Thermal conductivity and shrinkage properties of slag-based cement concretes

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Abstract. The thermal conductivity, specific heat, and total drying shrinkage test of slag blended OPC cement is conducted by using a Hotdisk-2500S thermal conductivity, and non-contact shrinkage deformation measurement apparatus based on ISO 22007-2 and GB/T50082-2009 test standards, respectively. The influence of replacement rates of slag cement (0, 30, 50, and 70%) and high-temperature exposure (21, 200, 400, 600, and 800 °C) on the thermal properties of concrete is analysed. The results show that for all three concretes, the thermal conductivity initially decreases with increasing temperature up to 400 °C, then after it remains almost constant between 400 and 600 °C, and gradually begins to decrease again up to 800 °C. Furthermore, thermal diffusivity of concrete group G-70, shows 21.4, 21.6, and 37.6% increment in 21, 200, and 600 °C temperature exposure respectively compared to concrete group G-0. Though, as the exposure temperature keeps rise to 800 °C, its value starts to decrease. Furthermore, the results indicated that high volume slag cement content in the concrete mix lessen the drying shrinkage of the concrete at later age. Test data is used as a function of temperature and slag replacement to establish high temperature relations for thermal properties. The proposed thermal property relationships can be used as input data for validation in computer programs and to evaluate the response of OPC and slag blended Portland cement concrete structures subjected to fire.

1. Introduction

Thermal properties of concrete are critical for evaluating temperature rise in concrete members, which are needed for defining strength and stiffness degradation and ultimately fire resistance of concrete structural members [1],[2]. These thermal properties vary with temperatures and thus accurate predictions of temperatures in concrete members require temperature dependent thermal property relations. As we can see from the previously published literature [3]–[7], there is shortage of data specific to high temperature thermal properties of new types of slag cement blended concrete. To develop such information classification of high temperature thermal properties of various percentage of slag cement replacement is undertaken.

Thermal conductivity, specific heat, and thermal diffusivity are the principal thermal properties that influence the temperature rise and fire induced forces in concrete structural members. At present, as a function of temperature, some codes and design specifications have thermal property relations (ASCE, 1992; Eurocode 2, 2004) [8]. These relationships are primarily derived from traditional normal strength concrete experimental studies and in some cases, conventional high strength concrete.
However, factors such as percentage of slag, OPC or silica fume, mix proportions, w/c ratio and curing temperature influence the thermal properties of slag blended cement concrete, especially at elevated temperatures. A series of thermal property tests were performed on different types of slag mixed cement concrete specimens to measure the impact of some of these factors, and furthermore the effect of some of these factors on the thermal properties of slag cement concrete was also quantified. Based on the test data obtained from these thermal property tests, simple empirical relations for high temperature thermal properties are also presented. A detailed description of the tests and discussion of test results on thermal properties is presented afterwards. The state-of-the-art study equipment called Hot Disk was used for thermal conductivity and specific heat measurements. In contrast to other existing test equipment utilizing separate equipment for measuring thermal conductivity, thermal diffusivity, and specific heat, the Hot Disk is a relatively new equipment and incorporates the measurement of three heat transfer properties (thermal conductivity, thermal diffusivity, and specific heat) in one single test [4],[7]. Thermal conductivity and thermal diffusivity are specifically determined in the case of the Hot Disk, and specific heat is calculated internally based on the measured thermal conductivity and thermal diffusivity.

The aim of this study is to evaluate high temperature thermal and shrinkage properties of OPC and slag cement concrete with various replacement range. Thermal properties consisting of specific heat, thermal conductivity, and thermal diffusivity and total drying shrinkage properties were measured. All properties except for total drying shrinkage were measured in the temperature range of 20 – 800 °C, while shrinkage measurements were carried out at room temperature range. Data generated from tests was utilized to develop simplified relations for expressing thermal properties of OPC and slag cement blended concrete as a function of temperature.

