ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 112-M67

Thermal Conductivity Studies for Self-Consolidating Concrete with Sand and Fly Ash Variation

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*The thermal properties of self-consolidating concrete (SCC) influence its durability performance. Thermal properties (specific heat, coefficient of thermal expansion, and thermal conductivity) of concrete are governed by the thermal properties of the constituent materials. Fine aggregates have a significant role in fresh as well as hardened state properties of the concrete mixture. The availability of natural sand (NS) is limited due to environmental regulations. Crushed sand (CS) is an emerging alternative to NS for concrete preparation. An experimental study was undertaken to measure thermal conductivity (*k*) values for an M-40 grade SCC mixture, with varying fly ash dosage, prepared with NS and CS. The* k *values were determined for normal service temperature range of 86 to 176°F (30 to 80°C) using the steady-state method. The experimental results were analyzed and empirical relations between the* k *value and the density, as well as with temperature, were developed. The 28-day compressive strength for SCC mixtures with CS was 18% and 35% more than the NS concrete mixtures at 0% fly ash and at 40% fly ash addition level, respectively. The* k *value for the SCC mixtures with CS was 6.25% and 2.38% more than the SCC mixtures with NS at a temperature range of 86 to 104°F (30 to 40°C) and 158 to 176°F (70 to 80°C), respectively, without any fly ash addition. At 40% fly ash addition level, the* k *value for the SCC mixtures with CS was 26.39% and 4.12% more than NS-based mixtures at 86 to 104°F (30 to 40°C) and at 158 to 176°F (70 to 80°C), respectively. Durability and sustainability of concretes may be enhanced by using CS instead of NS.*

Keywords: crushed sand; fly ash; natural sand; self-consolidating concrete (SCC); thermal conductivity.

INTRODUCTION

Nowadays, concrete is a preferred construction material. This is attributed to its versatile applications, ease in manufacture with locally available materials and wide acceptability over other construction materials.[1] Concrete is a multi-phase, heterogeneous material. It comprises cement, coarse aggregate, fine aggregate, and water. However, in most structural analyses, it is assumed to be homogeneous, isotropic, and uniform. Due to its wide-ranging and challenging applications, conventional concrete is transformed into a high-performance concrete (HPC). HPC has improved specific properties as compared to conventional concrete. Self-consolidating concrete (SCC) is a widely used HPC in the construction industry. The high performance of SCC is attributed to its ability to flow under its own weight without any external aid. Fine aggregate or sand is a significant component in SCC. The flowability of SCC with minimum segregation is on account of high fines content along with high-range water-reducing admixture (HRWRA) dosage. The fine aggregate added to the concrete not only influences the fresh-state properties (workability) but also the hardened-state performance (strength, durability, and thermal properties). The type of sand used influences the thermal conductivity of the concrete.[2] As per IS 383,[3] the fine aggregates used for concrete preparation can be natural sand (NS), crushed stone sand (CS), or crushed gravel sand. In this study, SCC mixtures with NS and CS were used. Due to the wide-ranging applications of concrete, the thermal properties of the concrete play an important role in the serviceability of concrete. The thermal properties of concrete such as specific heat, thermal expansion, and thermal conductivity (k) have a significant role in deciding the use of a particular concrete mixture for specific environmental conditions.[4] The k values of the SCC mixtures with fly ash variation (as partial replacement for cement) using NS and CS were determined experimentally. The k values were found at normal service temperature conditions, 86 to 176°F (30 to 80°C), using the two-slab guarded hot plate method (steady state method) in accordance with IS 3346[5] and ASTM C177.[6] The results obtained from the study were used to develop simple empirical relations, expressing the relation between k and concrete density as well as k and temperature.

RESEARCH SIGNIFICANCE

Due to the environmental effects of natural sand mining, the regulations discourage the use of NS for concrete manufacture. CS is a viable alternative to NS application in concrete.[7] The round shape and smooth surface of NS helps to improve the workability of the mixture at lower HRWRA dosages. The angular shape and rough texture of CS helps to improve the mechanical properties of the hardened concrete.[8] CS is manufactured by crushing rock sections to obtain fine aggregates having angular shape and rough texture.[9,10] The difference in the particle shape and texture of NS and CS affects not only the workability and particle packing but also the density of the concrete mixture. As per studies undertaken, concrete mixtures with granite CS exhibited improved mechanical and durability performance as compared to CS of dolomite and sandstone origin.[9] Apart from the fresh state properties (workability) that ensure uniform distribution of the concrete in the structure, the hardened state performance (strength and durability) of the concrete plays an important

ACI Materials Journal, V. 112, No. 6, November-December 2015.
MS No. M-2014-117.R4, doi: 10.14359/51687976, received February 21, 2015, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published ten months from this journal's date if the discussion is received within four months of the paper's print publication.

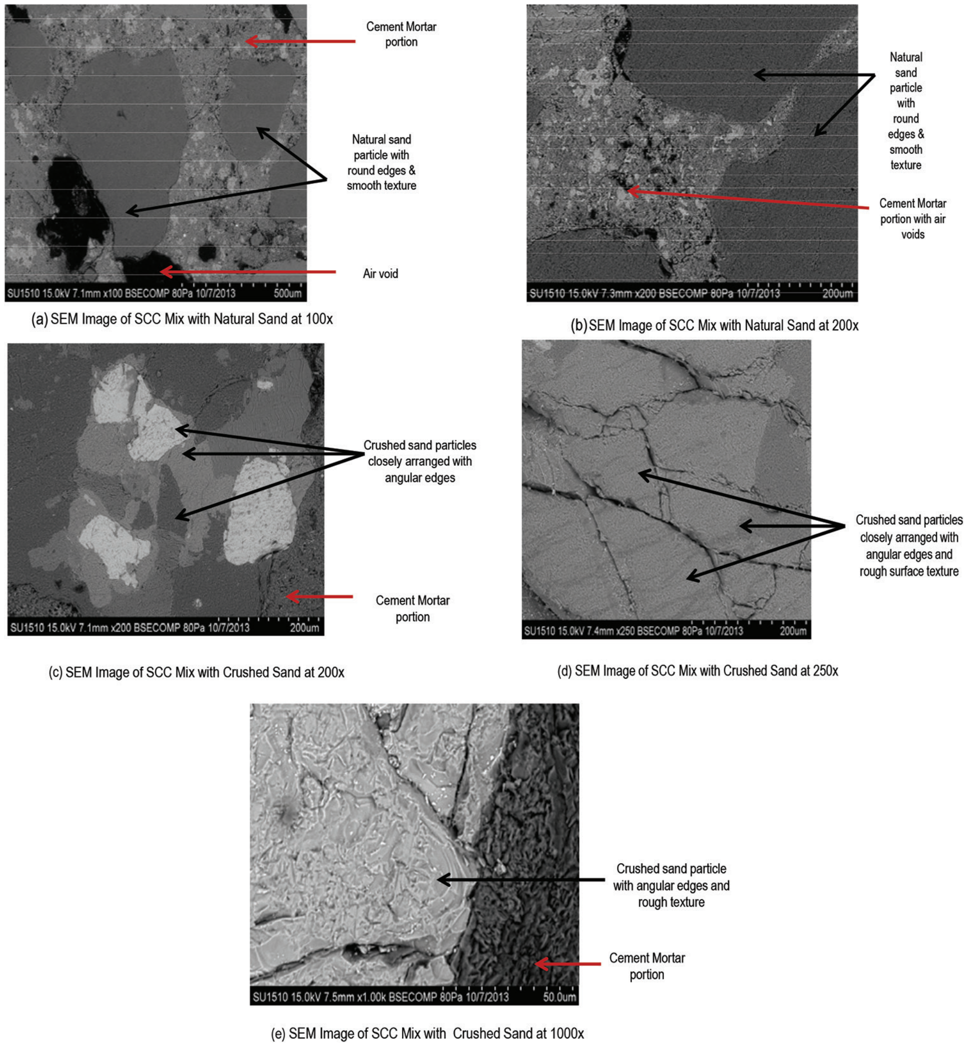


Fig. 1—SEM images of M-40 grade SCC with NS and CS at various magnification levels.

