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Development of low drying shrinkage foamed concrete and hygro-mechanical finite element model for prefabricated building fasçade applications

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ABSTRACT

Prefabricated lightweight concrete building fasçade can improve the energy efficiency of buildings and reduce the carbon emission of transportation. However, it is essential to maintain the dimensional stability of the full scale element. The drying shrinkage of lightweight foamed concrete was investigated in this study. The hypothesis of using the drying shrinkage of normal weight concrete to approximate that of lightweight foamed concrete of dry density about 1500 kg/m^3 counterpart was verified. Three different strategies of reducing drying shrinkage were studied. The drying shrinkage of common ingredients of ordinary Portland cement (OPC) and ground granulated blast-furnace slag (GGBS) was commonly up to 2000–3000 $\mu\varepsilon$. The use of magnesium expansive agent with different calcination conditions could not reduce the drying shrinkage. The use of calcium sulfoaluminate (CSA) cement with OPC and GGBS could significantly reduce the drying shrinkage within 1000 $\mu\varepsilon$ in standard testing environment. The formulation developed in laboratory was scaled up in a concrete production plant for prefabricated concrete elements. A lightweight full scale panel (the wet density was about 1700 kg/m^3) was fabricated. The drying shrinkage of the developed formulation with CSA cement was only 161 $\mu\varepsilon$ in the field test. A hygro-mechanical model was developed to model the diffusion, shrinkage and plastic strain evolution. The incremental stress-strain constitutive relationship of the hygro-mechanical model was derived for incorporating it into general finite element routine. The model parameters were calibrated by the drying shrinkage measurements in this study. The calibrated model demonstrated the cracking potential of three typical reinforced concrete panels of three different formulations studied in this study.

1. Introduction

Residential buildings in densely populated regions are commonly made of reinforced concrete. About 40–50% of energy consumed in buildings is spent on space heating and cooling. Heat is wasted through the building envelope. Even inside the building, heat may be transferred from one compartment to another unintentionally. The problem is exacerbated when floor heating system is used [1]. To improve the energy efficiency of building, it is desirable to minimise the heat transfer through the building envelope and partition of compartments by reducing the thermal conductivity, which is defined by the product of thermal diffusivity, specific heat capacity and density. As a general rule, the lower the density is, the lower the thermal conductivity for the same type of material. The density of concrete or cementitious material can be reduced by using lightweight aggregate [2,3], incorporating significant volume of air void (aerated concrete) [4,5] or the combination of both [6–9]. The air void of aerated concrete can be incorporated by gas-forming chemicals (aluminium powder, hydrogen peroxide, potassium permanganate or calcium carbide) or preformed foam by mixing with compressed air, pressurised water and foaming agent (detergents, resin soap, saponin or hydrolysed proteins) [10–12]. Alternatively, if the targeted dry density is higher than 1200 kg/m^3, it is possible to mix foaming agent in the wet mix to incorporate sufficient air void in the matrix by the shear stress

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induced during mixing. However, the dosage of foaming agent to achieve the targeted density depends on the type of foaming agent, rheology of the mix, mixer type and mixing time [13].

There are satisfactory solutions of internal non-structural partition walls such as autoclaved aerated concrete blocks and lightweight gypsum blocks. However, they are not suitable for the external walls and floor slabs which are usually structural elements. An alternative is to reduce the density of normal concrete of the building envelope and floor slab. Nevertheless, it is more difficult to control the quality of cast-in-situ lightweight concrete because it is sensitive to temperature, member geometry and casting procedure. Instead, the quality assurance can be improved by prefabrication in factory. Moreover, it is more environmental friendly and the productivity is higher to adopt prefabricated reinforced concrete elements compared to traditional cast-in-situ method [14–16].

The authors used OpenLCA 1.6.3 with the European reference Life Cycle Database (ELCD) to estimate the Global Warming Potential (GWP) of the transportation of twelve 2.9 m $\times$ 2 m $\times$ 0.06 m prefabricated reinforced concrete walls with different specific gravity for 200 km from the factory to construction site by a typical lorry. The GWP is reduced by 44% when the density of the material is two-third of normal reinforced concrete while it is 75% less when the density is reduced by half (the reference density is assumed to be 2400 kg/m^3) (Fig. 1).

