PREDICTION OF THE THERMAL CONDUCTIVITY OF CONCRETE USING ABAQUS MODEL

Tumadhir Merawi Borhan
Department of Civil Engineering, Al-Qadisiyah University, P.O. Box 1881, Ad Diwaniyah, Iraq
Tumadhir_borhan@qadissuni.edu.iq

ABSTRACT

An attempt to determine an easy and accurate method to predict the thermal conductivity of concrete is presented in this paper. The new method is based on the heat transfer test results and the finite element software package ABAQUS. The boundary condition for this model was the temperature profile of the exposed side of the specimen which was taken from the heat transfer tests. The values of the thermal conductivity that give the closed agreement curve for the unexposed surface temperature profile were recorded for a different temperature levels. This method can be adopted to compare the value of the thermal conductivity of any type of concrete with other concrete as an easy and fast alternative method to the standard test methods.

KEYWORDS: Concrete**,** Thermal conductivity, heat transfer test, ABAQUS model.

تقدير معامل الموصلية الحرارية للخرسانة باستخدام برنامج ABAQUS

الخلاصة

يقدم هذا البحث محاولة جديدة لايجاد طريقة سهلة ودقيقة لتقدير معامل الموصلية الحرارية للخرسانة . تستند هذه الطريقة على نتائج اختبار انتقال الحرارة وعلى طريقة التحليل بالعناصر المحددة باستخدام البرنامج ABAQUS. ان المحددات لطريقة العناصر المحددة هي التغير الحراري مع الزمن للسطح المعرض للحرارة بصورة مباشرة والسطح الغير معرض للحرارة. سجلت قيم الموصلية الحرارية التي تعطي أفضل توافق لمنحنى التغير بدرجة الحرارة للسطح الغير معرض للحرارة بصورة مباشرة. اظهرت النتائج انه بالامكان اعتماد هذه الطريقة للحصول على قيمة تقريبية لمعامل الموصلية الحرارية بصورة سريعة ودقة لاي نوع من انواع الخرسانة والاستفادة منها للمقارنة مع انواع اخرى من الخرسانة في حالة تعذر اجراء الطريقة القياسية للفحص.

INTRODUCTION

Thermal conductivity is a measurement of the ability of the material to conduct heat. The coefficient of thermal conductivity of concrete depends on the moisture content, type of aggregate, porosity, density, presence of fibre and temperature.

Two techniques are commonly used to measure the thermal properties of concrete; these are the steady state method and the transient method. The principles of the steady state technique are based on creating a steady temperature gradient across a known thickness specimen by controlling the heat flow from one side to another. The determination of the thermal conductivity can be obtained by applying

Fourier's law in one dimension. The most common methods used are the guarded hot plate and the heat flow meter method (Franco 2007). These methods, however, require a long time to establish the steady state temperature gradient across the specimen where the gradient is required to be large. The size of the specimen is also required to be large. Another problem related to this method is a potentially great influence of thermal contact resistances between the sample and other elements of the measurement system on the results. This problem is particularly significant if the contact surfaces are rough and filled with air (Nenad Stepanić 2009)

On the other hand, transient techniques perform a measurement during the process of heating. The advantage is that these may be made relatively quickly. The most common method used is the transient plane source method which is also called the hot disk method. A plane sensor, a special mathematical model describing the heat conductivity, combined with precise electronics, enables the method to be used to measure thermal transport properties. The disadvantage is that the mathematical analysis of the data is in general more difficult than the steady state methods.

A comparison study showed that over a large range of conductivities (1.4 to ~5 W/ m. K) and rock types there is almost no difference between the results obtained from using both methods (Sass et al. 1984).

A number of researchers have attempted to predict the thermal conductivity of concrete using theoretical models (Choktaweekarn et al.2009, Kim et al. 2003, Khan 2002). These models take into consideration the thermal conductivity of each ingredient of concrete, the moisture content, porosity, and other factors. However, they are not suitable for some types of concrete, such as fibre reinforced concrete, nor for all environmental conditions such as fire condition. An easy and accurate method to determine the thermal conductivity of concrete still needs further research.