2. Experimental Program

2.1. Materials

In the production of blended cement concrete, commercially available ground granulated blast furnace slag was used. The chemical and physical properties of OPC and Slag cements used for this experimental work has previously determined by Shumuye et al. (2020)[10]. The cement content and w/cm ratio were 431 kg/m³ and 0.47 respectively for the concrete mixtures and were also constant during the whole sample preparation. ASTM Type I Portland cement was used in the study. In addition, naturally available river sand and coarse aggregate having a maximum aggregate size of 20 mm were used. Consolidation of concrete was done by viberator table. The details of the concrete mix proportions were given in Table 1.

| Materials      | Mixture Designation | G-70 | G-50 | G-30 | G-0 |
|----------------|---------------------|------|------|------|-----|
| OPC (kg)       |                     | 129.3| 215.5| 301.7| 431 |
| GGBS Cement (kg)|                    | 301.7| 215.5| 129.3| -   |
| Water (kg)     |                     | 202.7| 202.7| 202.7| 202.7|
| w/cm           |                     | 0.47 | 0.47 | 0.47 | 0.47|
| Coarse aggregates (kg) |               | 1052.6| 1052.6| 1052.6| 1052.6|
| Fine aggregates (kg)  |               | 755.2 | 755.2 | 755.2 | 755.2|

2.2. Methods

2.2.1. Total shrinkage measurement: A total of 12 prismatic specimens with the size of 100 mm × 100 mm × 515 mm will be tested for all 4 - concrete group as shown in the Figure 1. The shrinkage test was carried out following non-contact test standard according to Chinese standard (GB/T50082-2009) [11]. Non-contact shrinkage deformation of concrete tester, model NELD-NES, was used to determine
the development of autogenous shrinkage of OPC and slag blended OPC concrete. Figure 1(a) shows the details of the schematic test setup. The shrinkage or expansion could be monitored by two steel bars in the concrete. In order to avoid potential water evaporation, the fresh concrete mixture was cast into the mould and coated with a polyethylene film.

2.2.2. Thermal conductivity and specific heat measurement: Thermal conductivity and specific heat measurements were carried out using Hot Disk (TPS 2500S) apparatus on 100 × 100 × 50 mm test specimens. The specimens were air dried and the surfaces were smooth using a smoother to ensure proper contact with the sensor. Five temperature points, namely 21±2 (room temperature), 200, 400, 600, and 800 °C, were measured for thermal conductivity and specific heat. The smaller heating rate to higher temperatures were intended to capture the effect of concrete phase changes on thermal properties [12]. The concrete age was 3 months or older at the time of thermal property calculation tests. The Kapton sensor was used to carry out room temperature (21 °C) test. This Kapton sensor is attached to the hot disk and is placed between two halves of concrete test samples. The sample and sensor assembly are located on a room temperature sample holder platform (Figure 3). The system sends and receives a signal through a sensor linked to the TPS 2500S and is monitored by a computer program. To determine the best test parameters, measurements at room temperature with a kapton sensor are critical as acceptable test results obtained at room temperature provide suitable parameters to be used in high temperature tests. The mica sensor was placed between two specimens for high temperature tests and the sample was subjected to elevated temperatures in a furnace connected to the Hot Disk apparatus.

Figure 2(b) shows the mica sensor being positioned in the holder assembly between two samples of concrete. Furthermore, this holder assembly is put inside the furnace for high temperature exposure. The temperatures of the specimen and the furnace are controlled by a computer program. In a furnace linked to the Hot Disk apparatus, the concrete specimens are subjected to high temperatures according to specified test conditions. The test condition parameters namely, probing depth, sensor type, initial thermal coefficient of resistance (TCR), hold time at steady state, measurement power, and measurement times are to be programmed (as input) by the user into the Hot Disk system [9], [12]. Initial TCR of 0.004686 /K, probe depth of 20 mm, sensor measuring power of 20 mW, hold time of 0.48738 second and measuring time of 5 seconds were used for these experiments. A built-in TCR value was used for high temperature measurements at each temperature, as per the type of sensor. At each target temperature, thermal conductivity and specific heat are registered until the thermal equilibrium is reached. The temperature in the furnace is then elevated to the next target temperature and this procedure is continued till 800 °C. To reach a target temperature with 100 °C increments, it took an average of 25 minutes and an average of 17 minutes to reach a target temperature with 50 °C increments. The total stabilization time in the specimens to achieve a uniform temperature was 300 minutes for 100 °C increments and 210 minutes for 50 °C increments. This resulted in an average time of approximately 52 hours running a full test on each specimen. The selected ramp was 10 °C per
minute for concrete specimens. For each specimen, it took three hours and twenty minutes to achieve the target temperature of 800 °C. The heating rate used in thermal expansion tests is shown in figure 2.

