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Effects of insulation materials on mass concrete with pozzolans

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HIGHLIGHTS

- The maximum temperature rise and maximum temperature differential are examined.
- Insulation materials: included XPS, EPS, and PE boards.
- The IMTC (K_o), temperature–time gradient (λ), and R-value are examined.
- The correlations of K_o vs. λ, K_o vs. R-value, and K_o vs. R-value are analysed.
- A 1-in. XPS board enhances efficiency on mass concrete for top and side isolation.

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ABSTRACT

A mix incorporates cement(II), fly ash, and slag to design mass concrete. A simplified box is set up to measure K_o. Two blocks are established to evaluate the insulation with thin sides (1/2-in.PE; top: none) and thick sides (1-in.XPS and 1-in.EPS; top: 1-in.XPS) and wrapped with canvas. Results for K_o were 1-in. XPS < 1-in.PE < 1-in.EPS < 1/2-in.PE. The maximum temperature differentials are less than 12 °C. The insulation effect of the face was 1/2-in.PE < 1-in.EPS < 1-in XPS, and the top 1-in.XPS enhanced insulation effectively. The values of R^2 for K_o vs. λ, λ vs. R-value, K_o and vs. R-value were 0.995, 0.987, and 0.966 to assess appropriate insulation materials.

1. Insulation and materials

ACI 301 in ACI 116R defines mass concrete as any volume of concrete with dimensions large enough (at least 4 in. (120 cm)), where measures are required to cope with the generation of heat from hydration of the cement (more than 660 lb/yd^3 (390 kg/m^3)) and attendant volume changes in order to minimise cracking [1–4]. ACI 207.2R [5] states 'All concrete elements and structures are subject to volume change in varying degrees, dependent upon the makeup, configuration, and environment of the concrete'. For sizes of 5 ft. (1.5 m) or greater and lateral form dimensions of around 8–10 ft. (2.4–3 m), the temperature rise is essentially adiabatic in the central part of the mass of fresh concrete. At exposed surfaces (formed or unformed), the heat generated is dissipated into the surrounding air at a rate dependent upon the temperature differential (gradient). Therefore, the net temperature rise in concrete adjacent to the surface (or forms) is less than that in the interior. While this results in a gradually increasing temperature gradient from the surface to the interior, little or no stress (or strain) is developed because the concrete is not yet elastic. ACI 207.4R-05 'Cooling and Insulating Systems for Mass Concrete' [6] states that the need to control volume change induced primarily by temperature change in mass concrete often requires cooling and insulating systems. For mass concrete, to protect the temperature gradient of the surface through core temperature not exceeded too many to induce cracking [7,8].

Abbreviations: XPS, extruded expanded polystyrene board; DEF, delayed ettringite formation; FDOT, Florida Department of Transportation; GDOT, Georgia Department of Transportation; HRWRA, high-range water-reducing agent; IMTC, insulation material temperature conductivity; EPS, expanded polystyrene; PE, polyethylene; SCC, self-consolidating concrete.

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Mass concrete has two major important thermal characteristics, the temperature rise and the temperature differential. An excessive temperature rise (over 160 °F (71.1 °C)) may induce thermal cracking and delayed ettringite formation (DEF) [9–13]. However, in the Florida Department of Transportation (FDOT) [14] and in the Georgia Department of Transportation (GDOT) [15], the maximum temperature rise for mass concrete is up to 160 °F (71.1 °C). Due to the thermal movement restraint of structural elements for mass concrete, the temperature differential between adjacent positions (a point at the centre of a section and the adjacent surface) should not be greater than 20 °C between the centre of the concrete section and the surface. Otherwise, it may be constrained to increase the interior, exterior, or both restraints so as to enhance the probability of cracking [7,8]. In the GDOT, the maximum temperature differential is limited to 36 °F (20 °C) [15]. The thermal characteristics of mass concrete will affect its hardened properties and its long-term durability (only if it cracks).

