water demand and technological difficulties in the manufacturing and compaction of concrete mix [6]. As a result, it is difficult to keep low water/cement ratio of the mix while maintaining the desired homogeneity and consistency of concrete mix. Therefore an increased permeability of concrete made of the above-listed special aggregates can be expected.

The measurement of concrete permeability can be carried out using various methods. It is important that the measuring method enables concrete to be assessed at the stage of the design of its composition and also during a periodic inspection of concrete permeability in structural elements. The recommendations of IAEA [1] regarding nuclear containments suggest three methods of determining the air permeability of concrete, i.e. the Torrent method [10], the Autoclam method [11] and the method of surface airflow [12]. Comparative analysis of various methods that was presented in [13] indicated that the criteria for the evaluation of permeability (categories of concrete permeability) are generally defined with respect to specimens dried at a temperature of 105°C up to a constant mass. This applies to the methods of Torrent and Autoclam, as well as to the method of RILEM – Cembureau. There were also attempts to dry the surface of a concrete specimens using different methods [14], however they did not give satisfactory results. Numerous studies have shown that air permeability depends largely on the water content in concrete [15–17]. Therefore, correction coefficients and diagrams are used to approximately determine the surface moisture content of concrete on the basis of an electrical resistance measurement [18]. Due to the occurrence of near-surface moisture gradients [19] such dependence is difficult to establish.

The determination of the air permeability of concrete in a state of partial saturation of water meets the requirements of operation in nuclear power shielding constructions. On the basis of measurements of temperature and the relative humidity of concrete, Oxfall et al. proved the variability of hygrothermal parameters in different parts of single-shelled containment walls of a nuclear reactor [20]. Representative environmental conditions are determined by the temperature of concrete ranging from 50 to 65°C, and also a relative humidity (RH) from 40 to 60%. With the exception of the concrete layer in the close vicinity of a reactor, the relative humidity of concrete is maintained at this level after many years of reactor operation. The water content in concrete is also important with regards to shielding against neutron radiation [21], as hydrogen contained in water contributes significantly to neutron thermalization. Therefore, characterization of concrete as a shielding material, both against ionizing radiation and also against the infiltration of potentially contaminated air, should take into account water saturation.

The study of [22] focused on the tightness of the containment walls of nuclear power plants in the case of an accident caused by a loss of coolant, resulting in increased air–steam mixture pressure at an increased temperature to about 140°C. The effects of induced stresses and microcracks on the tightness integrity of a concrete wall were particularly studied. The results indicated that the degree of saturation level significantly affected the gas mixture leakage rate through undamaged concrete specimens. The vaporization of free water and the thermal expansion of water could create strong moisture gradients that are able to cause micro-cracks and influence permeability. It was suggested that the greater the initial water content, the more concrete porosity increases, and thus the water vapor leakage rate will therefore be greater. The authors of [23] proposed to spray water on dry and cracked concrete as a method to recover a large part of its gas tightness.

A low permeability of concrete is considered to prevent any significant leakage in undamaged zones but the air flow rate in containment buildings is significantly influenced by cracks [24,25]. The effects of microcracking on the air permeability of concrete, considered very relevant to the containment integrity evaluation, were studied for structural concrete by Wu et al. [26]. It was found that microcracking increased when the drying regime became more severe. The authors concluded that drying-induced microcracks must be considered when interpreting and comparing permeability results. However, the issue of permeability of damaged concrete is not pursued in this study.

The determination of concrete air permeability in a specified state of water saturation was considered in the works [27–30]. The authors highlighted the fact that specimens should be brought to the same humidity before testing due to the significant impact of concrete humidity on the results of permeability tests. However, frequently used intensive drying at a temperature of 105°C results in concrete damage, the formation of microcracks and also chemical changes, which affect the permeability test results. Proposals of specimen preparation methods that do not require drying at a temperature above 50°C have therefore been presented. The authors draw attention to the need to test specimens with a uniform specified humidity and to also determine the dependency between permeability and concrete humidity.

A significant impact of concrete composition on gas permeability is primarily known with regards to w/c ratio and also the content and type of supplementary cementitious materials. An improvement in the impermeability of concrete containing fly ash is assigned to pozzolanic reaction effects and also changes in the phase composition of hardened cement paste [28,31,32]. It has been found that the use of multi-component cements that contain fly ash and also granulated blast-furnace slag or limestone causes a reduction in air permeability [33]. The results of tests [19] proved that an increase in w/c ratio from 0.45 to 0.55 resulted in more than a twofold increase in air permeability. The influence of w/c ratio is crucial – according to [34] it is the basis when considering the usefulness of air permeability measurements in the assessment of the suitability of concrete in XC exposure classes according to PN-EN 206 [35].

The influence of type of aggregate on the air permeability of concrete was not systematically studied for radiation shielding concrete, however some results regarding aggregates used in ordinary concrete are known [36–38]. A significant decrease in air permeability was noticed when replacing granite aggregate for crushed marble aggregate. Microscopic analysis of the contact zone between grains and cement paste showed more detachments in the case of granite aggregate. It has been suggested that the type of aggregate mineral has an influence on the formation of defects and cracks in the contact zone, and this zone's defects contribute to an increase of airflow in the capillary pore system of the cement paste. It has been noticed, regardless of the type of aggregate, that there is a decrease in air permeability with a reduction of the aggregate grain size or a decrease of coarse aggregate content in the mix. It seems to be related to a better packing density aggregate grains.

The objective of the research undertaken by the authors is to determine the impact of special aggregates on the air permeability of shielding concrete at its specified humidity. In order to control the humidity of concrete, two variants of the methodology of preparing and testing concrete specimens have been developed. The scope of research does not include effects of the w/c ratio or the content of supplementary cementitious materials in concrete, but it does include the effects of using CEM I and CEM III/A cements i.e. Portland cement and slag cement.