role in the service life of the concrete.[4] Among the various durability factors, temperature-related factors (external temperature, freezing-and-thawing, and heat of hydration) play an important role in crack formation and propagation in the hardened concrete.[4] The temperature-related performance of concrete is dependent on the thermal properties of the individual material that constitute it. The thermal properties of concrete affect its durability, fire-resistance properties, and development of temperature-related stresses. Depending on the application of the concrete, a specific *k* value is required. Low *k* values are important for insulation-related application of concrete (furnace lining), while high *k* values ensure reduced temperature gradient, thereby reducing the thermal stress in the structure (pavement application). The effect of the use of CS on the *k* values of SCC mixtures was compared with NS-based SCC mixtures at varying fly ash dosages. This paper presents the results of the studies undertaken for determination of the *k* values, by steady state method, for M-40 grade SCC with NS and CS and fly ash variation.

SELF-CONSOLIDATING CONCRETE (SCC)

SCC is a type of concrete that achieves complete and uniform compaction without any external vibration. It is a highly cohesive concrete, flowing under its own weight with minimum segregation.[8,9,11] compared to normal concrete, the proportion of fine aggregates in SCC is higher. The fine aggregates used for concrete production can be either NS or CS.

NS particles have a smooth texture and round shape.[8] This is attributed to the fact that these sands undergo the cumulative effects of multiple collisions and abrasions during transportation by natural media. Due to the round shape of NS particles, there is significant improvement in the workability of concrete.[8,12]

CS is obtained at the end of the tertiary stage of crushing rocks.[9,10] It is uniformly graded, with angular-shaped particles having a rough surface texture.[9] The rough surface of sand particles ensures improved bond between the paste and particle.[10,11]

Figure 1 represents scanning electron microscope (SEM) images of representative specimens of the SCC mixtures with NS and CS used in the present study. Figures 1(a) and (b) represent SCC mixtures with NS. The images clearly show the voids present (black spots) in the matrix phase of the concrete mixture. SCC mixtures with CS show the fine particles in close contact with each other in the matrix phase (Fig. 1(c) through (e)). Thus, from the SEM images it was observed that SCC mixtures with NS had poor particle packing arrangement. This influenced the density of the mixtures and in turn the mechanical properties of hardened concrete. In the present study, the SCC mixtures with CS had higher density compared to SCC with NS.

Another important aspect related to use of CS in concrete is the proportion of fines. CS has a higher fines content in the form of rock dust compared to NS. This rock dust acts as filler, densifying the matrix phase of SCC, and improves its viscosity.[9] However, the standard guidelines recommend a limit to the proportion of fines in the concrete as it impacts the water demand and workability of the mortar. As per ASTM C33,[13] the maximum permissible limit for fines in CS passing a No. 200 sieve (75 μm) is 7%, while as per IS 383,[3] the limit recommended passing a No. 100 sieve (150 μm) is 20%. In the present study, the amount of fines passing No. 100 sieve (150μm) for CS was 9%.

The mixture design composition, water-cement ratio (w/c), and HRWRA dosage influence the workability of the fresh mixture and the density of the hardened mixture. Due to the use of HRWRAs, the SCC mixtures can be prepared with lower w/c. A low-w/c SCC mixture has a higher density on account of reduced pore structure.

THERMAL CONDUCTIVITY

Thermal conductivity (k) of a material is its ability to conduct heat. The k value of concrete is a time dependent property, influenced by the variation in temperature as well as boundary conditions.[14] The k value of concrete can be determined experimentally either by steady-state or transient-state method.[15] In the steady-state condition, the heat flux is proportional to the temperature gradient developed in the direction of flow. This proportionality constant is termed as thermal conductivity (k).[16] The steady-state procedure is time-consuming, but the results obtained are accurate. The method is mainly applicable for homogenous materials. The transient-state procedures are mainly used for heterogenous materials with moisture. The transient-state procedures are speedy, but the accuracy of results is low.[15]

SCC mainly comprises two phases: the aggregate phase and the matrix phase. The k value of the hardened concrete depends on its age, porosity, aggregates, density, and cement paste matrix composition.[17-19] As the moisture content in the pores of the hardened concrete increases, the k value increases.[20] With aging, the concrete porosity increases, reducing its density and k value (provided that the pores are dry and moisture-free). Cement replacement materials such as fly ash and silica fume also reduce the k values of concrete.[21] Powder additions lower the density of the matrix phase. The reaction between cement and powder additives creates a thermal barrier increasing the thermal resistance and thus lowering the k value. The more porous a concrete composition, the lower is its k value. In the present study, the SCC mixtures with NS exhibited a more porous structure in the matrix phase compared to SCC mixtures with CS, as seen in Fig. 1.

Valore[22] proposed a relationship between k value and oven-dried density (d) of concrete

$$k_c = 0.5e^{0.02d} \text{ (inch-pound units)} \quad (1)$$

$$k_c = 0.072e^{0.00125d} \text{ (SI units)} \quad (2)$$

The k values obtained using Eq. (1) and (2) were valid for concrete with oven-dried densities in the range of 20 to 100 lb/ft^3 (320 to 1600 kg/m^3).

The k value of concrete is also dependent on the temperature. Temperature is a measure of the kinetic energy of particles (atoms) in a material. The particles are in a state of motion, which is dependent on temperature. The higher the temperature, the faster the movement of the particles. This causes higher a number of collisions and better heat transfer. This holds true in the case of metals.[23] However, in the case of concrete, k value decreases when temperature increases. This is because of the heterogeneous composition of concrete along with factors such as pore structure, moisture content and ambient conditions. At low ambient temperatures, concrete pores are occupied by residual moisture. Water is 25 times more conductive than air.[24,25] The moisture in the concrete pore acts as a thermal bridge, thereby increasing the k value. As temperature increases, this pore moisture dries up and is replaced by air. Air, being a poor conductor of heat, decreases the k value of the concrete with an increase in temperature. The temperature dependence of the k value causes considerable complexity in the thermal analysis of the material.[26] Hence, the k value is measured at an average temperature and is considered to be constant for the analysis. It is reported in the literature that the k value of concrete at room temperature is not available.[26] The temperature-thermal conductivity models are dependent on w/c, powder additions, and aggregate type and proportion, along with the porosity of concrete.[26] Kodur et al.[27] presented two models representing the relation between temperature (T) and thermal conductivity (k) for normal-strength concrete. They are the American Society of Civil Engineers (ASCE) model for siliceous and carbonate aggregates and the EC model (EN 1992-1-2). The second model did not differentiate the k value based on aggregates but, specified the upper and lower limits of k value. The models are represented as follows:

ASCE model—

For siliceous aggregate concrete

$$k_c = -0.000625T + 1.5 \quad \text{for } 68°\text{F} \leq T \leq 1472°\text{F } (20°\text{C} \leq T \leq 800°\text{C})$$

$$k_c = 1.0 \text{ for } 1472°\text{F} \leq T \text{ } (800°\text{C} \leq T) \quad (3)$$

For carbonate aggregate concrete

$$k_c = 1.355 \text{ for } 68°\text{F} \leq T \leq 560°\text{F } (20°\text{C} \leq T \leq 293°\text{C})$$

$$k_c = -0.001241T + 1.7162 \text{ for } 560°\text{F} \leq T \text{ } (293°\text{C} \leq T) \quad (4)$$

EC model—

Upper limit

$$k_c = 2 - 0.2451(T/100) + 0.0107\,(T/100)^2 \quad \text{for } 68°F \leq T \leq 2192°F\ (20°C \leq T \leq 1200°C) \tag{5}$$

Lower limit

$$k_c = 1.36 - 0.136(T/100) + 0.0057\,(T/100)^2 \quad \text{for } 68°F \leq T \leq 2192°F\ (20°C \leq T \leq 1200°C) \tag{6}$$

Kodur and Sultan[28] undertook studies to assess the effect of temperature on the thermal properties of high-strength concrete (HSC). Studies were undertaken to measure the thermal properties of HSC and the concrete mixtures with steel fibers. Siliceous and carbonate aggregates were used in the concrete. The k values were measured by the non-steady-state hot wire method. The properties were measured for a temperature range of 32 to 1832°F (0 to 1000°C). The empirical relation between the k value and temperature for both types of concrete were developed as follows.

