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Effect of Perlite on Thermal Conductivity of Self Compacting Concrete

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Abstract

Cement concrete pavement slabs used in highway construction are planer structures. Apart from regular factors considered in analysis of concrete pavements, temperature effects influence the slab size, joint spacing and temperature reinforcement design. The thermal performance of concrete pavement is governed by its thermal properties viz. coefficient of thermal expansion, specific heat and thermal conductivity. Studies have been undertaken to assess the thermal properties of normal concrete. The measurement of thermal conductivity for Self Compacting Concrete (SCC) has been proposed in this paper. SCC is a highly flowable and non-segregating concrete. SCC has the ability to flow through congested reinforcements efficiently irrespective of the structure geometry.

An experimental program has been undertaken, to assess the thermal conductivity values for M-40 grade of SCC mixes with manufactured sand. Class C flyash has been used as a cement replacement material. Perlite has been used as fine sand replacement material. The thermal conductivity values were measured using Guarded Hot Plate method (ASTM C177) as recommended in ACI 122R. This paper is an attempt to present the experimental results obtained for thermal conductivity studies undertaken on M-40 grade of SCC with optimized flyash dosage and perlite dosage.

Keywords: Self Compacting Concrete; Thermal Conductivity; Perlite

1. Introduction

Rigid pavements are mainly used for major highways and airport runways. Cement concrete pavements represent the group of rigid pavements. Concrete is a composite material comprising of cement, mineral aggregate, water and admixtures. A properly designed mix ensures strong, stable and durable pavement layer that offers better resistance to repetitive vehicular loads as well as withstand effects of environmental variations. Rigid

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pavements are analyzed as thick plate in which plane sections remain plane before and after bending (Huang, 2004). The major design factors considered for pavement analysis are traffic loading, environment (temperature and precipitation), materials and failure criteria. The daily repetitive vehicular traffic load causes fatigue failure of pavement, which is considered as a major design criterion for analysis of rigid pavements (Fwa & Liu, 2006). Equally important are the stresses induced in the pavement slab on account of thermal loads. The stresses developed on account of temperature changes can be of equal magnitude to the stresses induced by wheel loads (Fwa & Liu, 2006). The thermal stresses developed in the slab are tensile in nature. As cement concrete is a weak material in tension, the thermal stresses are as critical as wheel loads in the analysis of rigid pavements. The thermal stresses have an influence on the plan dimensions of the slab, design of temperature reinforcement alongwith joint design and spacing.

2. Temperature effects on cement concrete pavements

The daily and seasonal temperature variations, along with solar radiation, develop a temperature gradient in the concrete pavement. The temperature gradient so developed causes curling of the pavement slab. As per American Concrete Institute, curling is defined as distortion of any essentially linear or planar member into a curved shape such as warping of a slab due to creep or to differences of temperature or moisture content in the zones adjacent to its opposite faces (Gedafa et al, 2009). Due to the self weight of the concrete slab and interaction of slab base with founding layer the curling of slab is prevented. This induces stresses in the pavement (Huang, 2004 & Gedafa et al 2009). Curling is a daily phenomenan that develops stresses in the slab and also affects the slab-subgrade contact. The heating of slab surface during day time, causes curling downward (positive temperature gradient). During night time, cooling of the slab causes upward curling (negative temperature gradient).

The temperature effects on rigid pavements are studied from 1920s. Westergaard (1927), proposed the solution for temperature curling (4). Bradbury (1938), assumed linear temperature differential for curling stress analysis (4). Teller and Sutherland (4), reported that the actual temperature profile across the slab thickness is non-linear in nature (1935). Thomlinson (1940), addressed the curling stress problem due to non-linear temperature profile for the first time. Mirambell (1990), Choubane and Tia (1992, 1995), Lee and Darter (1993), Harik et al (1994), Masad et al (1996), Mohamed and Hansen (1997), Ioannides and Khazanovich (1998) and Ioannides and Salsilli-Murua (1999), have reported the non-linearity of temperature profile across slab thickness (Hiller & Roesler, 2010).

