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A COMPARATIVE STUDY ON THE THERMAL INSULATION PERFORMANCE OF UNLOADED AND PLASTICALLY DEFORMED HTPP-ECC

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Abstract: Engineered Cementitious Composite (ECC) is a type of micro-mechanically designed, high performance composite compared to conventional concrete. A considerable number of research in the existing literature concentrate on mechanical performance and ductility improvement of ECCs. In this paper, thermal properties of special type of ECC incorporating high tenacity polypropylene fiber by 2% of total matrix volume (HTPP-ECC) have been investigated. For this purpose, prismatic composites were prepared and thermal conductivity tests were performed. Tests results were compared with the data obtained from existing literature. The mechanical performance and multiple cracking ability of HTPP-ECCs were also tested under bending load. In addition to the existing literature, thermal heat insulation performance of HTPP-ECCs have been tested at virgin (before bending test), cracked (up to 10% of load drop after peak load) and failed (up to 5 mm major crack width at the bottom of the specimen) state by using an insulation test setup which simulates actual site conditions. The effect of steady state micro-cracking on the thermal insulation performance of HTPP-ECC was evaluated. Results showed that, HTPP-ECCs produced in this study has better performance in terms of thermal conductivity when compared to other types of cement-based materials even at the plastically deformed state. Also, HTPP-ECCs exhibited an effective thermal insulation performance even in micro-cracked state as a promising alternative thermal insulation material with improved mechanical properties and multiple cracking ability.
Keywords: Thermal properties, Engineered Cementitious Composites, HTPP, fiber, long term.

YÜK UYGULANMAMIŞ VE PLASTİK DEFORMASYONA UĞRATILMIŞ HTPP-ECC'LERİN TERMAL YALITIM PERFORMANSI ÜZERİNE KARŞILAŞTIRMALI BİR İNCELEME

Özet: Mühendislikçe geliştirilmiş çimentolu kompozitler (ECC) mikro-mekanik olarak tasarlanan geleneksel betona kıyasla yüksek performanslı kompozitlerdir. Mevcut literatürdeki önemli sayıda araştırma, ECC'lerin mekanik performansının ve sünekliğinin geliştirmesine odaklanmaktadır. Bu çalışmada, ECC'nin HTPP-ECC isimli özel bir türünün termal özellikleri araştırılmıştır. Bu amaç doğrultusunda, prizmatik kompozitler hazırlanmış ve termal iletkenlik deneyleri gerçekleştirilmiştir. Deney sonuçları mevcut literatürden elde edilen verilerle kıyaslanmıştır. Ayrıca, HTPP-ECC'lerin mekanik performansı ve çoklu çatlama yeteneği eğilme yükü altında test edilmiştir. Mevcut literatüre ek olarak, HTPP-ECC'lerin termal ısı yalıtım performansı, çatlamamış (eğilme testinden önce), çatlatılmış (tepe yüklemesinden sonra yük düşüşü % 10'a kadar) ve göçmüş (numunenin altında 5 mm genişliğinde büyük çatlak oluşana kadar) durumlarda gerçek saha koşullarını taklit eden bir yalıtım testi kurulumu kullanılarak test edilmiştir. Kararlı haldeki mikro-çatlakların HTPP-ECC'nin ısı yalıtım performansı üzerindeki etkisi değerlendirilmiştir. Sonuç olarak, bu çalışmada üretilen HTPP-ECC'lerin plastik olarak deforme olmuş halde bile çimento esaslı diğer materyallere kıyasla daha iyi bir termal iletkenlik performansı sergilediğini göstermiştir. Ayrıca, HTPP-ECC'ler mikro-çatlaklı halde bile gelişmiş mekanik özelliklere ve çoklu kırma yeteneğine sahip umut verici alternatif bir ısı yalıtım malzemesi olarak etkili bir ısı yalıtımı performansı sergilemiştir.
Anahtar Kelimeler: Termal özellikler, Mühendislikçe geliştirilmiş çimentolu kompozitler, HTPP, lif, uzun dönem.

INTRODUCTION

Recently, the importance of energy conservation is well recognized worldwide. The building sector is responsible for the 40% of total energy consumption in the world (Chwieduk, 2017). Therefore, an efficient thermal energy storage in buildings is becoming an essential part of country policies due to both economic and environmental reasons.