For HSC with siliceous aggregates—

$$k = 2.00 - 0.0011T \text{ for } 32°F \leq T \leq 1832°F\ (0°C \leq T \leq 1000°C) \tag{7}$$

For HSC with carbonate aggregates—

$$k = 2.00 - 0.0013T \text{ for } 32°F \leq T \leq 572°F\ (0°C \leq T \leq 300°C) \tag{8}$$

$$k = 2.21 - 0.0020T \quad \text{for } 572°F \leq T \leq 1832°F\ (300°C \leq T \leq 1000°C) \tag{9}$$

For steel fiber-reinforced concrete with siliceous aggregates—

$$k = 2.50 - 0.0034T \text{ for } 32°F \leq T \leq 392°F\ (0°C \leq T \leq 200°C) \tag{10}$$

$$k = 2.24 - 0.0021T \text{ for } 392°F \leq T \leq 752°F\ (200°C \leq T \leq 400°C) \tag{11}$$

$$k = 1.40 \text{ for } 752°F \leq T \leq 1832°F\ (400°C \leq T \leq 1000°C) \tag{12}$$

For steel fiber-reinforced concrete with carbonate aggregates—

$$k = 1.80 - 0.0016T \text{ for } 32°F \leq T \leq 932°F\ (0°C \leq T \leq 500°C) \tag{13}$$

$$k = 1.20 - 0.0004T \quad \text{for } 932°F \leq T \leq 1832°F\ (500°C \leq T \leq 1000°C) \tag{14}$$

Kodur and Khalid[29] also studied the effect of temperature on thermal properties of different types of HSC. The studies were undertaken at a temperature range of 68 to 1472°F (20 to 400°C). The k values were measured by transient method using transient plane source (TPS) technique. The study was undertaken on HSC, SCC, and fly ash concrete (FAC). As per Kodur and Khalid,[29] the k values for concrete at room temperature were in the range of 16.64 to 22.88 BTU.in/h.ft^2.°F (2.4 to 3 W/m.°K). At the end of the study, empirical relations between temperature and k values were developed as follows.

HSC—

$$k = 2.5 - 0.0033T \text{ for } 68°F \leq T \leq 752°F\ (20°C \leq T \leq 400°C) \tag{15}$$

$$k = 2.21 - 0.0020T \quad \text{for } 752°F \leq T \leq 1472°F\ (400°C \leq T \leq 800°C) \tag{16}$$

SCC—

$$k = 3.12 - 0.0045T \text{ for } 68°F \leq T \leq 752°F\ (20°C \leq T \leq 400°C) \tag{17}$$

$$k = 3.00 - 0.0025T \quad \text{for } 752°F \leq T \leq 1472°F\ (400°C \leq T \leq 800°C) \tag{18}$$

FAC—

$$k = 3.00 - 0.0045T \text{ for } 68°F \leq T \leq 752°F\ (20°C \leq T \leq 400°C) \tag{19}$$

$$k = 2.60 - 0.0025T \quad \text{for } 752°F \leq T \leq 1472°F\ (400°C \leq T \leq 800°C) \tag{20}$$

EXPERIMENTAL PROCEDURE

The experimental studies undertaken comprised two parts:

1. Mixture design and preparation and testing of fresh-state and hardened-state properties of M-40 grade SCC.
2. Thermal conductivity measurement using two-slab guarded hot plate method.

The fresh-state properties (Table 1 and Fig. 2), measured in the study include slump flow test and T_{50}, V-funnel test, and Visual Stability Index (VSI).[30] Cube compressive strength was measured as the hardened-state property at 3, 7, and 28 days.

SCC mixture design

As mentioned in the preceding section, M-40 grade SCC had been adopted in the present study. This grade of concrete is usually prescribed for pavement construction in India.[31] Of the various types of loads considered for pavement analysis, the thermal loads played a significant role in deciding the geometry of the pavement.[32] The pavement concrete is subjected to a temperature range of 86 to 176°F (30 to 80°C) in the area of the study; hence, for the present study, the k values of M-40 grade SCC were measured for the same temperature range.

The mixture proportioning of concrete constituents had been adopted as per the minimum guidelines prescribed in EFNARC.[33] From the literature study, it was noted that the SCC mixture design could be powder-based, admixture-based, or a combination.[34,35] In the present study, a powder-based mixture design for the SCC was adopted. The basic premise of powder-based SCC mixture design is to achieve acceptable fresh state properties using powder additions (pozzolanic or inert) at minimum HRWRA dosage.[34,36,37] Ordinary portland cement (Grade 53)

Table 1—Mixture design details and fresh properties of M-40 grade SCC with NS and CS

Material	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5	Mixture 6	Mixture 7	Mixture 8	Mixture 9
Cement, lb/yd^3	725	689	652	616	580	544	507	471	435
Fly ash, lb/yd^3	0	36	72	109	145	181	217	254	290
Fly ash replacement level, %	0	5	10	15	20	25	30	35	40
Fine aggregate, lb/yd^3	1914	1914	1914	1914	1914	1914	1914	1914	1914
Coarse aggregate, lb/yd^3	1062	1062	1062	1062	1062	1062	1062	1062	1062
Water, lb/yd^3	337	337	337	337	337	337	337	337	337
HRWRA dosage, L/cwt of binder	0.85 (NS) 0.95 (CS)	0.8 (NS) 0.9 (CS)	0.8 (NS) 0.85 (CS)	0.75 (NS) 0.85(CS)	0.75 (NS) 0.8 (CS)	0.7 (NS) 0.8 (CS)	0.7 (NS) 0.75 (CS)	0.7 (NS) 0.75 (CS)	0.65 (NS) 0.7 (CS)
Fresh properties of SCC									
Slump flow, in.									
NS	24	24	24.5	24.5	25	25	25	25.5	25.5
CS	23	23	23	24	23.5	24	24	24	25
T_{50}, s									
NS	5.6	5.5	5.4	5.3	5.4	5.4	5.2	5.2	4.8
CS	5.5	6.5	6	5.8	7	6.5	5.2	5.2	5
VSI									
NS	1	1	1	1	1	1	1	1	1
CS	2	1	1	1	0	0	0	0	0
V-Funnel time, s									
NS	13	13	12	11	12	11	11	11	10
CS	14	14	13	12	13	12	11	11	11

Notes: 1 lb/yd^3 = 0.5933 kg/m^3; 1 in. = 25.4 mm.

conforming to IS 12269[38] and Class C fly ash conforming to IS 3812-2[39] were used. Polycarboxylate ether (PCE)-based HRWRA satisfying the guidelines mentioned in IS 9103[40] was used. The coarse aggregates and CS, obtained from a local quarry, were of granite origin. NS from the Manjira River, flowing near Hyderabad, India, was used for the NS mixtures. The coarse and fine aggregates (NS and CS) satisfied all the recommendations of IS 2386.[41-44] Both NS and CS were of siliceous type. As per the laboratory sieve analysis tests conducted for the present study (Fig. 3), the fineness modulus for NS and CS was 2.57 and 2.68 respectively. Fly ash was used as a cement replacement additive, with the replacement level ranging from 0% (Mixture 1) to 40% (Mixture 9) (at a 5% interval). As reported in the literature, higher fly ash dosages (>25%) improve the fresh-state properties but reduce the rate of gain of 28-day strength of the concrete mixture.[45,46] As per guidelines mentioned in ACI 211.4,[47] the recommended fly ash addition level for Class C fly ash is 20 to 35% by weight. As per IRC 44,[48] the maximum dosage for fly ash in cement concrete for pavement application is 20%. The fly ash addition dosage was limited to 40% in the present study. Table 1 gives the mixture design details of the SCC mixtures.