The curling in concrete slab is actually a combination of five components, which are primarily nonlinear in nature (Rao & Roesler, 2005). Curling comprises of temperature gradient through the slab, moisture gradient through the slab, built in temperature gradient, differential drying shrinkage and creep.

The temperature gradient induced curling stresses may cause premature cracking of concrete pavements. The thermal conductivity of concrete and heat transfer coefficient have influence on temperature gradient along the concrete slab. These value help to predict the pavement slab performance vis-à-vis temperature variations (Kim, Jeon, Kim, & Yang, 2003).

3. Thermal Conductivity of cement concrete

The property that characterizes the ability of the material to transfer heat is thermal conductivity (k). It is a specific property of the material. k, is a measure of the rate at which heat (energy) passes perpendicularly through a unit area of a homogenous material of unit thickness for a temperature difference of one degree. Thermal conductivity measurement is important to understand the heat flow in cement concrete pavements.

There are two main methods to measure thermal conductivity of materials, viz. the steady state method and the transient method (Bindiganavile, Batool & Suresh, 2012). Steady state methods are adopted for homogeneous materials. In this method, the flux is proportional to the temperature gradient along the direction of flow. The experimental procedures are time consuming however, the thermal conductivity values obtained by this method are accurate. The methods of steady state thermal conductivity analysis include, guarded hot plate method, unguarded hot plate method and cylindrical probe method to name a few. The transient analyses are the non-steady methods adopted for heterogenous materials with moisture. Though the test procedures are relatively fast, the accuracy of the k value is less. The common methods adopted for transient analysis are laser flash method, step method, transient line, transient strip and transient plane method.

In the present study, steady state method has been adopted to measure the thermal conductivity values. The guarded hot plate method (ASTM C177) as recommended in ACI 122R , has been adopted for the present study. This is a commonly used test method for measuring thermal conductivity of cement concrete for pavement applications (Wang, Hu & Ge, 2008). The thermal conductivity of concrete governs the rate of heat flow through the concrete structure. The main factors that influence the thermal conductivity of concrete are mineralogical characters of the aggregates, cement content, water content, and air void content alongwith temperature and moisture condition of concrete (Wang, Hu & Ge, 2008). Of the above mentioned factors, the important factors that govern the thermal conductivity of concrete are the mineralogical characters of the aggregate and the exposure of concrete to moisture conditions. Concrete prepared with siliceous aggregates have higher thermal conductivity than concrete prepared with carbonate aggregates (Kodur & Sultan, 2003). Addition of light weight aggregate material like perlite helps reduce the k values (Demirboğa & Gül, 2003). The thermal conductivity of water is much higher than air (10). Hence, the thermal conductivity of moist concrete will be more than the dry specimen. Cement content in the concrete mix also influences the k values. Increase in cement content, increases the thermal conductivity. Powder additions (like flyash, slag) help lower the k values by reducing the cement content. Of all the powder additions, flyash is more effective in reducing the thermal conductivity values of concrete (Demirboğa & Gül, 2003).

4. Guarded Hot Plate Method (ASTM C177)

ASTM C177, specifies the test procedure for laboratory measurement of the steady state heat flux through flat, homogenous specimens with their specimens in contact with solid, parallel boundaries held at constant temperature using the guarded hot plates. Fig. 1, shows a typical schematic of two slab guarded hot plate method apparatus used for measuring the thermal conductivity of cement concrete specimen by steady state method.

