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An investigation into the thermal conductivity of hydrating sprayed concrete

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HIGHLIGHTS

- Early age thermal conductivity is mainly influenced by free water content.
- Mature age thermal conductivity is mainly influenced by porosity.
- Thermal conductivity is found to exponentially vary with density.

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ABSTRACT

Information about the thermal conductivity of sprayed concrete is useful for calibration exercises using sprayed panels, where heat flows need to be estimated, and future enhancements to the method to include estimates of concrete temperature across the thickness of the lining. However, the necessary information about thermal conductivity of sprayed concrete is rare, and no information about the early age thermal conductivity of sprayed concrete has been found. The thermal conductivity of sprayed concrete aging from five hours after casting to 20 days was continuously measured by a transient method. Thermal conductivity was found to be higher than expected at early age and decreased to the mature value as the concrete cured. Based on these results it is hypothesized that early age thermal conductivity is mainly influenced by free water content, while at a mature stage the key determinants are the structural features of the cement matrix. Thermal conductivity is discovered to have an exponential relationship with density, regardless of mix constituents. A convenient numerical approach is proposed to estimate thermal conductivity for concretes and its accuracy has been verified by data from tests on a wide range of concretes with density ranging from 0.2 g/cm^3 to 2.5 g/cm^3.

1. Introduction

The new method of strength monitoring using thermal imaging, known as SMUTI, provides a system that measures the surface temperature of the sprayed concrete tunnel lining to assess the curing of concrete [1]. The temperature history is then used to calculate compressive strength using an Arrhenius equation-based time-stepping algorithm [2]. This technique will especially benefit sprayed concrete tunnel construction since it will improve work efficiency and safety by reducing the need for a large amount of in situ testing, removing the need to access the face area of the tunnel, and by providing the compressive strength of the whole tunnel lining and not just discrete areas.

Although not essential to SMUTI, information about the thermal conductivity of sprayed concrete is useful for calibration exercises using sprayed panels, where heat flows need to be estimated, and future enhancements to the method to include estimates of concrete temperature across the thickness of the lining. However, the necessary information about thermal conductivity of sprayed concrete is rare, and no information about the early age thermal conductivity of sprayed concrete has been found. Thus, the aim of this paper is: (1) to prepare concrete identical with the one used in practice; (2) experimentally determine the effective thermal conductivity (ETC) of sprayed concrete; (3) establish a numerical model for evaluating ETC of concrete; (4) validate the numerical model with experimental results; (5) evaluate the effect of steel-fiber reinforcement on ETC.

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1.1. Sprayed concrete

Sprayed concrete can be traced back to 1911 when it was known as "gunite" [3]. It is pneumatically projected through a nozzle where a chemical accelerator is added [4]. In this way layers may be built up to form a tunnel lining. Sprayed concrete has a different mix design compared to conventional in situ poured concrete. Fine particles (fine aggregate and cement) are dominant in the mix, cement content is between 400 and 450 kg/m^3, and often silica fume is added. The fraction of coarse aggregates greater than 4 mm, usually with a maximum size of 8–10 mm, is only approximately one quarter of the mass of sand (<4 mm), which is the opposite of what is normal for conventional concrete. Thus, a higher pump-ability and workability is achieved with very little segregation or bleeding. Chemicals are used to control hydration of cement (retarders and alkali-free accelerators) or adjust water content (superplasticisers). Sometimes pozzolanic or/and latent hydraulic binding material is added to improve certain properties in the plastic and/or hardened state, and steel reinforcement (wire mesh, bars or fibers) is used to increase the flexural strength and control cracking. Today, sprayed concrete is widely used in underground construction, requiring a fast setting and adequate early-age compressive strength to provide structural support.

In tunnel construction, the development of the early age compressive strength of sprayed concrete is critical not only because of its structural function and the need to support the ground before continuing excavation, but also for protection of the workers from falling ground or indeed falling sprayed concrete. However, the currently recommended strength testing methods, which are penetration needle tests and stud driving method [5], have their inherent defects: difficult and time-consuming operation, small examined areas and scattered data. Usually early age strength tests are performed on a panel sprayed at the same time as the tunnel lining. In order to test the actual tunnel lining, the engineer would have to be exposed to the risk of falling ground or shotcrete, and may need special plant or scaffolding for access.