Table 2 specifies the density and compressive strength values at different ages for the SCC mixtures, using NS and CS with varying fly ash dosages. Figure 4 represents the comparative plot of the density of M-40 grade SCC with NS and CS with varying fly ash dosages at various ages. Figure 5 represents the plot of variation of compressive strength of M-40 grade SCC with NS and CS with varying fly ash dosages at various ages.

Steady-state thermal conductivity measurement

The *k* value of concrete is dependent on its composition and structure.[26] It governs the rate of heat flow through the concrete. Amongst all other factors, the *k* value of concrete is influenced by the mineralogical character of aggregates, moisture conditions and ambient temperature. The *k* value of moist concrete will be more than dry concrete. The denser the concrete, the higher its *k* value. As discussed in ACI 122,[18] the thermal conductivity of concrete or insulating material is determined in accordance with ASTM C177.[6] Figure 6 represents the two-slab guarded hot plate setup to determine the *k* value by steady state method, as per IS 3346[5] and ASTM C177.[6] In the test setup, the heat flux was applied to two identical specimens (7 in. [180 mm] diameter and 0.6 in. [16 mm] thick) held between the hot and cold plates, ensuring unidirectional heat flow through the specimen. Thermocouples were provided to measure the temperature at each face of the specimen. The heat transferred through the specimen was equal to the power supplied to the heater. Thermal equilibrium (steady state) was achieved when the temperature and voltage observations remained constant. The stabilization time depends on the apparatus, control system, test temperatures and the thermal diffusivity and thickness of the specimen.[5] In the present study, the average

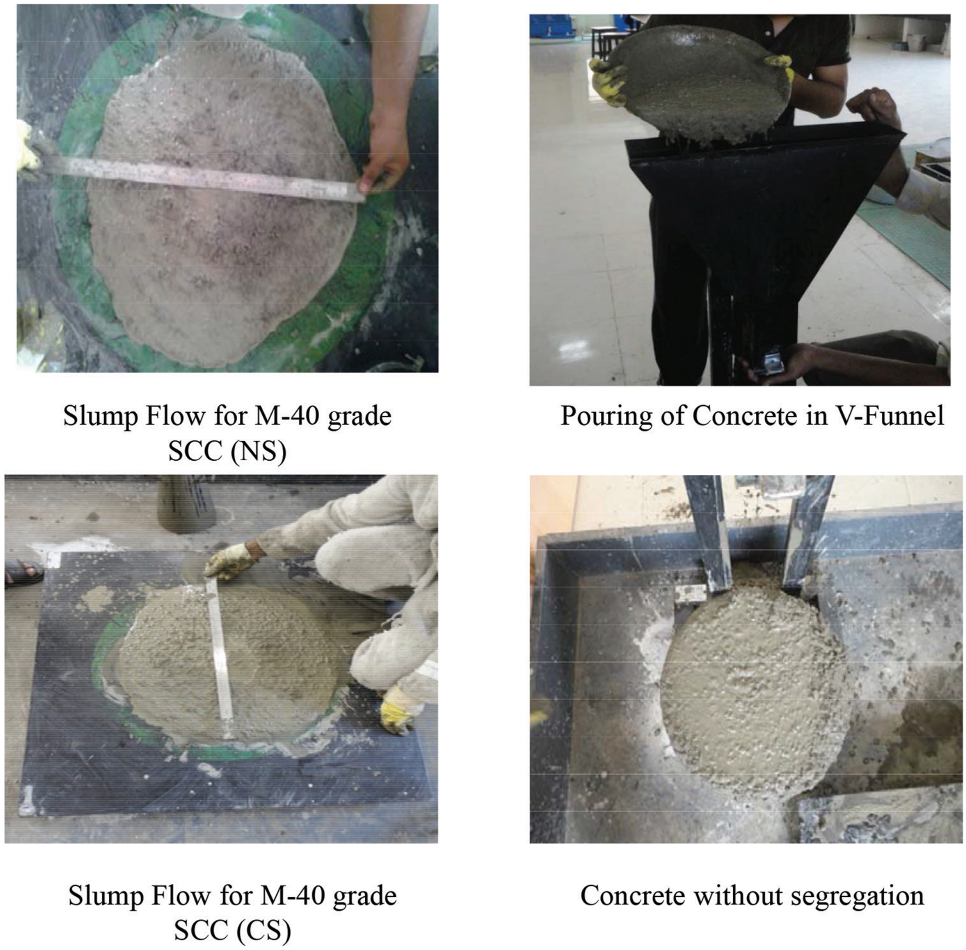


Fig. 2—Fresh-state properties of SCC.

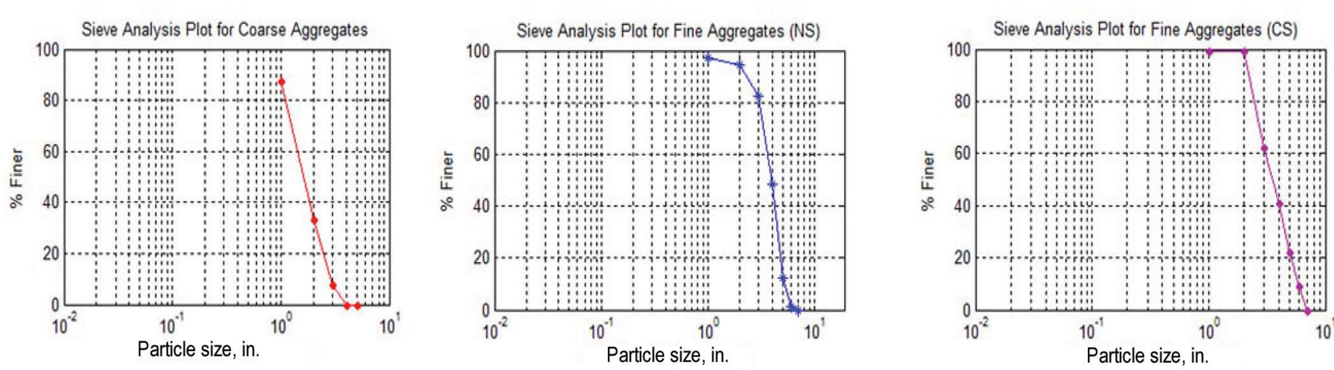


Fig. 3—Sieve analysis plots for coarse and fine aggregates. (Note: 1 in. = 25.4 mm.)

stabilization time observed was 30 minutes for temperature up to 122°F (50°C) and 45 minutes for temperature up to 176°F (80°C). The observations were recorded at an interval not less than 30 minutes, until four successive observations gave the *k* values differing not more than 1%. The specimens were cured for 28 days in a curing tank and oven dried before the test. It has to be noted that, in normal use, the concrete is not in the oven-dried state. The thermal conductivity values determined have to be corrected for moisture effects. As per Valore,[22] for every 1% increase in weight of concrete due to moisture content, the *k* value of the concrete specimen can be increased by 6%. The moisture content in the concrete specimen can be determined by ultrasonic pulse velocity test, ground-penetrating radar, or nuclear magnetic resonance[26] (NMR) method. The specimens considered for the study were subjected to initial conditioning as prescribed in IS 3346.[5] The surface of the specimens was made as smooth as possible to ensure intimate contact between the specimen and plate. Single-side testing was undertaken for the present study.