This study presented a new attempt to predict the thermal conductivity of concrete. The new method is a combination of a simple heat transfer test, conducted by Borhan (Borhan 2012), and the finite element software package ABAQUS. The results from ABAQUS model was validated against Borhan's experimental results and discussed.

EXPERIMENTAL WORK

The results from the developed heat transfer tests conducted by Borhan (Borhan 2012) were used in the author's study. Borhan's mixes were produced from a concrete reinforced with different volume fractions of basalt fibre (0, 0.1, 0.3, and 0.5% by total mix volume). The binder consists of ordinary Portland cement and metakaolin (china clay) (CC) (10% by weight of cement was added to cement). The coarse aggregate (CA) used in this study was limestone of 10mm maximum size and natural sand was used as a fine aggregate. The superplasticizer (SP) used was a sulphonated formaldehyde condensate (Daracem SP6). The optimum dosage of the SP, which gives 50 mm slump, was chosen by doing a trial mixes for concrete mixture which contains 0.5% basalt fibre. The mix proportions for all mixes were 1:1.75:3.5 (cement: sand: coarse aggregate) by weight with (0.55) water to binder ratio. The control mix (F0) details is shown in Table 1, the other mixes are marked as F1, F3, F5 for 0.1, 0.3 and 0.5% (by total mix volume) basalt fibre respectively. The physical and the chemical properties of the materials used in Borhan's study were presented in Table 2.

A heat transfer test was developed by Borhan (Borhan 2012) to measure the heat transfer through the thickness of concrete specimen (Figure 1). The test procedure utilizes a standard kiln with automatic temperature control. Small specimens (300x100x25) mm, from different mixes, were placed on the top of the kiln and insulated from the other directions (Figure 1). The temperature was raised to 600^{o}C at a rate of 5^{o}C/min. Thermocouples (type k) were used to record the temperature of the top and the bottom surfaces of the specimens (one thermocouple for each surface). The thermocouples were adhered at the centre of the two surfaces using a special type of glue (thermo –glue). The differential temperature between the outside and the inside faces of the specimen was calculated. The temperature difference- time history was plotted for each mix (Figure 4).

PREDICTION OF THE THERMAL CONDUCTIVITY

The finite element programme ABAQUS was adopted to predict an approximate value for the thermal conductivity (TC) together with the heat transfer test. The geometry of the specimen for the heat transfer test was modelled (Figure 2). 20-node quadratic heat transfer brick elements (DC3D20) were used. The boundary condition for this model was the temperature profile for the exposed side of the specimen which was taken from the heat transfer test. The density for each mix was taken from the unit weight test results (Borhan 2012) (Table 3) . The data of the specific heat (SH) was used according to BSEN1992-1-2 (BSEN1992:1-2 2004) for normal weight concrete (NWS). The recorded moisture content of the specimens was between 3 to 5% (Borhan 2012).

To find the suitable range of the variations in the analysis of the thermal conductivity and the specific heat values in the model that can effect the results, a sensitivity test was carried out to show the differences in the results when the values of the thermal conductivity and the specific heat changed above or below the recorded values by 0.1 and 0.2 W/m.K for the thermal conductivity and 100 J/kg.^{o}C for the specific heat (Figure 3). ABAQUS heat transfer model parameters (the film coefficient (h) and the sink temperature) used in this model were 25 W/m^{2} K and 20^{o}C respectively for unexposed side and 25 W/m^{2} K and 1 for the exposed side (with temperatures amplitude recorded by the thermocouples). The specific heat was modelled as temperature-dependent properties and the data according to the BSEN1992-1-2, at moisture content 3%, were adopted for the control mix to start with (Table 4).