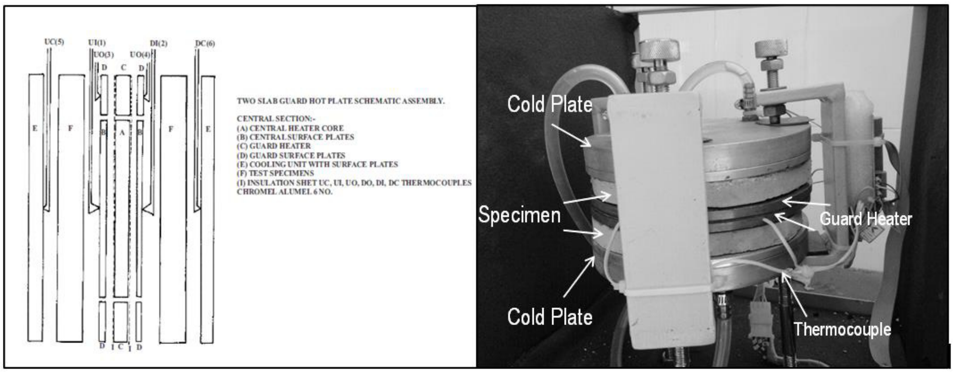


Fig.1. Schematic of Two Slab Guarded Hot Plate Method

In this test, two concrete specimens are placed between two copper plates. These plates are heated internally by special electrical resistance heaters. These plates are known as central heaters and are surrounded circumferentially by guard heaters. The guard heaters ensure unidirectional heat flow through the specimen. Thermocouples are provided to monitor the temperature at each face of the specimen. The heat transferred through the specimen is equal to the power supplied to the heater. Thermal equilibrium (steady state) is achieved when temperature and voltage observations are steady.

5. Self Compacting Concrete (SCC)

SCC is a rheodynamic concrete that flows under its own weight with minimal segregation, ensuring a uniform, defect free and quality product (EFNARC, 2005; Domone, 2006; Mehta & Monteiro, 2006). SCC differs from normal concrete in three aspects, viz. high cement content, high fines content and use of high range water reducing admixtures (HRWR) or superplasticizers. SCC was first conceptualized in Japan in 1980. As per the mix design proposed by Okamura (Naik, Kumar, Ramme & Canpolat, 2012), the mix proportioning of SCC is done in such a way that,

- The coarse aggregate content is limited to 50% of the solid volume.
- The fine aggregate content is fixed at 40% of the mortar fraction.
- Water cement ratio by volume is in the range of 0.9 to 1 depending on the properties of cementitious mix.
- The HRWR dosage is determined on the basis of degree of self compactability desired.

Once the mix design is finalized, the ingredients are mixed and tested for the fresh properties viz. filling ability (slump flow test – ASTM C1611), passing ability (J-ring test – ASTM C1621) and segregation resistance (Visual Stability Index VSI). The mechanical properties of SCC are tested as per the procedures laid down in the reference codes for the test of normal concrete.

6. Experimental Programme

The experimental program has been divided in two stages viz.

Stage 1: Mix design for M-40 grade of Self Compacting Concrete (SCC) with crushed (manufactured) sand, flyash (as cement replacement) and perlite (as sand replacement) alongwith testing of fresh state and hardened state properties.

Stage 2: Thermal conductivity (k) studies on SCC mix with optimized flyash dosage and varying perlite dosage.

There are three mix design methodologies for SCC reported in the literature viz. the powder method, the admixture method and the combination of powder and admixture method (Türkel & Ali, 2010; Hodgson et al, 2005).

For the present study, powder mix design method has been adopted for SCC. Further the mix design guidelines prescribed in EFNARC and discussed by Naik, Kumar, Ramme and Canpolat (2012) have been adopted.

6.1 Materials

Ordinary Portland cement (Grade 53) confirming to IS: 12269-1987 has been adopted for the laboratory trials. The results of tests results of various physical properties of cement and perlite have been given in Table 1. Table 2 lists all the chemical composition and compressive strength test result of cement. Coarse aggregates (CA) and fine aggregates (FA) (manufactured sand) were procured from local quarry. All the physical and mechanical property tests prescribed for aggregates in IS: 2386 (Part I to IV)-1963 have been performed. Class C flyash confirming to IS: 3812 (Part 2)-2003 from Ramagundam thermal power plant has been used. The chemical composition of flyash used has been given in Table 2. Lightweight aggregate, Perlite, has been used as a replacement material for FA. The sieve analysis of perlite, confirms to the specification prescribed in ASTM C332-99. The chemical composition and properties of perlite have been specified in Table 2.Polycarboxylate ether based (PCE) superplasticizer (HRWR) has been used for the proposed mix.

Table 1. Test results on various properties of Cement.