Table 3 highlights the *k* values obtained for both mixtures at a temperature range of 86 to 176°F (30 to 80°C) using the steady-state test procedure.

Table 2—Density and cube compressive strength of M-40 grade SCC with NS and CS at various ages

Mixture details	3 days				7 days				28 days			
	Density, lb/ft³		Compressive strength, psi		Density, lb/ft³		Compressive strength, psi		Density, lb/ft³		Compressive strength, psi	
	NS	CS	NS	CS	NS	CS	NS	CS	NS	CS	NS	CS
Mixture 1	145.8	147.0	5651	6245	146.4	148.9	6532	7005	147.9	149.7	7091	8380
Mixture 2	145.4	146.0	4243	5242	145.9	148.1	5426	6247	147.0	148.8	6725	7688
Mixture 3	145.3	145.9	4287	5133	145.9	147.7	5049	5660	146.7	148.5	6596	7403
Mixture 4	145.1	145.3	4211	4366	145.5	146.7	5017	5447	146.3	148.2	6210	7394
Mixture 5	143.4	145.2	3954	3983	145.1	146.2	4684	4722	146.0	147.7	6081	7306
Mixture 6	143.3	145.0	3664	3893	145.0	145.7	4577	4693	145.8	147.8	5340	6432
Mixture 7	142.9	144.7	3481	3514	144.7	145.7	4457	4555	145.6	147.0	5146	6382
Mixture 8	142.6	144.0	3137	3315	144.5	145.1	4018	4390	145.2	146.7	5049	6379
Mixture 9	141.2	143.8	2859	3357	143.8	144.9	3513	4328	144.2	145.1	4630	6263

Notes: 1 lb/ft³ = 16.02 kg/m³; 1 psi = 6.895 × 10^{-3} MPa.

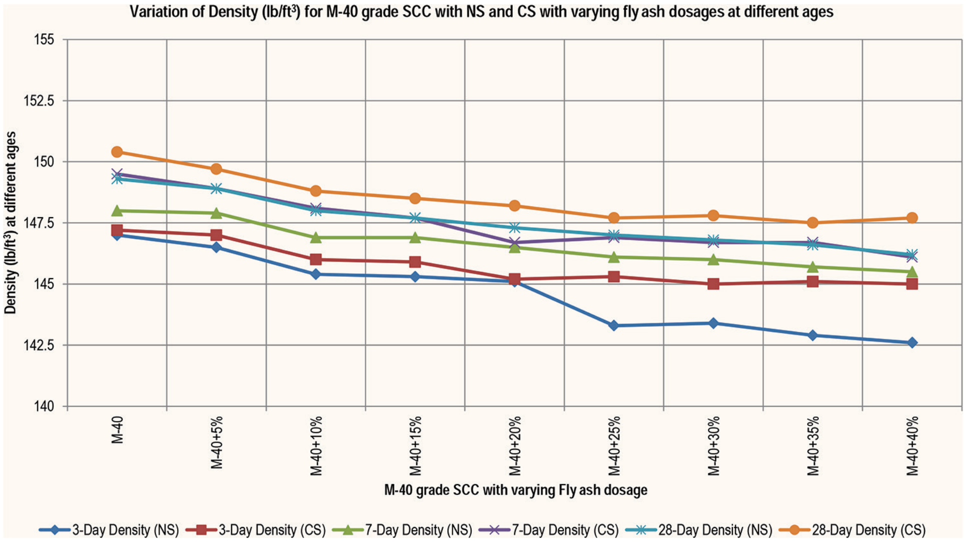


Fig. 4—Variation in density of M-40 grade SCC with NS and CS with varying fly ash dosages at different ages. (Note: 1 lb/ft³ = 16.02 kg/m³.)

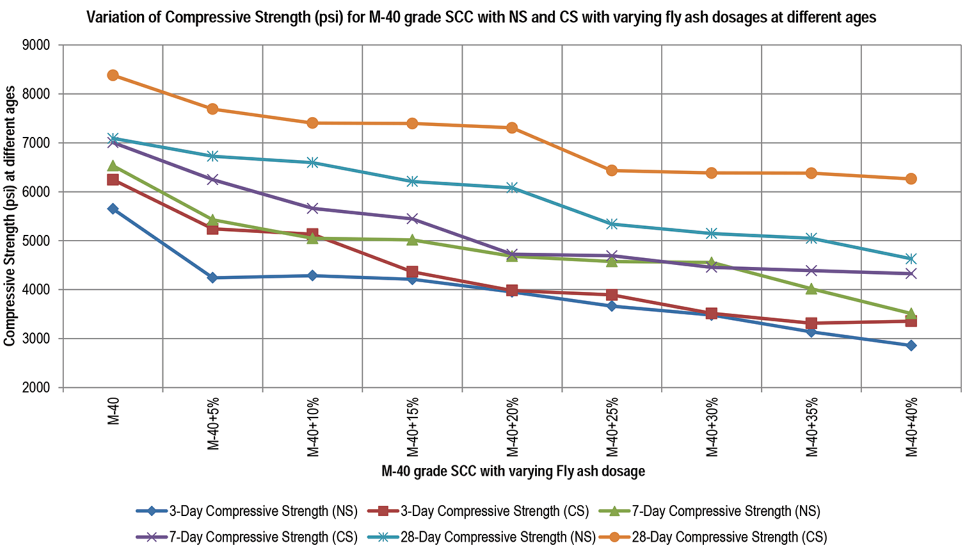
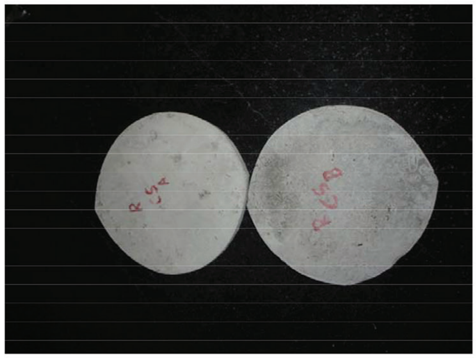
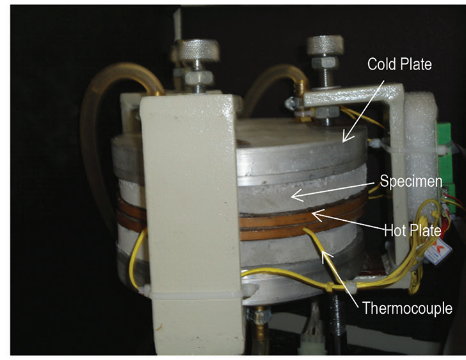


Fig. 5—Variation in compressive strength of M-40 grade SCC with NS and CS with varying fly ash dosages at different ages. (Note: 1 psi = 6.895 × 10^{-3} MPa.)