By iteration technique , following the heat transfer test results indication as a guide, the values of the thermal conductivity that give the closed agreement curve for the unexposed surface temperature profile were recorded for a different temperature levels and for nearest 0.05 W/m.K (Figure 4 and Table 5).

From Figure 5 it can be seen that increasing basalt fibre content results in decreasing the thermal conductivity of concrete at all temperature levels. This mainly due to the nature of the basalt rocks, which intern leads to the volumetric stability of basalt fibres which confirms higher resistance against high temperature exposure (Sim et al. 2005). According to the data provided by BSEN1992-1-2 (BSEN1992:1-2 2004) for normal weight concrete (NWC), high strength concrete (HSC) and lightweight concrete (LWC), with increasing the temperature, the thermal conductivity of concrete decreases and it also depends on the type of concrete as shown in Figure 6, which confirms the results obtained in this study.

The results show that this method can give approximate values for the thermal conductivity (±0.05) and the specific heat that can be used to model different types of concrete. However, further experimental work is needed to compare the results from a standard thermal conductivity test with the results from ABAQUS model.

CONCLUSION

ABAQUS with the heat transfer tests were used to predict an approximate value for the thermal conductivity. This method can be useful to compare the value of the thermal conductivity of different types of concrete as an easy and fast alternative method to the standard test methods. Further research is needed to develop this model by conducting standard tests to validate ABAQUS model.

REFERENCES

Borhan, T. M. (2012) Properties of glass concrete reinforced with short basalt fibre. *Materials & Design,* 42**,** 265-271.

BSEN1992:1-2. 2004. Eurocode 2, Design of Concrete Structures. General Rules - Structural Fire Design. British Standards.

Choktaweekarn, P., Saengsoy, W. & Tangtermsirikul, S., (2009) A model for predicting thermal conductivity of concrete. *Magazine of Concrete Research,* 61**,** 271-280.

Franco, A. (2007) An apparatus for the routine measurement of thermal conductivity of materials for building application based on a transient hot-wire method. *Applied Thermal Engineering,* 27**,** 2495-2504.

Khan, M. (2002) Factors affecting the thermal properties of concrete and applicability of its prediction models. *Building and Environment,* 37**,** 607-614.

Kim, K.-H., Jeon, S.-E., Kim, J.-K., & Yang, S., (2003) An experimental study on thermal conductivity of concrete. *Cement and Concrete Research,* 33**,** 363-371.

Nenad Stepanić, a., Nenad Milošević (2009) Correction on the Influence of Thermal Contact Resistance in Thermal Conductivity Measurements Using the Guarded Hot Plate Method. *Serbian Journal Of Electrical Engineering,* 6**,** 479-488.

Sass, J. H., Stone, C., & Munroe, R. J., (1984) Thermal conductivity determinations on solid rock — a comparison between a steady-state divided-bar apparatus and a commercial transient line-source device. *Journal of Volcanology and Geothermal Research,* 20**,** 145-153.

Sim, J., C. Park & D. Moon (2005) Characteristics of basalt fiber as a strengthening material for concrete structures. *Composites Part B: Engineering,* 36**,** 504-512.

Table 1: Control mix details

Ingredient	Cement kg/m^3	Water kg/m^3	Sand kg/m^3	CA kg/m^3	BASALT kg/m^3	SP ml	CC kg/m^3
Content (F0)	400	242	700	1400	0	4000	40