Insulation or insulated formwork is often used to retain heat at a concrete surface and reduce the temperature differential, which in turn reduces the potential for thermal cracking. For most mass pours, surface insulation does not appreciably increase the maximum concrete temperature, but it can significantly decrease the rate of cooling. Insulation is inexpensive, but delays resulting from the reduced cooling rate can be costly. Insulation often has to remain in place for several weeks or longer. Removing it too soon can cause the surface to cool quickly (causing thermal shock) and crack. A thermal resistance (R-value) of 4.0 h ft^2 °F/Btu (0.70 m^2 K/W) has been found to be effective for moderate climates. This is provided by a 1-in.-thick expanded synthetic material such as polystyrene or urethane. According to ACI 207.4r-05, acceptable temperature gradients can be maintained during the winter season in moderate climates by the application of insulation with an R-value of 4.0 h ft^2 °F/Btu (0.70 m^2 K/W). In severe climates, insulation with a R-value of 10.0 (1.76 ft^2 K/W) is recommended. Many types of insulation materials (such as black blankets, polyethylene (PE; 1-in. R-3.0) boards, expanded polystyrene (EPS; 1-in. R-4.0) boards, extruded expanded polystyrene (XPS; 1-in. R-5.0) boards, canvases, *etc.* are available, and insulation levels can be optimised to meet the required temperature differentials to maximise the rate of cooling and to improve the construction economy [6,16–20]. A maximum allowable temperature differential of 36 °F (20 °C) is often specified in specifications for mass concrete. This temperature difference is a general guideline based on experience with unreinforced mass concrete installed in Europe more than 75 years ago. In many situations, limiting the temperature differential to 36 °F (20 °C) is overly restrictive; thermal cracking may not occur even at a higher temperature differential. In other cases, significant thermal cracking may still occur even when the temperature differential is less than 36 °F (20 °C) [1,17]. The maximum allowable temperature differential is a function of the mechanical properties of the concrete, such as thermal expansion (coarse aggregate), tensile strength, and elastic modulus, as well as the size and restraints of the concrete element. Some have suggested that, for concrete with gravel, granite, and limestone coarse aggregates, the temperature difference limit should be 36 °F (20 °C), 45 °F (25 °C) and 56 °F (31 °C), respectively. The coarse aggregate should also be from a single source to limit temperature differentials in order to avoid cracking [19].

Options open to an engineer seeking to limit heat generation of concrete include: (a) the use of Type I, Type II (moderate heat, MH), Type IV (low heat, LH), and Type V Portland cement, with specific maximum heat options to limit hydration if necessary (as covered by ASTM C150); (b) the use of blended hydraulic cements (Types IS, I(PM), IP, P, and I(SM), as covered by ASTM C150, C595, and C1157), which exhibit favourable characteristics for heat of hydration, which may be more firmly achieved by imposing limits on heat of hydration for the cement clinker; (c) the use of hydraulic cements (Types GU, MS, HS, MH, and LH, as covered by ASTM C1157), and (d) the reduction of cement content by using a pozzolanic material, either fly ash or slag or both, to provide a reduction in maximum temperatures produced without sacrificing the long-term strength development and durability. When cement is used with pozzolans or with other cements, the materials are batched separately at the mixing plant, and improved economy and low temperature rises are both achieved by limiting the total cement content to as small an amount as possible. Type I and GU cements are suitable for use in general construction. However, they are not recommended for use alone in mass concrete without other measures that help to control temperature problems, because of their substantially higher heat of hydration [5,6,21].

Structural concrete that uses ternary binders (cement, slag, and fly ash) is a more recent application in Taiwan. Internationally, most mass concrete uses binary cementitious materials, such as cement and fly ash or ground granulated blast-furnace slag. A large portion in the USA uses all three. For example, in Canada and some states of the USA, it has been suggested to adopt ternary binders, including cement, fly ash, and slag, for the mixture of mass concrete. A total cement substitution of 50% [22–24] slag and fly ash is licensed by the Departments of Transportation of Iowa, Kentucky, West Virginia, and Florida [14]. For mass concrete in Canada [25], in order to significantly reduce the heat of hydration, it is recommended to use a minimum of 50% fly ash Type F or CI, or a mixture of both, or a minimum of 65% fly ash Type CH or slag, or a mixture of both, in hot weather (above 81 °F (27 °C)). Fly ash Type F, CI, and CH have CaO contents of less than 8%, 8–20%, and greater than 20%, respectively. Lawrence et al. [26] used a 3-D finite element analysis to study the effect of early age strength on cracking in mass concrete containing different supplementary cementitious materials, including a mixture with cement, fly ash (20%), and slag (30%).

This paper examines mass concrete used in a new large medical building located in the city of Kaohsiung in southern Taiwan (note that the weather here is similar to that in Florida and Hong Kong). The concrete structure had non-reinforced mass concrete and was designed temperature steel reinforcement. The thickness of the mass concrete for a wall structure serving as a proton radiation engineering barrier was between 5 and 12 ft., and temperature differential was limited to 25 °C (construction took place below 20 °C). Before construction at the job site, a test model (block 1 or 2) of the mass concrete was selected in order to find the most locally appropriate insulation materials that conform to the requirements of controlled temperature and prevention of cracks.

2. Materials and methods

The cementitious materials included Type-II Portland cement (ASTM C150; not Type-II (MH) cement), ground granulated blast-furnace slag (Grade 100, ASTM C989), and Class-F fly ash (ASTM C618). The properties of the binders are as shown in Table 1. The coarse and fine aggregates comprised crushed stone and natural sand. The maximum aggregate size was 3/4 in., and the fineness modulus of the sand was 2.81. The properties comply with ASTM C33. The high-range water-reducing agent (HRWRA) was ASTM C494 Type G. The water used was potable water.

3. Mixture design and experiments

3.1. Mixture design

The specifications for the mass concrete are as follows:

- The water-to-cementitious ratio (W/CM) less than 0.45;