Concrete Specimen for *k* value measurement



Two-Slab Guarded Hot Plate Method

Fig. 6—Specimens used for two-slab guarded hot plate method of k *value measurement.*

Table 3—*k* values for various mixtures of M-40 grade SCC, BTU.in./h.ft^2.°F

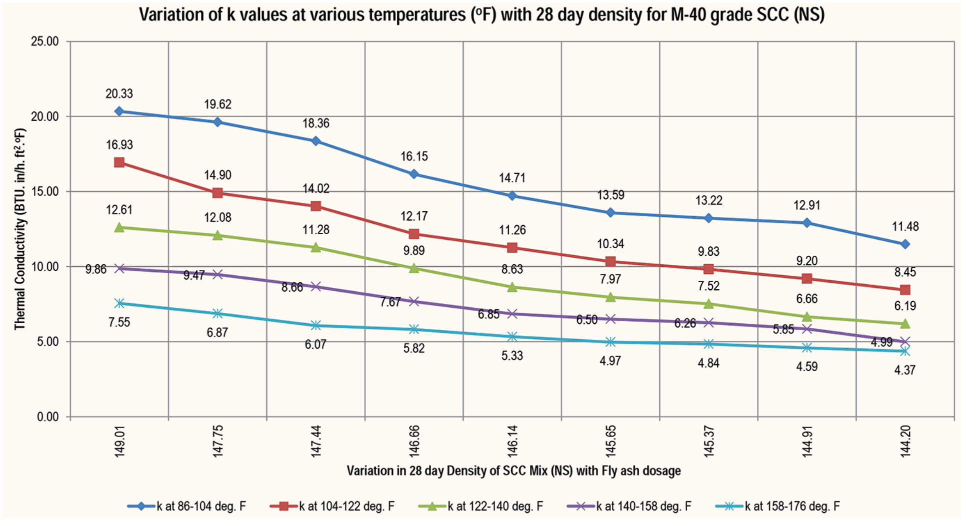
Mixture details	*k* value at different temperatures for NS					*k* value at different temperatures for CS				
	86 to 104°F	104 to 122°F	122 to 140°F	140 to 158°F	158 to 176°F	86 to 104°F	104 to 122°F	122 to 140°F	140 to 158°F	158 to 176°F
Mixture 1	20.33	16.93	12.61	9.86	7.55	21.60	17.71	13.11	10.14	7.73
Mixture 2	19.62	14.90	12.08	9.47	6.87	21.01	16.30	12.44	9.89	7.61
Mixture 3	18.36	14.02	11.28	8.66	6.07	20.48	15.49	12.00	9.67	6.72
Mixture 4	16.15	12.17	9.86	7.67	5.82	19.67	15.31	11.63	9.33	6.18
Mixture 5	14.71	11.26	8.63	6.85	5.33	19.06	15.24	11.46	9.28	5.87
Mixture 6	13.59	10.34	7.97	6.50	4.97	16.79	14.12	10.71	9.06	5.51
Mixture 7	13.22	9.83	7.52	6.26	4.84	16.35	13.45	10.55	8.99	5.49
Mixture 8	12.91	9.20	6.66	5.85	4.59	15.16	12.10	10.36	8.03	5.19
Mixture 9	11.48	8.45	6.19	4.99	4.37	14.51	11.87	9.59	7.23	4.52

Notes: 1 BTU.in./h.ft^2.°F = 0.1442 W/m°C; °F = (°C × 9/5) + 32.

RESULTS AND DISCUSSIONS

Fresh state and mechanical properties of SCC

It was observed from the experimental results (Table 1) that with an increase in the fly ash proportion, the HRWRA dosage reduced in both the NS and CS mixtures. The slump flow for SCC mixtures with NS (24 in. [609 mm] for Mixture 1 to 25.5 in. [648 mm] for Mixture 9) was more than the slump flow for SCC mixtures with CS (23 in. [584 mm] for Mixture 1 to 24.5 in. [620 mm] for Mixture 9). This was due to the rounded, smooth surface particles of NS. However, in case of NS mixtures, bleeding was observed in all mixtures (VSI = 1). This was attributed to the lack of fines in the NS to absorb the bleed water. In case of SCC mixtures with CS, the initial HRWRA dosages were too high to achieve the flow. This led to pronounced bleeding (VSI 2 for Mixture 1). However, with an increase in the fly ash proportion, the HRWRA dosage required to achieve desired flow reduced with absence of bleeding (VSI 0 from Mixture 5 onwards). This was due to the presence of fines in the CS mixtures that absorbed the bleed water. Due to high flow values, the V-funnel emptying times for the SCC mixtures with NS (13 seconds for Mixture 1 to 10 seconds for Mixture 9) were lower than the corresponding values for the CS mixtures (14 seconds for Mixture 1 to 11 seconds for Mixture 9). Table 2 represents the density and cube compressive strength results at 3, 7, and 28 days. It was observed that the SCC mixtures with CS had higher density at all ages as compared to the NS mixtures for all nine mixtures. For Mixture 1, the 3-day density for the CS mixture was 0.82% more than the NS mixture, while for Mixture 9, the density of the CS mixture was 1.84% more than the NS mixture at same age. The 7-day density of the CS mixture was 1.71% and 0.77% more than the NS mixture for Mixture 1 and Mixture 9, respectively. The 28-day density of the CS mixture was 1.22% more for Mixture 1 and 0.62% more for Mixture 9 as compared to the NS mixture. The compressive strength of the CS mixtures was higher than that of the NS mixtures at all ages for all nine mixtures. The number of large-sized particles in NS was higher compared to CS. The particles in CS were elongated and angular as compared to the round and spherical-shaped NS particles. This ensured better particle packing due to the filler effect in the SCC mixtures with CS. From the representative SEM images of the samples (Fig. 1), the presence of air voids was observed in the matrix phase for the NS mixtures. The air voids were not observed in the CS mixtures. The observations of the voids in the SEM images were substantiated by the sieve analysis plots. The absence of voids in the matrix phase improved the density and load-carrying capacity of SCC mixtures with CS. Also, it was observed that the rate of gain of strength was slow in the case of SCC mixtures with NS. The 3-day compressive strength of SCC mixtures with CS (6245 psi [43.06 MPa]



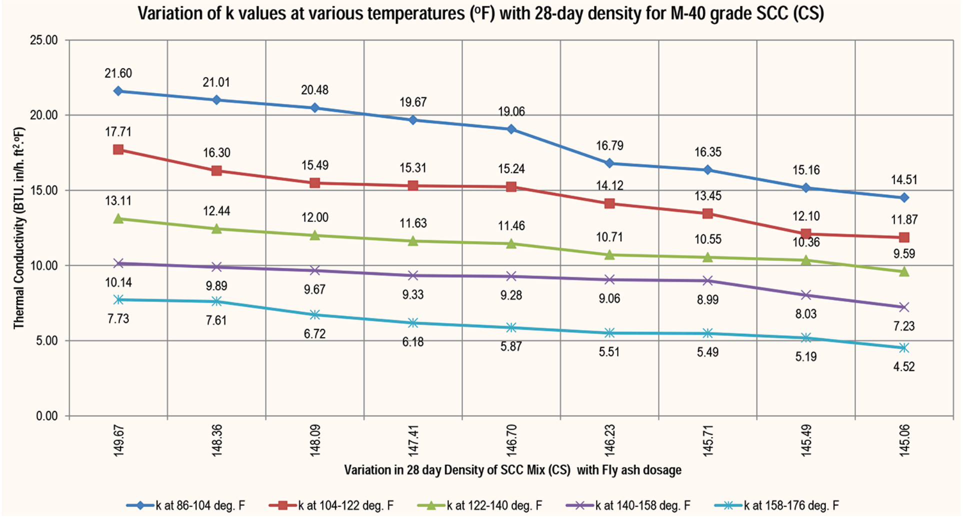


Fig. 7—Variation of k *value with 28-day density of concrete mixture at various test temperatures. (Note: 1 BTU.in./h.ft^2.°F = 0.1442 W/m°C; °F = (°C × 9/5) + 32.)*

for Mixture 1 to 3357 psi [23.14 MPa] for Mixture 9) was approximately equal to the 7-day compressive strength of SCC mixtures with NS (6532 psi [45.04 MPa] for Mixture 1 to 3513 psi [24.22 MPa] for Mixture 9). The same trend was observed for the 7-day compressive strength of CS mixtures (7005 psi [48.30 MPa] for Mixture 1 to 4328 psi [29.84 MPa] for Mixture 9) when compared with the 28-day strength of NS mixtures (7091 psi [48.89 MPa] for Mixture 1 to 4630 psi [31.93 MPa] for Mixture 9). From the test results, it was observed that for Mixture 1 with CS, the 3-day strength was 10.51%, the 7-day strength was 7.14%, and the 28-day strength was 18% more than the NS mixture at corresponding age. For Mixture 9 with CS, the 3-day strength was 17.42%, 7-day strength was 23.19%, and 28-day strength was 35% more than the NS mixture at the corresponding age.