Engineered Cementitious Composite (ECC) is a micro-mechanically designed, high performance composite when compared to conventional concrete and fiber reinforced composites. ECC exhibits higher ductility and enhanced durability properties depending on the saturated stable micro-cracking and pseudo-strain hardening behavior by only addition of 2% polymeric micro-fibers into cement based matrix (Li, 1997). Ultra-high molecular weight poly-ethylene (UHMWPE) and poly-vinyl alcohol (PVA) fibers were used in ECC production in general (Li et al., 1996, Li et al., 2001). Last decades, high tenacity poly-propylene fibers were also introduced as an economic alternate and used in HTPP-ECC production successfully (Yang, 2006, Felekoglu and Keskinates, 2016). Various types of ECCs have been developed by adjusting the micro-mechanic design theory to fulfill the intended characteristics for special construction topics such as dam retrofitting, anti-seismic building material production and highway applications (Li and Kanda, 1998, Rokugo et al., 2009, Muzenski et al., 2015). However, most of the studies in the literature have focused on improving the mechanical, ductility or durability properties of ECCs and their thermal properties were investigated, rarely. Huang et al. (2013) studied the mechanical and thermal properties of green lightweight polyvinyl alcohol (PVA) fiber reinforced ECCs and reported that the use of hollow fly ash cenospheres reduced the thermal conductivity of PVA-ECCs. Xu and Li (2014) investigated the thermal energy storage of ECCs (TES-ECC) incorporating a paraffin/diatomite composite phase change material (PCM). They concluded that the thermal conductivity of TES-ECCs were about 42-45% lower than the ordinary fiber reinforced cementitious composites. In another study, the addition of PCM by 3% increased the thermal resistance of PVA-ECC by 22% (Desai et al., 2014). Up to 23.3% reduction in thermal conductivity has been reported by using different fly ashes (FA) and aerogel combinations and correlated with the hollow structure of the FA, the air voids entrapped within the composite, and the open nano-porous nature of aerogel particles (Hanif et al., 2016). Wu et al. (2015) developed ultra-lightweight cement composites that incorporating polyethylene (PE) fiber by 0.5% of total volume, and their thermal conductivities ranged between 0.28-0.80 W/mK. Zhang and Li (2015) designed a fireproofing ECC material by using high tenacity polypropylene fiber (HTPP), which was also suitable for spray applications. However, it should be noted that all these experiments were conducted on the virgin (unloaded) specimens.

As first in the literature, long-term thermal performances of HTPP-ECC specimens have been investigated at virgin (unloaded) and different plastically deformed states. First, thermal conductivity of virgin HTPP-ECC is tested. The conductivity performance of HTPP-ECC has been compared with the conductivity values of familiar materials that obtained from literature. As an addition to the recent literature, thermal insulation performance of HTPP-ECC was also examined at virgin (unloaded), cracked (10% of load drop after peak load) and failed (by loading up to 5 mm crack width at the bottom of the specimen) state.

MATERIALS AND METHODS

In the matrix phase of the composites, Type I ordinary Portland cement (OPC) conforming to the requirements of ASTM C150, calcined kaolin (CK), limestone powder (LP) and standard sand described in EN 196-1 were used. The chemical and physical properties of OPC and CK are given in Table 1 and Table 2. LP used in the mixture has a specific gravity of 2.69 and a min. 90% of $Ca(CO)_3$. HTPP fibers with 12 µm diameter and 10 mm length were used. The density, nominal tensile strength, Young's modulus, and elongation at rupture of HTPP fibers were 0.91 g/cm^3, 850 MPa, 6 GPa, and 21%, respectively (Ikai et al., 2006). A polycarboxylate-based high range water reducing admixture (HRWRA) was also used in order to disperse fiber to whole matrix, homogenously. The mix proportions of materials that used in composite preparation were presented in Table 3.

Table 1. Chemical and physical properties of Type I 42.5 R ordinary Portland cement.

Chemical Analysis (Basic Oxides) (% bw*)		Physical Properties	
SiO_2	18.46	Specific Gravity	3.10
Al_2O_3	4.18	Specific Surface Area (m^2/kg)	305
Fe_2O_3	3.17	Retaining on 0.090mm sieve (% bw)	1.5
CaO	64.28	Retaining on 0.045mm sieve (% bw)	23.1
MgO	1.27	Vol. stability (mm)	0.5
Na_2O	0.50	Vicat water (% bw)	28
K_2O	0.84	Retaining on 0.045mm sieve (% bw)	23.1
SO_3	3.14	*bw: by weight of cement	
Cl	0.006		
F. CaO	1.80		

Table 2. Chemical and physical properties of Calcined kaolin.