Table2: Chemical and some physical properties of the materials used
1

Portland cement		Metakaolin		Superplasticizer		Basalt fibre	
Property	%	Property		Property		Property	
SiO_2	31.135	Colour	White	Appearance	Dark brown liquid	Density of unsized filament matl	2.67kg/dm^3
Al_2O_3	10.29	ISO brightness	>82.5	Air Entrainment	1% - 2%	Moisture content of basaltic rock	0.1%
Fe_2O_3	4.295	-2µ (mass%)	>60	Chloride Content	Nil	Melting point	1350°C
CaO	48.5	+325 mesh (mass%)	<0.03	Freezing Point	0°C	Filament breaking load	> 85 - 67cN/tex
MgO	2.27	Moisture (mass%)	<1			Elongation at break	2.8%
SO_3	2.49	Aerated powder density (kg/m^3)	320			E-Modulus	84 GPa
K_2O	0.835	Tapped powder density (kg/m^3)	620			Continuous max temperature	-250°C to 550°C 1200°C fire barrier
TiO_2	-	Surface area (m^2/g)	14				
Na_2O	0.22	Pozzolanic reactivity (mg $Ca(OH)_2$/g)	>950				
Eq Na_2O	0.765						
L.O.I	1.98						
Other	-						

Table (3) the density value for each mix (Borhan 2012)

Specimen Mark.	**Fibre% By Vol.**	**Density (kg/m^3)**
F0	0	2418
F1	0.1	2415
F3	0.3	2412
F5	0.5	2410

Table (4) Specific Heat Value (ABAQUS)

Mix	Specific Heat J/kg.^{o}C					
	20C^o	100C^o	150C^o	200C^o	400C^o	600C^o
F0	1000	1000	2020	2020	1100	1100
F1	1000	1000	2020	2020	2020	2020
F3	1000	1000	2020	2020	2020	2020
F5	1000	1000	2020	2020	2020	2020

Table (5) Thermal Conductivity Values (ABAQUS)

Mix	Thermal conductivity (W/m.K)			
	60C^o	100C^o	350C^o	600C^o
F0	1.15	0.90	0.85	0.65
F1	1.10	0.85	0.80	0.60
F3	1.10	0.80	0.65	0.55
F5	0.90	0.60	0.55	0.50