Variation of thermal conductivity with density

The plot of variation in *k* value with density of the mixture at various temperatures for varying fly ash dosage in M-40 grade SCC with NS and CS is given in Fig. 7. It was observed that the *k* value decreased at all test temperatures with a decrease in the density of the concrete mixture. The reduction in *k* values for NS mixtures was significant with density variation compared to the CS mixtures. This was on account of the voids in the matrix phase of the NS mixtures. This was reflected by the lower density values for NS mixtures.

In both types of mixtures, the reduction in *k* value with density was more pronounced at lower temperatures (up to 122°F [50°C]). At higher temperatures (122 to 176°F [50 to 80°C]), the *k* values were fairly constant with the change in the density for both mixtures. SCC mixtures with CS showed higher *k* values than the mixtures with NS. This was due to efficient particle packing of the angular particles in the matrix phase and large proportion of fines in the CS as compared to those in NS.

As discussed in the preceding section, Valore[22] proposed a relation between density of the concrete mixture and the *k* value for oven dried densities in the range of 20 to 100 lb/ft^3 (320 to 1600 kg/m^3). The model has been used as guideline for analyzing the density and *k* value variation for M-40 grade SCC with NS and CS. A curve-fitting exercise was undertaken for the experimental plots and following equation was obtained.

Table 4—Values of constants for relationship between *k* value and density of M-40 grade SCC at various temperatures for NS and CS

	M-40 grade SCC with NS				M-40 grade SCC with CS			
Temperature, °F (°C)	k_o, BTU.in./h.ft^2.°F (W/m°C)	A, BTU.in./h.ft^2.°F (W/m°C)	d', lb/ft^3 (kg/m^3)	B, lb/ft^3 (kg/m^3)	k_o, BTU.in./h.ft^2.°F (W/m°C)	A, BTU.in./h.ft^2.°F (W/m°C)	d', lb/ft^3 (kg/m^3)	B, lb/ft^3 (kg/m^3)
86 to 104 (30 to 40)	58.08 (8.38)	–47.00 (–4.45)	144.2 (2310.08)	20.61 (205.35)	23.44 (3.38)	–9.25 (–1.34)	145.06 (2323.86)	2.65 (42.6)
104 to 122 (40 to 50)	44.67 (6.44)	–36.79 (–5.28)	144.2 (2310.08)	18.02 (288.10)	19.62 (2.83)	–7.77 (–1.09)	145.06 (2323.86)	3.74 (57.1)
122 to 140 (50 to 60)	25.12 (3.62)	–19.41 (–2.73)	144.2 (2310.08)	10.28 (158.50)	15.76 (2.27)	–5.98 (–0.83)	145.06 (2323.86)	5.84 (87.02)
140 to 158 (60 to 70)	23.39 (3.37)	–18.50 (–2.52)	144.2 (2310.08)	14.52 (216.33)	9.92 (1.43)	–2.61 (–0.38)	145.06 (2323.86)	1.03 (15.46)
158 to 176 (70 to 80)	19.11 (2.76)	–14.97 (–2.14)	144.2 (2310.08)	20.12 (316.68)	14.18 (2.05)	–9.48 (–1.23)	145.06 (2323.86)	11.43 (161.18)

Notes: 1 BTU.in./h.ft^2.°F = 0.1442 W/m°C; 1 lb/ft^3 = 16.02 kg/m^3; °F = (°C × 9/5) + 32.

$$k - k_o = A^{(-[d-d']/B)} \quad (21)$$

where k is thermal conductivity; k_o is reference thermal conductivity for specific temperature; d is the density of the mixture; d' is the reference density; and A and B are constants.

The values of A and B as tabulated in Table 4 are applicable for the various concrete mixtures considered in the present study. It was observed that constants A and B and reference thermal conductivity values were dependent on the temperature range considered in the study.

Variation of thermal conductivity with temperature

Figure 8 represents the plot of the k values for the NS and CS mixtures versus the test temperatures. From the plot, it was observed that the k values drop significantly upto the test temperature of 122°F (50°C). Beyond 122°F (50°C), the drop in k value was steady for both mixtures. Although oven-dried specimens (devoid of free water) were used for the test procedure, there was some amount of physically bound moisture present in the concrete at the microstructure level. The bound moisture, along with the PCE admixture used in SCC, led to a significant drop in the k values in the initial stage. It was observed that the drop in k values for NS and CS mixtures had the same pattern. However, the k values of the CS mixtures were higher due to the efficient particle packing in the matrix phase compared to the NS mixtures. Overall, the k value of the SCC mixtures was higher, than the normal concrete due to high paste content and chemical admixture.[29,49]

Using Eq. (7) to (12) and (15) to (20) as a guideline, a graph of k value variation with temperature was plotted (Fig. 8). A curve-fitting exercise for the given set of results yielded Eq. (22) and (23)

$$k = A + BT \quad (22)$$

where k represents thermal conductivity; T represents temperature; and A and B are constants.

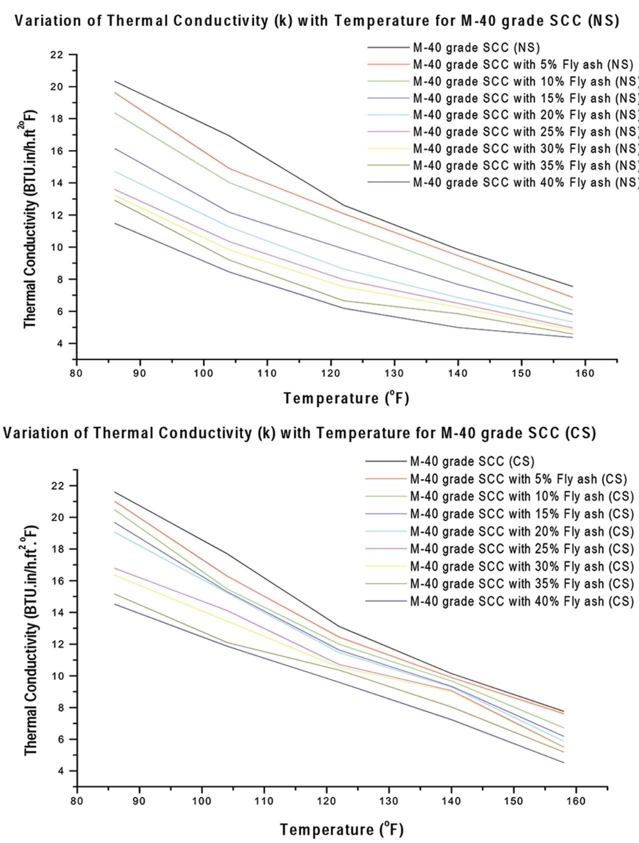


Fig. 8—Variation in k *value with temperature for various concrete mixtures. (Note: 1 BTU.in./h.ft^2.°F = 0.1442 W/m°C.)*

Eq. (22) was formulated on lines similar to the ASCE model. Table 5 represents the values of A and B for NS and CS mixtures. The values of A and B were in line with the coefficients reported by Kodur et al. (Eq. (17)).