Estimation methods of early-age compressive strength have been proposed, such as maturity methods based on the principle that concrete strength is directly related to both age and evolution of temperature in time, i.e. a relationship between the evolution of temperature and age and the strength development is mathematically established. But surface or embedded temperature measurement using thermocouples or other devices would be difficult in a sprayed concrete lining, and would not remove the safety risks related to access or the drawbacks associated with testing discrete locations. Using a thermal imaging camera enables the engineer to remotely scan the whole sprayed concrete lining from a position of safety, without interfering with plant movements necessary for continuous production.

1.2. Thermal conductivity of concrete

ETC varies depending on the concrete mix, and it also varies with age. Cement hydration [6,7], which is responsible for converting a concrete from a fluid to a rigid, load-bearing and durable solid element, alters the volume fractions and spatial arrangement of solids, liquid, and gases within the concrete during hydration and aging. Thus, thermal conductivity at early age differs from one at mature age. For mature concrete ETC has been widely investigated, generally ranging between 1 and 2.5 W/(m °C) [7]. It can reach even lower values, such as 0.1 W/(m °C), for air-rich concrete [7,8].

The fraction and types of each component material, coupled with ambient conditions, all have been considered as factors affecting ETC [6,7,9,10]. According to research conducted by the Bureau of Reclamation, US Department of the Interior, the type of coarse aggregate is the most important factor [4]. They experimentally investigated the effect of these constituents on ETC for conventional concretes and mortars and found that the types and fractions of aggregates affected the thermal conductivity more than other constituents. The importance of aggregate was corroborated by Kim et al. [11]. ETC of individual common concrete constituent materials is known alone, selected one of which has been shown in Table 1.

Table 1
Thermal conductivity of common concrete materials at 25 °C [12].

Materials	Thermal conductivity (W/(m °C))
Gravels	0.7
Granite	1.73–3.98
Limestone	1.26–1.33
Sand (moist)	0.25–2
Sandstone	1.7
Water	0.58
Air	0.026
Portland cement powder	0.29

Water/cement (w/c) ratio, curing temperature, and other factors have been observed influencing ETC of concretes to different extents. Increasing the w/c ratio decreases the ultimate ETC of concrete as it increases the volume of micropores and subsequently adds to the resistance to heat flow [3,6,13,14]. Ukrainczyk & Matusinović studied the influence of temperature on thermal properties and found the ETC of cement pastes increasing with curing temperature rising from 20 °C to 80 °C [15]. The Hashin-Shtrikman boundary conditions and a simple law of mixtures was successfully applied in their work for estimating thermal properties. The work done by Demirboga showed a reduction of ETC caused by addition of mineral admixtures [16].

Reinforcement by steel fibers has been observed to not only enable a notable impact on concrete strength, toughness and resistance to cracking and spalling [14–19], but also has an influence on the thermal properties of concretes. To a concrete having perlite as main coarse aggregate, the addition of 1.75% mass of wavy steel fibers has been observed to increase the thermal conductivity of concrete by 31.2% [17]. But not all previous studies have observed the same effect; this will be discussed in detail later.

Although many studies have been conducted for conventional concrete, not much is known about the thermal properties of sprayed concrete. Assuming its ETC is the same as for conventional concrete is not a safe assumption because its different composition may have a significant effect on ETC.

Studies measuring ETC of hydrating cement pastes presented changing thermal conductivity with time at early hydration ages and showed some dependency on hydration rate [4,10,11,18]. A cement paste hydrated at the fastest rate and reaching the highest peak temperature had a higher thermal conductivity than that of a fresh cement paste by about 40% and hardened paste by about 30%. The hardened paste had a reaction degree of 55%. In some works, during the first 10 h the ETC of cement pastes increased and then dropped consistently during the following 20 h [14,20]. The biggest drop of 0.5 W/(m °C) occurred with CEM I paste. These results imply that concrete may have a changing thermal conductivity at early age and this may be accentuated in sprayed concrete, which tends to have a higher volume fraction of cement paste than conventional concrete.

2. Thermal conductivity assessment approaches

Thermal conductivity for concretes can be measured directly by generating a controlled heat flow through the tested material in a prescribed direction, to ensure that the boundary conditions agree with theoretical technical assumptions. The current most popular