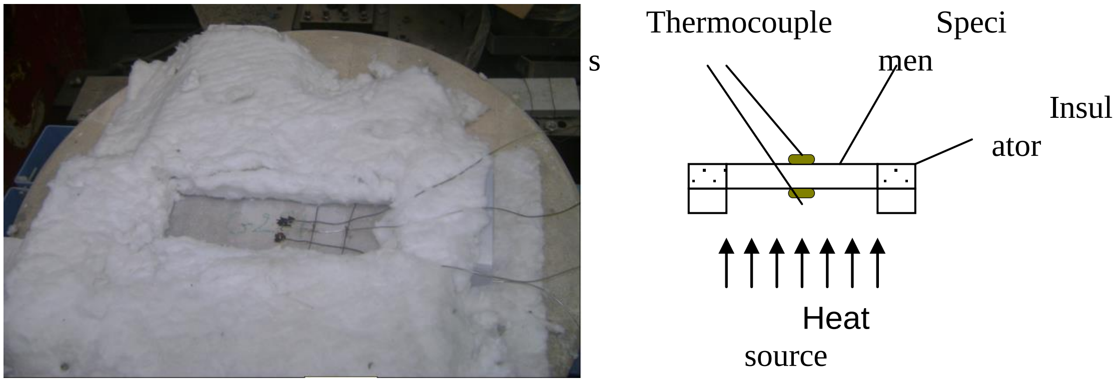


Figure 1 Heat transfer test

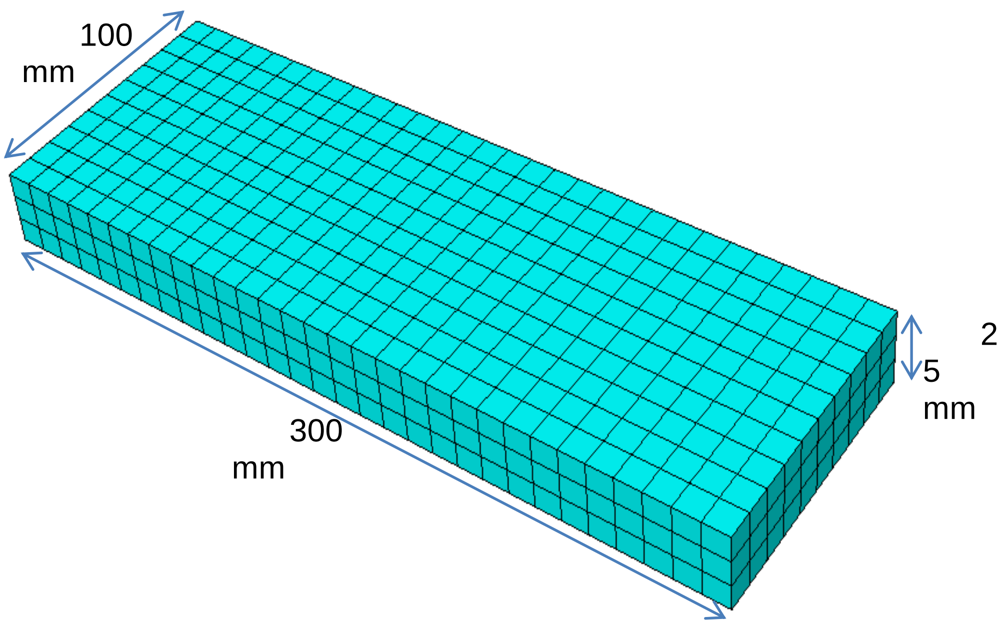
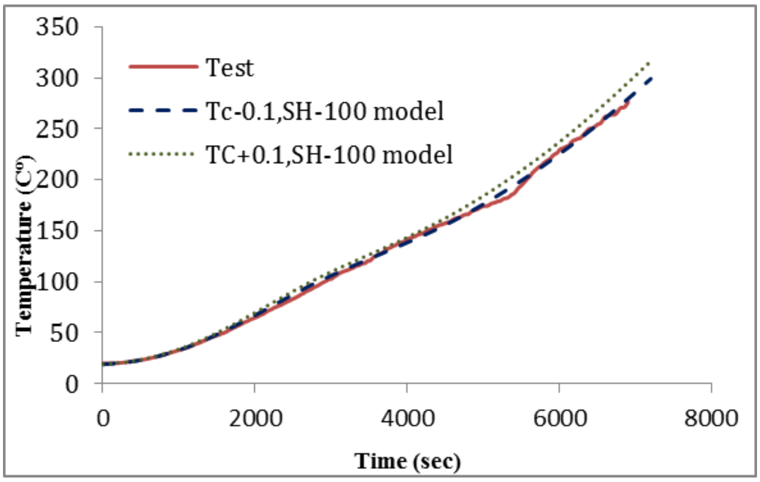
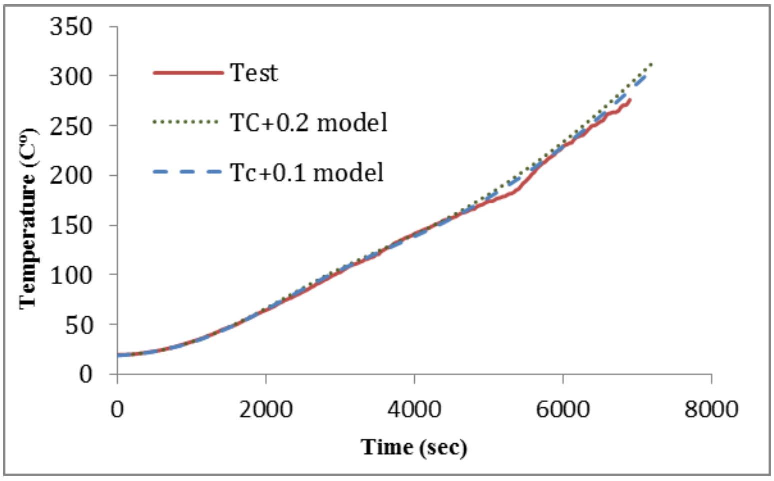