Physical Properties of Cement			**Physical properties of Perlite**	
	Test Result	**IS:12269-1987 requirement**		
Fineness (m^2/kg)	290	225	Colour	Grey
Standard Consistency (%)	29		pH	7
Setting time (minutes)			Specific Gravity	0.8
Initial	180	30 (Min.)	Thermal Conductivity	0.044 W/m ^oK
Final	250	600 (Max.)	Sieve Analysis	
Soundness			Sieve Size	% Passing
Le-Chatelier Expansion (mm)	0.5	10.0 (Max.)	1.18mm	98
			600 µm	80
			300 µm	50
			150 µm	1

Table 2. Chemical composition of cement, flyash and perlite and mechanical properties of cement.

Chemical Properties of Cement			**Chemical Properties of Flyash**		**Chemical Properties of Perlite**	
	Test Result	**IS:12269-1987 requirement**	**Component**	**Percentage**	**Component**	**Percentage**
$\frac{CaO - 0.7SO_3}{2.8SiO_3 + 1.2Al_2O_3 + 0.65 Fe_2O_3}$	0.88	0.8 (Min.) 1.02 (Max.	SiO_2	56.54%	SiO2	71% - 76%
Al_2O_3/Fe_2O_3	1.24	0.66 (Min.)	Al_2O_3	23.66%	Al2O3	10% - 14%
Insoluble residue (% by mass)	1.88	2.00 (Max.)	Na_2O	2.18%	Fe2O3 (max.)	0.4%
Magnesia (% by mass)	0.90	6.00 (Max.)	K_2O	2.85%	FeO (max.)	0.5%
Sulphuric Anhydride (% by mass)	1.80	3.00 (Max.)	CaO	9.61%	CaO	0.5%
Total loss on ignition (% by mass)	1.80	4.00 (Max.)	MgO	0.92%	MgO	0.2%
Total Chlorides (% by mass)	0.008	0.10 (Max.)	Fe_2O_3	4.65%	Na_2O	3% - 4%
Mechanical Properties of Cement			Mn_3O_4	0.13%	K_2O	4% - 5%
Compressive Strength (MPa)			TiO_2	1.37%	Organic matter	Trace
72 ± 1 hr. (3 days)	38.0	27 (Min.)	P_2O_5	1.58%		
168 ± 2 hr. (7 days)	51.0	37 (Min.)	SO_3	0.48%		
672 ± 4 hr. (28 days)	71.5	53 (Min.)				

6.2 Concrete Mix

As per the IRC: 58-2011 guidelines, cement concrete pavement slab is designed on the basis of flexural strength. Further, it has been mentioned that in no case the 28 day flexural strength of pavement quality concrete (PQC) should be less than 4.5MPa. The flexural strength of concrete is measured as per IS: 516-1959 or as per the relationship prescribed in IS: 456-2000,

$$F_{cr} = 0.7 \times \sqrt{f_{ck}}$$

where,

F_{cr}: flexural strength of concrete (modulus of rupture) MPa.

f_{ck}: characteristic compressive cube strength of concrete MPa.

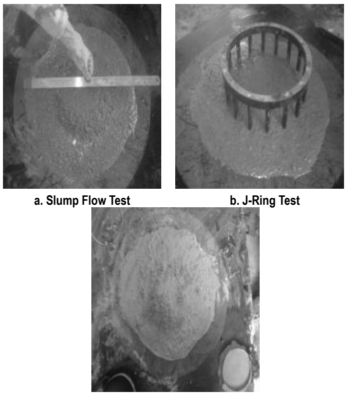
By substituting the 28 day flexural strength of 4.5MPa, it is found that the characteristic strength is around 41MPa. Hence, for pavement applications, it can be deduced that the minimum grade of concrete has to be M40. As per the mix design procedure, prescribed by IS: 10262-2009, the target compressive strength for M40 grade of concrete is 48.25MPa.