2.2.3. Mixing, curing, and testing: Slag cement was used as 0%, 70%, 50%, and 30% replacement of OPC and three concrete prism specimens were produced for each mixture proportions (Table 1). All the concretes were mixed in a revolving drum pan mixer of 60 L capacity in the laboratory. Several standard test specimens of different sizes were chosen to investigate the various parameters. Prisms of 100 × 100 × 515 mm and 100 × 100 × 100 mm concrete cube were cast for the determination of drying shrinkage and thermal conductivity of concretes mixes, compiling with Chinese standard (GB/T50082-2009) [11] and ISO 22007-2 respectively. For each test, three specimens were casted. The mixing and curing of concrete adopted for this test has been described earlier in following papers [13]. Samples were kept for 24 h in the laboratory atmosphere. The samples were subsequently demoulded and preserved at a constant temperature of 20±2 °C (ASTM C09 Committee 2004) [14] and 95 percent relative humidity (RH) for 7, 28, and 56 d. in the normal curing state.

Figure 2. Heating rate for furnace

Figure 3. Test setup and apparatus for room temperature and high temperature thermal exposure

Figure 4. Two types of sensors used
3. Result and discussions

3.1. Drying shrinkage of OPC and blended cement concrete

Figure 5 exhibit the influence of slag cement on total shrinkage in concrete at early and later age. The experimental results show that, the total shrinkage of concrete with different replacement of slag cement increases gradually as ages goes by. The concrete mix group made from 30% slag cement (G30) had almost the same early age drying shrinkage as compared to concrete mix group made from 50% slag cement (G50). The early age drying shrinkage of concrete mix group made from 70% slag cement (G70) had greater than concrete mix group made from 50% slag cement (G50). Concrete mix group G70 had the lowest early age drying shrinkage. This early age shrinkage was typically related to the first 24 h hydration reaction period, high slag content reduced the early age drying shrinkage.

Additionally, the results indicated that high volume slag cement content in the concrete mix lessen the drying shrinkage of the concrete at later age. The drying shrinkage result for all concrete mix groups at later ages had similar trend but different magnitude. The presence of moisture in the concrete affected the drying shrinkage. It is known that the evaporation of moisture from the concrete surface to the environment had an influence on the drying shrinkage of the concrete [15], [16].

![Figure 5. Total shrinkage of OPC and Slag cement concrete at (left): early age (right): later age](image)

3.2. Thermal conductivity of OPC and blended cement concrete

Thermal conductivity values of concrete have been measured on prism samples (100 × 100 × 50 mm) using Hotdisk-2500S thermal conductivity measurement apparatus based on ISO 22007-2 test standard. The Hotdisk is equipped with an extensometer that allows the measurement of the strain of the sample during heating. More details on the experimental device are presented by Khaliq (2012)[12].

Figure 6 shows the thermal conductivity curves of almost all the studied concretes with respect to change in temperature. For all three concretes, the thermal conductivity initially decreases with increasing temperature up to 400 °C, then after it remains almost constant between 400 and 600 °C, and gradually begins to decrease again up to 800 °C. This variation in thermal conductivity can be attributed from moisture content variation with increasing in temperature exposure[4], [12]. The initial steep slope of thermal conductivity up to 400 °C can be attributed to the loss of moisture at a faster rate due to the evaporation of free and chemically bonded water in concrete at higher temperatures. The slight difference in thermal conductivity between 400 and 600 °C is due to the decoupling of insignificant quantities of physically bound water contained in concrete as a result of phase change[13]. Thermal conductivity for G-70 and G-0 follows a very similar pattern and is closer to that of the G-50 concrete group, so it is assumed that the thermal conductivity values of G-50, G-70 and G-0 do not vary much. G-0 thermal conductivity follows the same pattern close G-70 concrete from 200 - 600 °C but tends to remain slightly higher after G-50 thermal conductivity. The main reason for dropping the thermal conductivity of all concrete above 600 °C is that maximum concrete dehydration has already
occurred and there is not much physically, or chemically bound water left to be released. As a result of prolonged curing time of concrete group G-50, a more condensed and thoroughly hydrated concrete obtained which results, a slight improvement in thermal conductivity of this concrete group due to the evaporation of chemically bonded water. This might be attributed to the fact that concrete group G-50 produced excessive hydration products, and thus it has increased the amount chemical compound dissociation and evaporation of chemically bonded water. According to (Kudus et al., 2020)[17], having higher concentration of chemical ions slightly increases thermal conductivity of slag blended cement concrete.

![Figure 6. Measured thermal conductivity as a function of temperature for OPC and Slag cement concrete](image)

Figure 6 shows the effect of slag cement on the thermal conductivity of OPC and slag blended cement concrete, as a function of temperature variations, respectively. For concrete group without the addition of slag cement (G-0), the trends indicate that addition of slag cement to concrete does not significantly alter the thermal conductivity for all temperature exposure. However, for concrete group having 50% slag cement and 50% OPC (G-50) have a minor impact, showing increment on thermal conductivity of slag blended cement concrete. This results from the dehydration of the C-S-H, and also due to the dehydration of chemically bonded water[18].