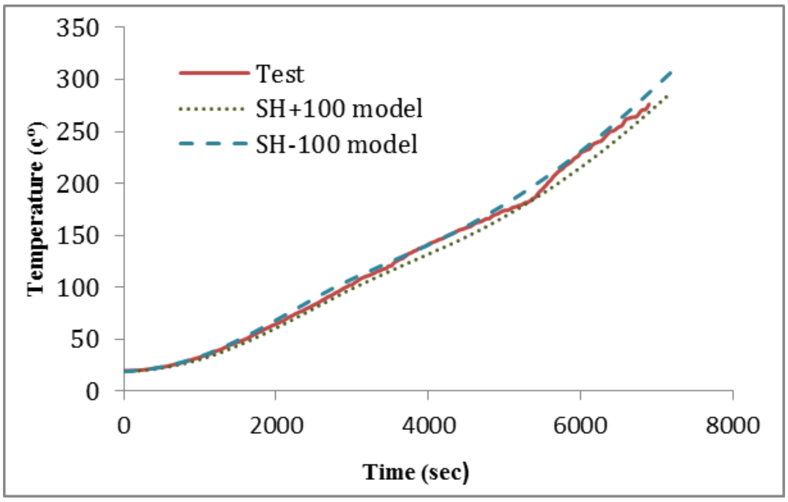
Figure 2 The ABAQUS Model



a) Increasing and decreasing TC with increasing and decreasing SH



b) Increasing TC value with SH constant



c) Increasing and decreasing SH value with TC constant

Figure 3 Prediction of TC and SH different cases

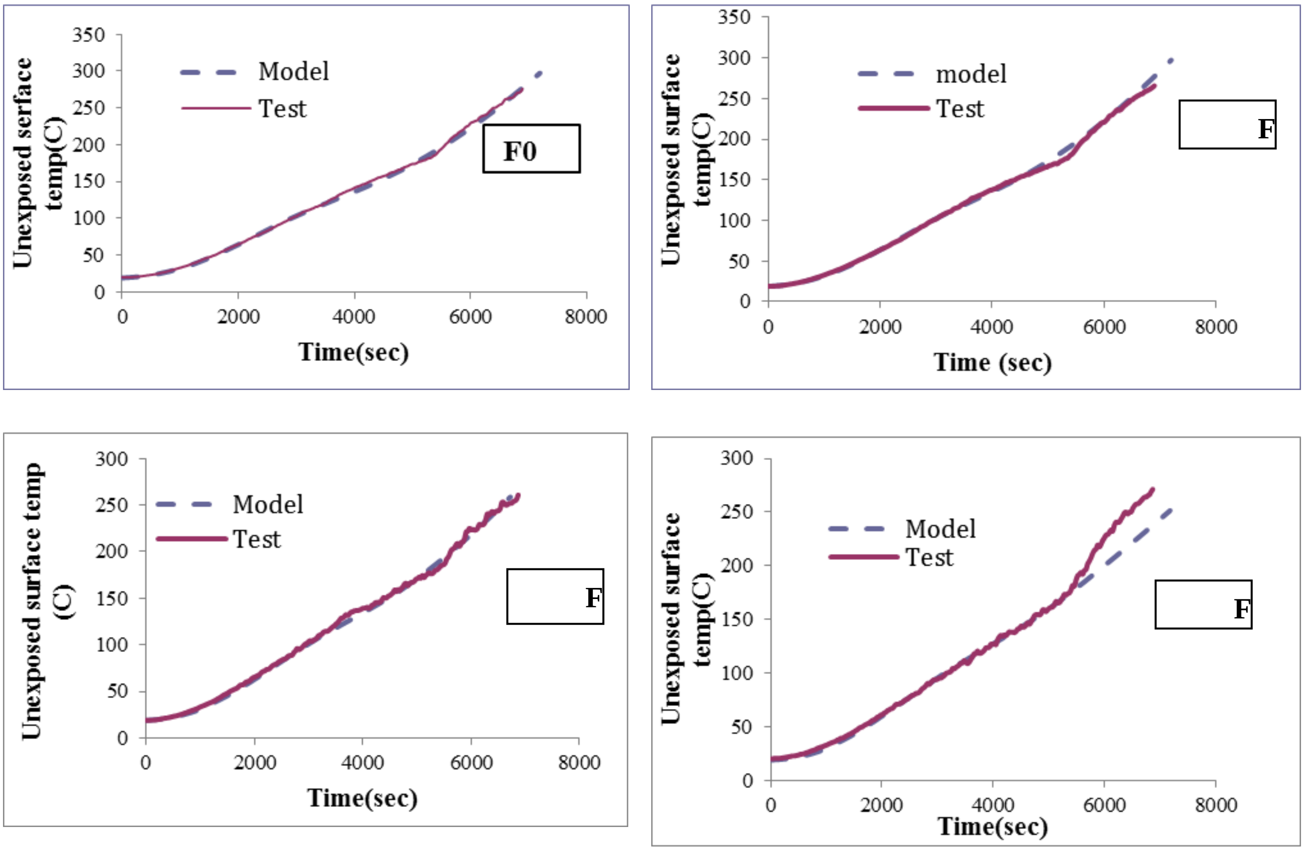