Based on the EC model for the given set of experimental results, Eq. (23) was derived

$$k = A + BT + CT^2 \quad (23)$$

where k represents thermal conductivity; T represents temperature; and A, B, and C are constants.

Table 5—Values of constants for linear relation between *k* value and temperature for M-40 grade SCC with fly ash variation for NS and CS mixtures

Mixture details		*A*, BTU.in./h.ft^2.°F (W/m°C)	*B*, BTU.in./h.ft^2.°F/°F (W/m°C/°C)	R^2
Mixture 1	NS	35.57 (4.29)	–0.18 (–0.047)	0.994
	CS	37.96 (4.58)	–0.20 (–0.051)	0.992
Mixture 2	NS	33.55 (4.05)	–0.17 (–0.045)	0.991
	CS	35.96 (4.33)	–0.19 (–0.048)	0.987
Mixture 3	NS	31.97 (3.84)	–0.17 (–0.043)	0.993
	CS	35.47 (4.25)	–0.19 (–0.048)	0.989
Mixture 4	NS	27.39 (3.31)	–0.14 (–0.036)	0.988
	CS	34.76 (4.17)	–0.18 (–0.048)	0.994
Mixture 5	NS	25.06 (3.02)	–0.13 (0.033)	0.985
	CS	34.10 (4.09)	–0.18 (–0.047)	0.996
Mixture 6	NS	22.96 (2.77)	–0.12 (–0.03)	0.984
	CS	29.96 (3.62)	–0.15 (–0.04)	0.996
Mixture 7	NS	22.11 (2.67)	–0.11 (–0.029)	0.977
	CS	28.71 (3.47)	–0.15 (–0.038)	0.995
Mixture 8	NS	21.39 (2.58)	–0.11 (–0.029)	0.959
	CS	26.44 (3.20)	–0.14 (–0.035)	0.997
Mixture 9	NS	19.08 (2.30)	–0.09 (–0.026)	0.963
	CS	26.23 (3.15)	–0.14 (–0.036)	0.999

Notes: 1 BTU.in./h.ft^2.°F = 0.1442 W/m° C; °F = (°C × 9/5) + 32.

Table 6—Values of constants for quadratic relation between *k* value and temperature for M-40 grade SCC with fly ash variation for NS and CS mixtures

Mixture details		*A*, BTU.in./h.ft^2.°F (W/m°C)	*B*, BTU.in./h.ft^2.°F/°F (W/m°C/°C)	*C*, BTU.in./h.ft^2.°F/°F^2 (W/m°C/°C^2)	R^2	$R^2_{adj.}$
Mixture 1	NS	47.34 (5.18)	–0.38 (–0.09)	8.27×10^{-4} (3.86×10^{-4})	0.997	0.994
	CS	52.55 (5.68)	–0.45 (–0.1)	1.03×10^{-3} (4.79×10^{-4})	0.997	0.994
Mixture 2	NS	47.52 (5.09)	–0.41 (–0.09)	9.81×10^{-4} (4.57×10^{-4})	0.996	0.992
	CS	55.32 (5.81)	–0.52 (–0.11)	1.36×10^{-3} (6.43×10^{-4})	0.999	0.998
Mixture 3	NS	43.33 (4.71)	–0.36 (–0.081)	7.98×10^{-4} (3.76×10^{-4})	0.997	0.994
	CS	51.92 (5.50)	–0.47 (–0.10)	1.16×10^{-3} (5.43×10^{-4})	0.996	0.992
Mixture 4	NS	40.95 (4.31)	–0.37 (–0.08)	9.52×10^{-4} (4.36×10^{-4})	0.996	0.992
	CS	46.69 (5.06)	–0.39 (–0.086)	8.38×10^{-4} (3.86×10^{-4})	0.997	0.994
Mixture 5	NS	39.84 (4.12)	–0.38 (–0.081)	1.04×10^{-3} (4.79×10^{-4})	0.999	0.998
	CS	41.69 (4.68)	–0.31 (–0.072)	5.34×10^{-4} (2.57×10^{-4})	0.996	0.992
Mixture 6	NS	36.58 (3.80)	–0.35 (–0.075)	9.57×10^{-4} (4.5×10^{-4})	0.998	0.996
	CS	29.96 (3.57)	–0.15 (–0.038)	2.24×10^{-4} (-2.14×10^{-5})	0.991	0.982
Mixture 7	NS	37.77 (3.86)	–0.38 (–0.081)	1.1×10^{-3} (5.14×10^{-4})	0.996	0.992
	CS	29.15 (3.51)	–0.15 (–0.039)	3.09×10^{-4} (1.43×10^{-5})	0.990	0.980
Mixture 8	NS	42.20 (4.14)	–0.47 (–0.097)	1.46×10^{-3} (6.79×10^{-4})	0.992	0.984
	CS	25.97 (3.19)	–0.13 (–0.034)	-3.31×10^{-5} (-7.14×10^{-6})	0.993	0.986
Mixture 9	NS	37.54 (3.72)	–0.42 (–0.087)	1.3×10^{-3} (6.14×10^{-4})	0.999	0.998
	CS	25.54 (3.10)	–0.13 (–0.034)	-4.85×10^{-5} (-2.14×10^{-5})	0.999	0.998

Notes: 1 BTU.in./h.ft^2.°F = 0.1442 W/m° C; °F = (°C × 9/5) + 32.

The values of constants *A*, *B*, and *C* are tabulated in Table 6. The values of *A*, *B*, and *C* in the study were on the higher side compared to corresponding values in Eq. (5) and (6).

The constants considered in Eq. (22) and (23) were dependent on the type of mixture (NS or CS) and fly ash dosage in the mixture.

CONCLUSIONS

The paper presents the experimental study undertaken to measure the *k* values (by steady state method) for M-40 grade SCC with varying fly ash dosage for NS and CS fine aggregates. Based on the experimental results, empirical mathematical equations were formulated highlighting the relation between *k* value and density of the concrete mixture, as well as between *k* value and temperature. The following conclusions were drawn from the study:

1. SCC mixtures with NS exhibited better fresh state properties as compared to SCC mixtures with CS, with reduced HRWRA dosages. This was attributed to the round shape and smooth surface of NS particles.

2. It was observed that an increase in fly ash dosage reduced the density and cube compressive strength values for NS and CS mixtures at all ages. Fly ash addition decreased the density of the matrix phase in SCC. However, in case of the CS mixtures, the density values were higher (by 0.93% at 3 days, 0.932% at 7 days, and 1.12% at 28 days) than the NS mixtures. This was due better particle packing arrangement in CS mixtures. This was also reflected by the higher compressive strength for the CS mixtures than the NS mixtures.

3. The *k* value for M-40 grade SCC with varying fly ash dosage for NS and CS was measured at normal service temperature of 86 to 176°F (30 to 80°C) by the steady state method. The average *k* value at all the test temperatures for the CS mixtures was higher (4.01% more for Mixture 1 to 34.16% more for Mixture 9) than the NS mixtures at the same fly ash replacement levels.

4. Thus, from the studies undertaken it can be concluded that the SCC mixtures with CS exhibits better mechanical properties compared to NS mixtures. The *k* values of the CS mixtures are relatively higher than the NS mixtures under similar test conditions. Hence, CS can be considered as a suitable alternative to NS for concrete mixtures, thereby protecting the environment from harmful effects of natural sand mining.

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