The mix proportion adopted for the study is M-40 grade of SCC. The material proportions adopted are tabulated in Table 3. Mix 1 corresponds to M-40 grade of SCC with crushed sand with 100% cement. No additives were added to this mix. Mix 2 represents SCC mix with 20% flyash added as a cement replacement admixture. 20% flyash addition has been decided based on the laboratory trials undertaken. 28-day compressive strength and 28-day flexural strength were the deciding criteria to fix the optimal flyash dosage level. The proposed flyash dosage is in line with the recommendations of NCHRP Report 628 (Khayat & Mitchell, 2009) that states, 20% flyash dosage to SCC mixes exhibits better workability, slump retention as well as high level of static stability (resistance to segregation). Mix 3 to 6 included perlite as a replacement material to fine aggregates. Based on the particle size of perlite, it was used to replace fine sand component of FA (300µ and 150µ size). The amount of perlite was varied at the rate of 2.5% of fine sand component.

Table 3. Mix proportion.

Material	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Cement (kg/m^3)	430	344	344	344	344	344
Flyash (kg/m^3)	0	86	86	86	86	86
Flyash dosage (% cement)	0	20	20	20	20	20
F. A. (kg/m^3)	1135	1135	1106.625	1078.25	1049.875	1021.5
Perlite (kg/m^3)	0	0	28.375	56.75	85.125	113.5
Perlite dosage (% FA replacement)	0	0	2.5	5	7.5	10
C. A. (kg/m^3)	630	630	630	630	630	630
Water (kg/m^3)	200	200	200	200	200	200
HRWR (lit/100kg of binder)	0.8	0.8	0.8	0.8	0.8	0.8
Slump flow (mm)	587	592	594	597	610	608
VSI	1	0	0	0	0	0

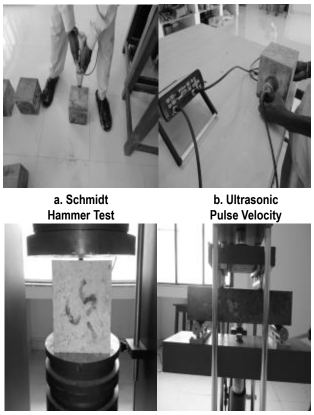
The fresh state properties of the proposed SCC mix viz. filling ability (slump flow test), passing ability (J-ring flow test) and segregation resistance (VSI) were performed [Fig. 2]. The results of these tests have been tabulated in Table 4. Cube specimen of 15cm side and beam specimen (50cm x 10cm x 10cm) were prepared and subjected to curing. The cured specimens were subjected to non-destructive testing as well as mechanical testing. The non-destructive tests performed on the cube specimen are Schmidt Hammer test (IS: 13311 (Part 2)-1992) and Ultrasonic Pulse velocity test (IS: 13311 (Part 1)-1992) [Fig. 2]. The compressive strength of the cube specimens were tested at 3-days, 7-days and 28-days [Fig. 2]. The beam specimens prepared were subjected to 7-day and 28-day flexural strength tests [Fig. 2]. The results of non-destructive tests as well as mechanical properties have been listed in Table 4.



a. Slump Flow Test

b. J-Ring Test

c. Slump Flow with VSI 0



a. Schmidt Hammer Test

b. Ultrasonic Pulse Velocity

c. Compressive Strength Test

d. Flexural Strength Test

Fig.2. Testing of Fresh Properties as well as mechanical properties of SCC Mix.

Table 4. Summary of test results of non-destructive as well as mechanical properties of various concrete mixes.

Sr. No.	Mix Details	Schmidt Hammer Test Strength (MPa)			Ultrasonic Pulse Velocity Test (km/s)			Compressive Strength (MPa)			Flexural Strength (MPa)	
		3 Day	7 Day	28 Day	3 Day	7 Day	28 Day	3 Day	7 Day	28 Day	7 Day	28 Day
1	M 40	13.967	17.400	21.800	4.508	4.620	4.728	43.055	48.296	57.778	6.600	7.333
2	M 40 + 20% Flyash	14.300	15.734	20.167	4.505	4.624	4.767	27.464	32.559	50.370	5.000	6.533
3	M 40 + 20% Flyash + 2.5% Perlite	11.634	13.634	17.567	3.870	3.954	4.109	27.313	34.422	51.556	6.533	7.933
4	M 40 + 20% Flyash + 5% Perlite	12.734	15.434	21.767	3.734	3.931	4.083	29.959	38.963	51.852	6.867	8.400
5	M 40 + 20% Flyash + 7.5% Perlite	11.834	17.534	18.934	3.810	3.917	4.068	28.847	37.926	51.556	6.000	7.867
6	M 40 + 20% Flyash + 10% Perlite	13.267	15.434	18.300	3.892	3.934	4.043	26.933	37.778	48.593	5.933	7.600