Chemical Analysis (Basic Oxides) (% bw*)		Physical Properties		Related Standard or Reference
SiO_2	52 ± 0.5	Whiteness (%)	> 93.5	ASTM E 313
Al_2O_3	45 ± 0.5	Particle Size (-2µm) (%)	88 ± 2	Mackkinon et al. (1993)
Fe_2O_3	< 0.35	Residue on 325 mesh (>44 µm) (%)	<0.003	ASTM C 325-81 ASTM C 371-09
TiO_2	< 0.50	Moisture (%)	< 0.5	ASTM C 323-56
CaO	< 0.30	Specific Gravity	2.50	ASTM D 854-14
MgO	< 0.20	*bw: by weight of cement		
K_2O	< 0.05			
Na_2O	< 0.15			

Table 3. Mix proportions of composite (kg/m^3).

Mix Code	Cement	Calcined Kaolin	Standard Sand	Water	HRWRA	HTPP fiber	Total
CK	297	742	132	521	15.2	18	1725

HTPP-ECC mixtures were prepared using a Hobart floor mixer with 40 L capacity. Powder ingredients were premixed without water for 2 min at low speed (56 rpm). Water and HRWRA were then added and mixed for 1 min at low speed and 2 min at moderate speed (104 rpm). HTPP fibers were added to the mixture and mixed for 2 min at moderate speed and for 3 min at high speed (185 rpm), respectively. After fiber addition, matrix was checked by hand if any fiber balling were present in fresh composite after the completion of mixing stage. If any fiber balling occurred, an additional mixing was proceeded to minimize the clumping. Fresh HTPP-ECC mixture was cast into three 25x60x300 mm prismatic molds and moderately vibrated on a vibration table. Specimens were demolded one day after mixing and their densities were measured. Composites were cured in water (20±2 °C) for 28 days and cured in air for another 152 days. After 180 days of composite preparation, mechanical and thermal properties of composites were investigated. Flowchart of testing procedure was presented in Fig. 1.

The air-dry densities of composites were calculated by dividing the air dry weight of each composite to their total volumes after 180 days and ranged between 1602-1690 kg/m^3. After density measurements, thermal conductivity and insulation tests have been performed by using a hotwire and infrared thermal camera based