Figure 4 Prediction of TC (best curve value) for different mixes

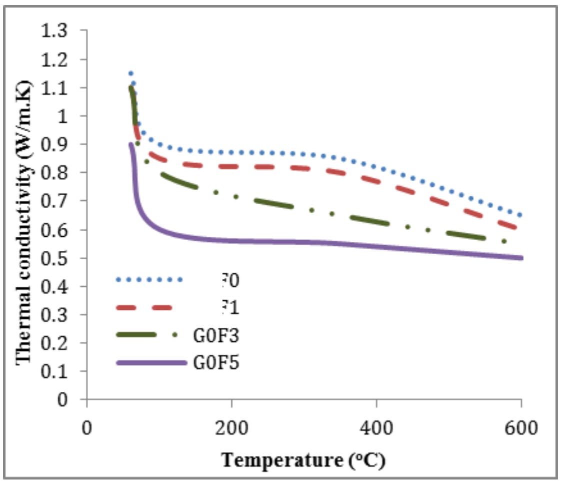


Figure 5 Thermal conductivity vs. temperature (ABAQUS)

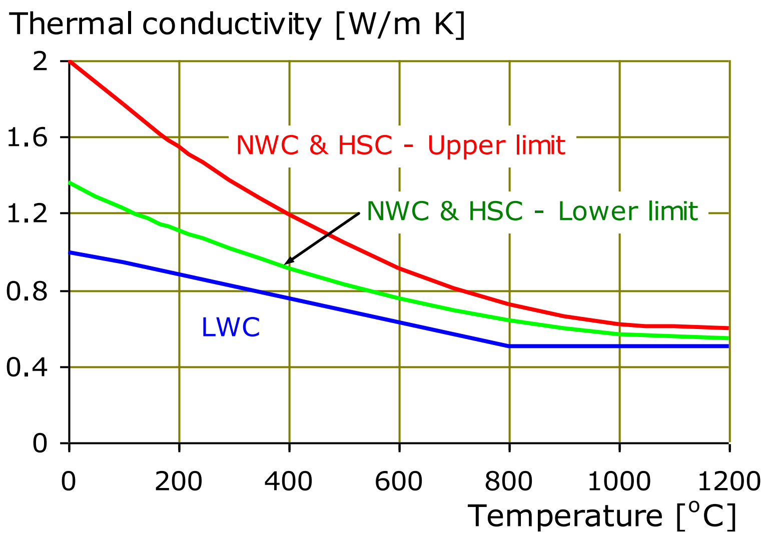


Figure 6 Thermal Conductivity of Different Type of Concrete Verse Temperatureaccording to BSEN 1994-1-2.