While it is more effective from energy efficiency point of view to adopt lightweight concrete for building envelope and floor slab, the structural engineers may concern the long term structural performance and durability. A compromise is to use lightweight concrete for prefabricated non-structural permanent formwork of the building envelope and shallow deck of floor slab while the structural wall or floor slab can be cast-in situ with normal reinforced concrete (Fig. 2). The lightweight permanent formwork can reduce the thermal conductivity of the external wall or slab significantly. Suppose the thickness and thermal conductivity of the lightweight permanent formwork (1500 kg/m^3) and the reinforced concrete wall is 60 mm, 0.5 W/m·K, 180 mm and 1.3 W/m·K, respectively. The U-value of a normal reinforced concrete/lightweight permanent formwork composite is about 46% and 28% lower than normal concrete wall of thickness of 180 mm and 240 mm, respectively.

When the moisture gradient in concrete is positive towards the environment, the evaporable (non-chemically bonded) pore water in the specimen will diffuse to the surfaces and evaporate. This drying process results in moisture loss and shrinkage. Depending on the level of pore relative humidity (h), one or a combination of the following drying-shrinkage mechanisms: capillary pressure, disjoining pressure, surface tension, pore blocking, and movement of interlayer water, can be activated. In the medium to high range of h (50–85%), the shrinkage is attributed to the coaction of the changes in capillary and disjoining pressures during the drying process [17–19]. A concave-curved meniscus is formed in the pores due to moisture loss. The resulted change in the capillary pressure will compress the solid skeleton and lead to volumetric contraction. The moisture loss can also reduce the disjoining pressure in the areas of hindered water adsorption, which in turn decreases the separation between the solid surfaces. When h is above 85%, the movement of the evaporable water in the gel pores can be effectively blocked or slowed down by the link-bottle effect [18] and that is the major cause of the hysteresis of sorption isotherms [20]. In the low range of h (<50%), the meniscus formation in the pores is unstable and the associated capillary pressure effect would become inactive. When drying occurs in this low range, the decrease of the disjoining pressure and increase of the surface tension between the cement gel particles [17,21] are the major mechanisms for the shrinkage. When drying occurs below 25%, the interlayer water adsorbed between CSH sheets can be removed and a more compact (i.e. reduction in volume) pore structure is formed [22,18].

There are extensive review on the mechanical properties and thermal conductivity of lightweight aggregates and foamed concrete, which is referred to cementitious mortar without coarse aggregates and it is the adopted terminology in this study, however, little investigation on the drying shrinkage based on different formulation of the mix is available in literature [12]. The reported drying shrinkage of lightweight aggregates concrete ranges between 600 and 1200 $\mu\varepsilon$ that depends on the aggregate type, aggregate content and initial saturation of the aggregates [23–25]. The drying shrinkage of foamed concrete ranges from 600 $\mu\varepsilon$ to 3000 $\mu\varepsilon$ [12].

In this paper, different approaches of reducing the drying shrinkage of foamed concrete was investigated. The same approach

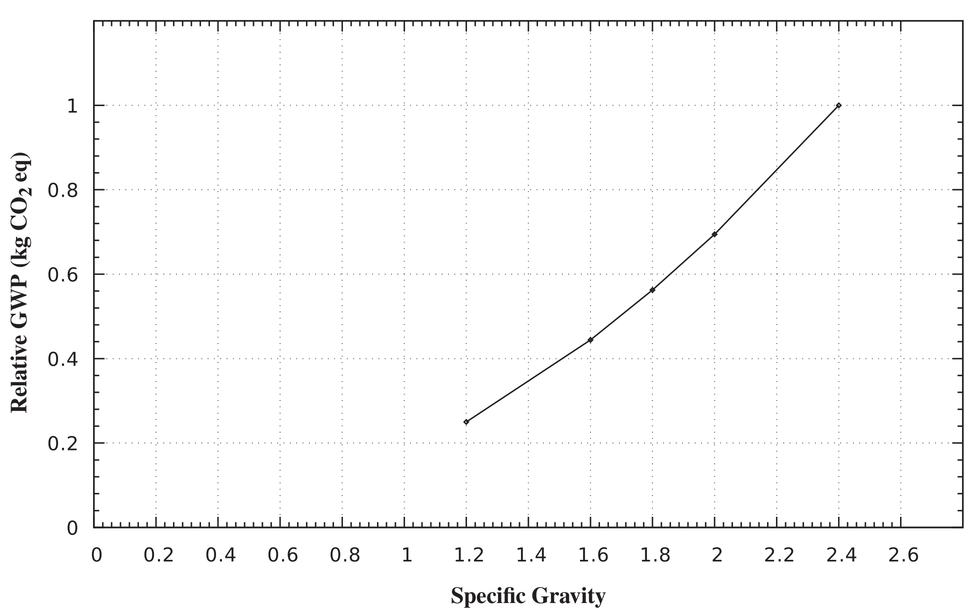

Fig. 1. Relative global warming potential (GWP) by lorry transport for 200 km with different density of 12 full scale building fasçades.