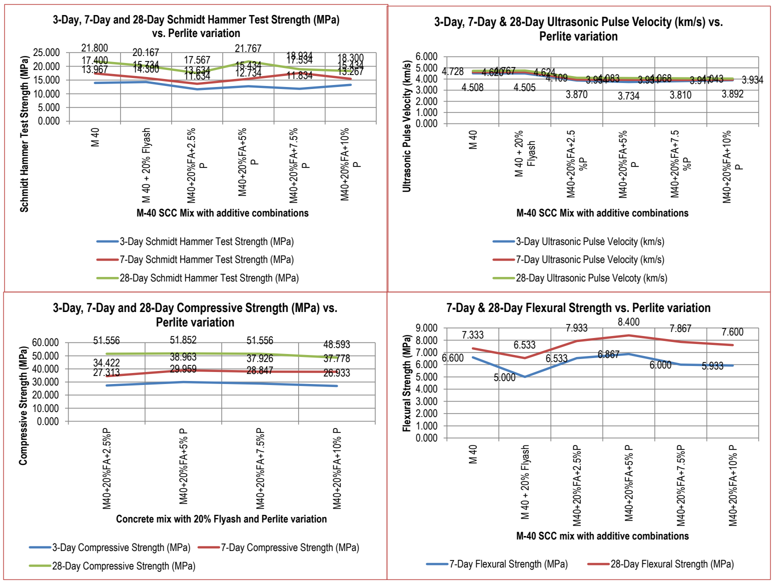


Fig.3. Variation in NDT and mechanical properties for M-40 grade of SCC with various additive combinations

6.3 Thermal Conductivity (k) Results

As discussed in the preceding section, the thermal conductivity studies were undertaken in accordance with the specification prescribed in ASTM C177. Cylindrical specimen of 18cm diameter and 1.5cm thickness were prepared from the same batch of concrete prepared for compressive strength and flexural strength tests. Typical specimens have been shown in Fig. 4.

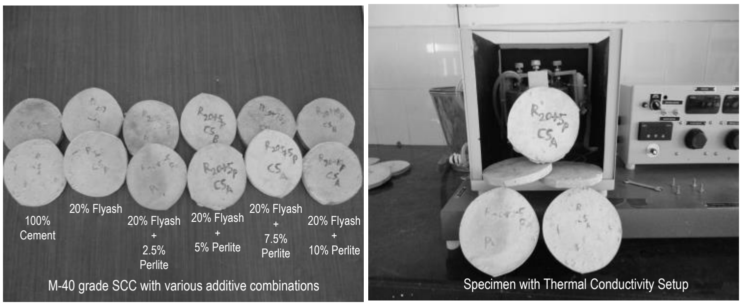


Fig.4. Specimen for Thermal conductivity test

Table 5, discusses the values of thermal conductivity obtained for various additive combinations for M-40 grade SCC mix. The thermal conductivity values were measured at five different temperature regimes viz. 30°C-40°C, 40°C-50°C, 50°C-60°C, 60°C-70°C and 70°C-80°C. The said temperature regimes were adopted based on the fact that the rigid pavement surface would be subjected to these temperature ranges throughout the day for its entire service life.

Table 5. Thermal Conductivity values for different additive combinations and temperature regimes.