Thermal conductivity of G-50 concrete group at room temperature was a little higher as compared to concrete group G-0, this can be attributed to the prolonged curing time and intense hydration of slag blended cement concrete. For instance, in room temperature exposure concrete group G-50, attains 17.5 & 31.3% increment compared with G-0 & G-70.

3.3. Specific heat of OPC and slag blended cement concrete

The variation of specific heat for concrete group G-0, G-50, and G-70 with different temperature exposure is illustrated in Figure 7 (a). The specific heat for concrete group G-70 remains constant starting from room temperature exposure up to 600 °C, then increases up to about 800 °C. However, for concrete group G-50 and G-0, the specific heat starts to fluctuate up to 400 °C, and then remains increasing significantly from 400 - 800 °C temperature exposure range. Concrete group G-50 and G-0 exhibit almost the same value in a temperature range of 21 - 400 °C, furthermore, the result also exhibit slightly higher value of specific heat compared to concrete group G-70, throughout the whole temperature exposure.

This might be due to having different permeability characteristics and internal microstructural formation of concrete. The permeability of the above-mentioned concrete has been studied in a separate section as reported in related literatures and shown in Figure 7 (b). As increasing the replacement of slag, the concrete porosity starts to decrease. It can be observed that slag blended cement concrete is less permeable than that of OPC concrete. Due to releasing of embedded moisture, extra heat is observed in these processes. As Khaliq (2012)[12]; reported that above 600 °C enormous
amount of heat is required to increase the temperature of the carbonate aggregate concrete. Likewise, slag blended cement has lower specific heat compared to OPC, which again can be attributed to presence of pores. This is further proved by the fact that 70% slag and 30% OPC has the lowest specific heat between 400 and 800 °C temperature range. This can be attributed to the lower permeability and dense microstructure of OPC concrete that requires extra heat to convert moisture into vapors. OPC displayed higher specific heat values as compared to specific heat of slag blended cement concrete as reported in literature[4].

![Figure 7. Measured specific heat as a function of temperature for OPC and Slag cement concrete and Total porosities of the specimens as a function of the replacement ratio of ground-granulated blast-furnace slag (GGBS)](image)

The effect of slag cement on the thermal diffusivity of concrete is also illustrated in Figure 8, as a function of temperature variations. For concrete group without the addition of slag cement (G-0), the trends showed that addition of slag cement to concrete significantly affect the thermal diffusivity of concrete by increasing its value in all temperature exposure. Furthermore, concrete group G-50 and G-70, follows almost the same trend in thermal diffusivity reduction till 400 °C then concrete group G-50, start to nose down instantly when the exposure temperature rise to 600 °C. However, at 800 °C exposure temperature the thermal diffusivity value starts to decrease for concrete group G-70. These results might be from the dehydration of the C-S-H, and also due to the dehydration of chemically bonded water.

Thermal diffusivity of concrete group G-70, shows 21.4, 21.6, and 37.6% increment in 21, 200, and 600 °C temperature exposure respectively compared to concrete group G-0. However, as the exposure temperature keeps rise to 800° C its value starts to decrease.
3.4. High temperature property relationships

In order to establish thermal property relationships for OPC and slag blended cement, data produced from the thermal property measurements were used. These properties are expressed in the form of analytical relationships for thermal conductivity, thermal diffusivity, and specific heat relationships of OPC and slag blended cement concrete over the temperature range of 20 - 800 °C. Based on linear regression analysis, these empirical relationships were arrived. Measured thermal properties were used as response parameters for the regression analysis, with temperature as the prediction parameter. In order to determine a linear fit through regression analysis, commercially available statistical software (Minitab) was used following the same procedure as Khaliq et. al. (2011)[4]. The accuracy of the statistical model is expressed by the R² determination coefficient, which represents the proportion of the number of squares of the response value deviations with respect to their prediction. The value of R² ranges between 0 and 1, where 1 is the perfect match for the underlying data in the equation. For the proposed equations, the R² value obtained is between 0.95 and 0.99 for thermal properties, in view of the high variability in individual properties, this reflects a relatively high degree of trust. For each concrete type, thermal conductivity relations are presented in two temperature ranges i.e. between 20 - 400 °C and 400 -800 °C.