Sr. No.	Mix Details	Avg. Density (kg/m^3) after curing	Thermal Conductivity (k) (W/m. °C)				
			30 – 40 °C	40 - 50 °C	50 - 60 °C	60 - 70 °C	70 - 80 °C
1	M-40 100% Cement	2394.69	3.115	2.554	1.891	1.462	1.114
2	M-40 + 20% Flyash	2305.46	2.836	2.197	1.652	1.338	0.846
3	M-40 + 20% Flyash + 2.5% Perlite	2292.36	2.430	2.038	1.547	1.307	0.793
4	M-40 + 20% Flyash + 5% Perlite	2279.26	2.355	1.944	1.498	1.298	0.761
5	M-40 + 20% Flyash + 7.5% Perlite	2253.06	2.179	1.739	1.425	1.156	0.738
6	M-40 + 20% Flyash + 10% Perlite	2226.83	2.094	1.708	1.379	1.030	0.715

It is observed that the k values decrease with the decrease in density and increase in temperature. The trend observed in this study is in line with the trend reported in the literature (Kodur & Sultan, 2003). This variation has been represented in Fig. 5.

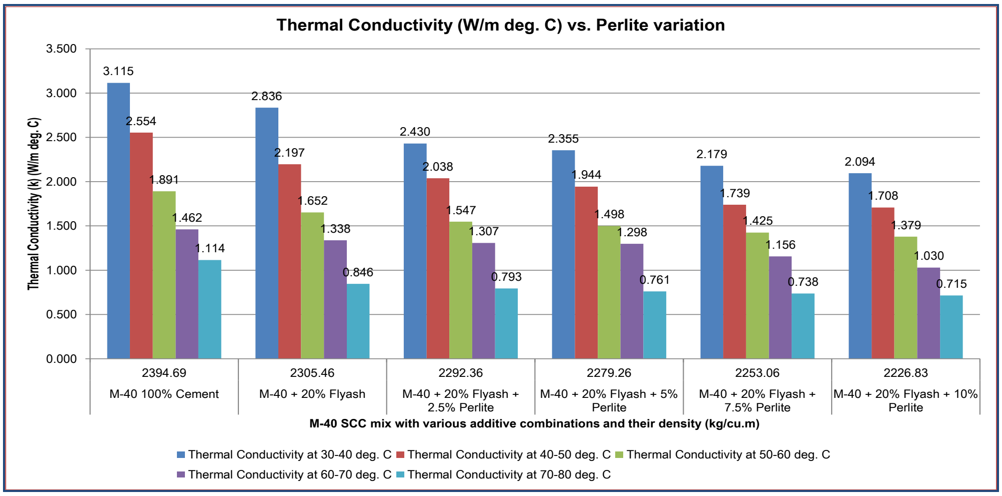


Fig.5. Results of Thermal Conductivity Test for various additive combinations for M-40 grade SCC mix.

7. Conclusions

Based on the above experimental study, following conclusions can be deduced;

- Thermal studies on cement concrete are important for rigid pavement analysis. The thermal stresses influence the joint spacing and design of temperature reinforcements for rigid pavements.
- The powder based SCC mix ensures a homogenous and dense matrix with minimum risk of segregation.
- From the test results on mechanical properties it is observed that, all the specimens satisfy the 28-day flexural strength criteria of 4.5MPa. Hence, the optimal value of perlite dosage has been decided on the basis of 28-day compressive strength. From the studies undertaken, it is observed that 5% perlite dosage gives a maximum 28-day compressive strength of 51.852MPa (28-day flexural strength of the said mix is 8.4MPa). Hence, 5% perlite dosage is preferred perlite dosage from the strength perspective.
- Addition of flyash and perlite brings down the density of the mix. The thermal conductivity values of the concrete mix decreases at all temperature ranges, with decrease in density.
- At lower temperature, the k values are higher as compared to the k value at higher temperature. This is attributed to the fact that, the residual moisture present in the concrete specimen gets dried up with increase in temperature. Hence, the k value decreases at higher temperature.
- Usually in Indian conditions, the peak pavement surface temperature is in the range of 50^{o}C to 60^{o}C during summer season.
- It is observed that addition of flyash (Mix 2) alone brings down the k value by 12.64% as compared to the k value of Mix 1 at 50^{o}C to 60^{o}C range.
- The k value of M40 SCC mix with 20% flyash and 5% perlite is 20.78% lower than the k value for M40 SCC mix with 100% cement at a temperature range of 50^{o}C to 60^{o}C.
- The reduction in k value, decreases the thermal gradient developed in the rigid pavement. This helps in preventing premature cracking of pavement on account of temperature variation.

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