The expression for thermal conductivity, thermal expansion, and specific heat of OPC and slag blended cement are presented in Table 2. Since thermal properties of concrete has a direct correlation with temperature, a single equation is developed in two temperature range as stated above. However, as it is observed that concrete permeability and presence of slag cement have different influence at different temperature range; three different thermal properties relations are presented to capture the trend. These relations are presented in table below.

Figures 9 - 11 show generated fitted line plots for concrete groups obtained by regression analysis in comparison with their measured data for thermal conductivity, specific heat, and thermal diffusivity, respectively. The fitted lines obtained by regression analysis indicate less variance in these figures and thus provide a near perfect fit for the measured results, except for the specific heat result only for G-0 and G-50 concrete groups. The proposed equations give either linear or bi-linear and tri-linear correlations due to property variations in different temperature ranges.
Table 2. High temperature property relationships for thermal properties of OPC and Slag cement concrete

| Property                  | Concrete type                        | Relation                                                                 |
|---------------------------|--------------------------------------|--------------------------------------------------------------------------|
| **Thermal conductivity (W/m°K)** | Conventional concrete (OPC)           | TC(0) = 2.1340 - 0.000948 Temperature; 20 >T≤ 400                         |
|                           |                                      | TC(0) = 1.874 - 0.000380 Temperature; 400 >T≤ 800                        |
|                           | 50% OPC and 50% Slag                 | TC(50) = 2.52714 - 0.000774 Temperature; 20 >T≤ 400                      |
|                           |                                      | TC(50) = 2.269 - 0.000355 Temperature; 400 >T≤ 800                       |
|                           | 70% Slag and 30% OPC                 | TC(70) = 1.93066 - 0.000729 Temperature; 20 >T≤ 400                      |
|                           |                                      | TC(70) = 1.941 - 0.000775 Temperature; 400 >T≤ 800                       |
| **Specific heat (MJ/m³°K)** | Conventional concrete (OPC)           | TC(0) = 1.739 - 0.000029 Temperature; 20 >T≤ 400                         |
|                           |                                      | TC(0) = 1.143 + 0.001250 Temperature; 400 >T≤ 800                        |
|                           | 50% OPC and 50% Slag                 | TC(50) = 1.719 + 0.000401 Temperature; 20 >T≤ 400                        |
|                           |                                      | TC(50) = 1.360 + 0.001640 Temperature; 400 >T≤ 800                       |
|                           | 70% Slag and 30% OPC                 | TC(70) = 1.48191 + 0.000060 Temperature; 20 >T≤ 400                      |
|                           |                                      | TC(70) = 0.2134 + 0.002191 Temperature; 400 >T≤ 800                      |
| **Thermal Diffusivity (mm²/s)** | Conventional concrete (OPC)           | TC(0) = 1.2050 - 0.000827 Temperature; 20 >T≤ 400                       |
|                           |                                      | TC(0) = 0.7747 - 0.000052 Temperature; 400 >T≤ 800                      |
|                           | 50% OPC and 50% Slag                 | TC(50) = 1.4141 - 0.001108 Temperature; 20 >T≤ 400                      |
|                           |                                      | TC(50) = 0.4612 + 0.000352 Temperature; 400 >T≤ 800                      |
|                           | 70% Slag and 30% OPC                 | TC(70) = 1.4501 - 0.000839 Temperature; 20 >T≤ 400                      |
|                           |                                      | TC(70) = 2.078 - 0.001759 Temperature; 400 >T≤ 800                      |

Figure 9. Thermal conductivity data verses fitted lines for G-0, G-50, and G-70 concrete group
4. Conclusion

Based on the experimental results presented on this paper the following conclusions are drawn:

- Temperature has significant influence on thermal conductivity, and specific heat of OPC and slag blended concrete. The thermal conductivity generally decreases with temperature up to 800 °C, while specific heat remains almost constant up to about 400 °C, and then increases with addition of slag cement.

- Addition of slag does significantly alter the thermal diffusivity of the concrete with temperature exposure up to 600°C. Slag cement improve the thermal diffusivity of a given concrete sample.

- Presence of high-volume slag cement content in the concrete mix lessen the drying shrinkage of the concrete at later age. The drying shrinkage result for all concrete mix groups at later ages had similar trend but different magnitude. Furthermore, the presence of moisture in the concrete affected the drying shrinkage.

- The proposed high temperature exposure and thermal property relationships can be used as input data for the evaluation of the fire response of OPC and Slag mixed cement concrete exposed to fire in computer programs.

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