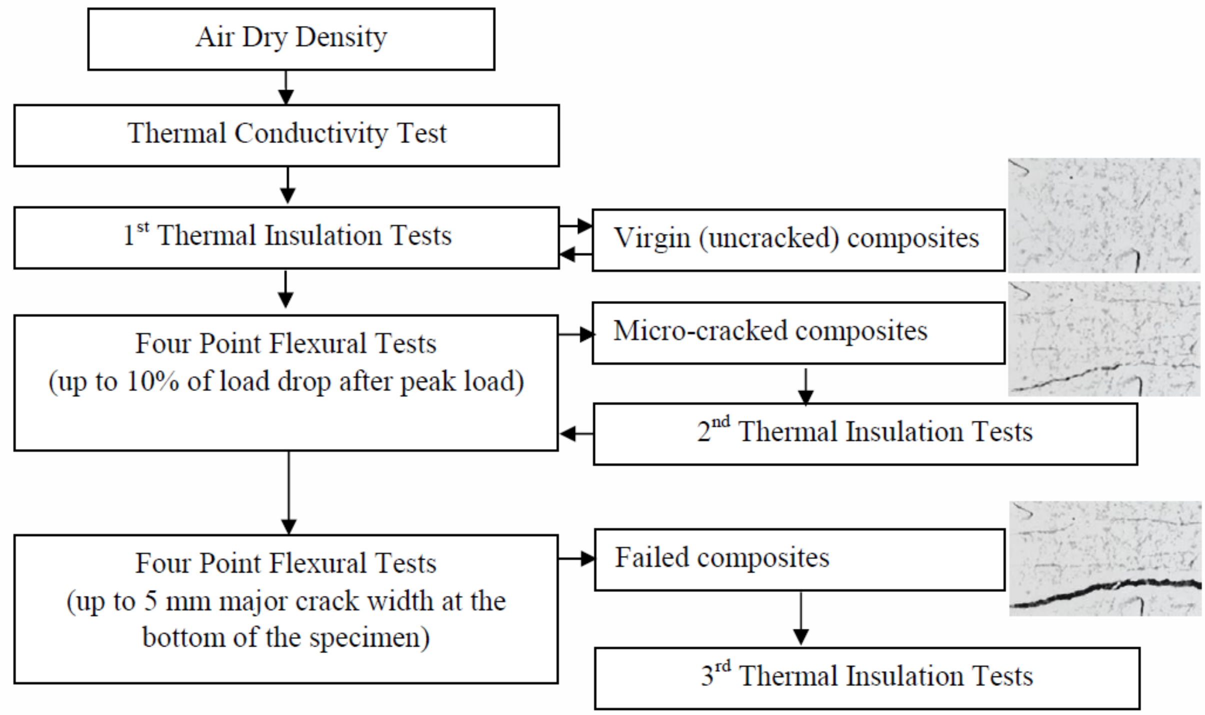


Figure 1. Flowchart diagram of testing procedure.

test setup (Fig. 2 and Fig. 3). Temperature and humidity values ranged between 18-21ºC and 50-55%, respectively. A quick thermal conductivity meter (Showa Denko K. K. – Shoterm QTM-D2) based on hot wire method was used to measure the thermal conductivity of composites (Fig. 2a) (ASTM C 1113-90). The device can measure the thermal conductivity between 0.02 and 10 W/m.K. Conductivity measurements were performed to each composite from the right, middle and left part of the composites at virgin (uncracked) state (Fig. 2b). First, hot wire included device placed on the left side of the specimen and 1st thermal conductivity was measured. Then, the device placed to the middle of the specimen and 2nd thermal conductivity was measured. Finally, the device placed to the right side of the specimen and 3rd thermal conductivity was measured. Their averages were assumed as the thermal conductivity for the specimen. This testing procedure was performed to other two specimens and their thermal conductivity values were obtained. By averaging the thermal conductivities of three specimens the thermal conductivity value of HTPP-ECC was calculated.

Thermal insulation test setup includes an infrared thermometer, a laboratory type-newly designed artificial heat source with digital temperature adjustment and timer (Fig. 3a). The experimental test setup, which designed for thermographic measurements, is completely isolated from the back and side walls. The front side of the device is covered with sodium silicate and quartz mixture. This mixture is a heat resistant material (can withstand 1200oC) that provides heat dissipation of heat treatment devices and provides uniform homogenous heat distribution to all surface areas of the samples placed. In addition, the heat distribution of the front side surface can be controlled over time by the thermocouples located about 5 mm below the front side dough for ensuring the homogeneous distribution of pre-determined temperatures to the samples placed on the device. The experimental setup was arranged regarding the technical specifications of the thermal camera used (Table 4). The field of view and accuracy was taken into account to adjust the setup and a distance of 2 meters from the composites surface was fixed. The artificial heat source, originally designed for homogeneous heat distribution along the surface area, was used to transfer heat on the rear side of the samples (Table 4).

A specimen holder was prepared by using Rockwool board and placed to the front side of the heat source (Fig. 3b). The samples were placed in to the holder and their back surfaces were completely contacted with the heat source (Fig. 3b). Temperature level of the heat source surface was adjusted digitally, kept constant and checked simultaneously by an infrared thermometer from the empty zone on the holder (Fig. 3b). Thermal insulation properties of composites have been investigated at 30ºC, 45ºC and 60ºC degrees for virgin (unloaded), cracked (10% of load drop after peak load) and failed (by loading up to 5 mm crack width at the bottom of the specimen) composites. Specimens initially conditioned at 20ºC and placed to test setup (Fig. 3b). Thermographic images were captured and recorded along 1 hour by 5 min. intervals for each temperature. Every temperature level was adjusted and setup was prepared individually regardless of previous measurements. The samples and heat source were reposed to reach constant ambient temperature prior to measurements. Their thermographic analyses have been examined with a software (FLIR Tools) by taking whole area of the composite into consideration and the ultimate surface temperature (UST) after 1 hour exposure to heat is measured (Fig. 3c). This value is assumed as an indicator of thermal insulation ability of composites where a low UST means improved insulation ability.

Mechanical performances of composites were tested by using a four-point flexural test setup under controlled displacement with a rate of 0.5 mm/min. A linear variable displacement transducer (LVDT) with a gage of 30 mm used to obtain deflection values of specimen at the mid-point. Flexural load and deflection values recorded via using data recorder software. Specimens that plastically deformed up to 10% of flexural load drop have been used as “cracked” specimens at thermal insulation measurements. An additional loading is

(a) (b)

Figure 2. a) Thermal conductivity test setup, b) Measurement method.

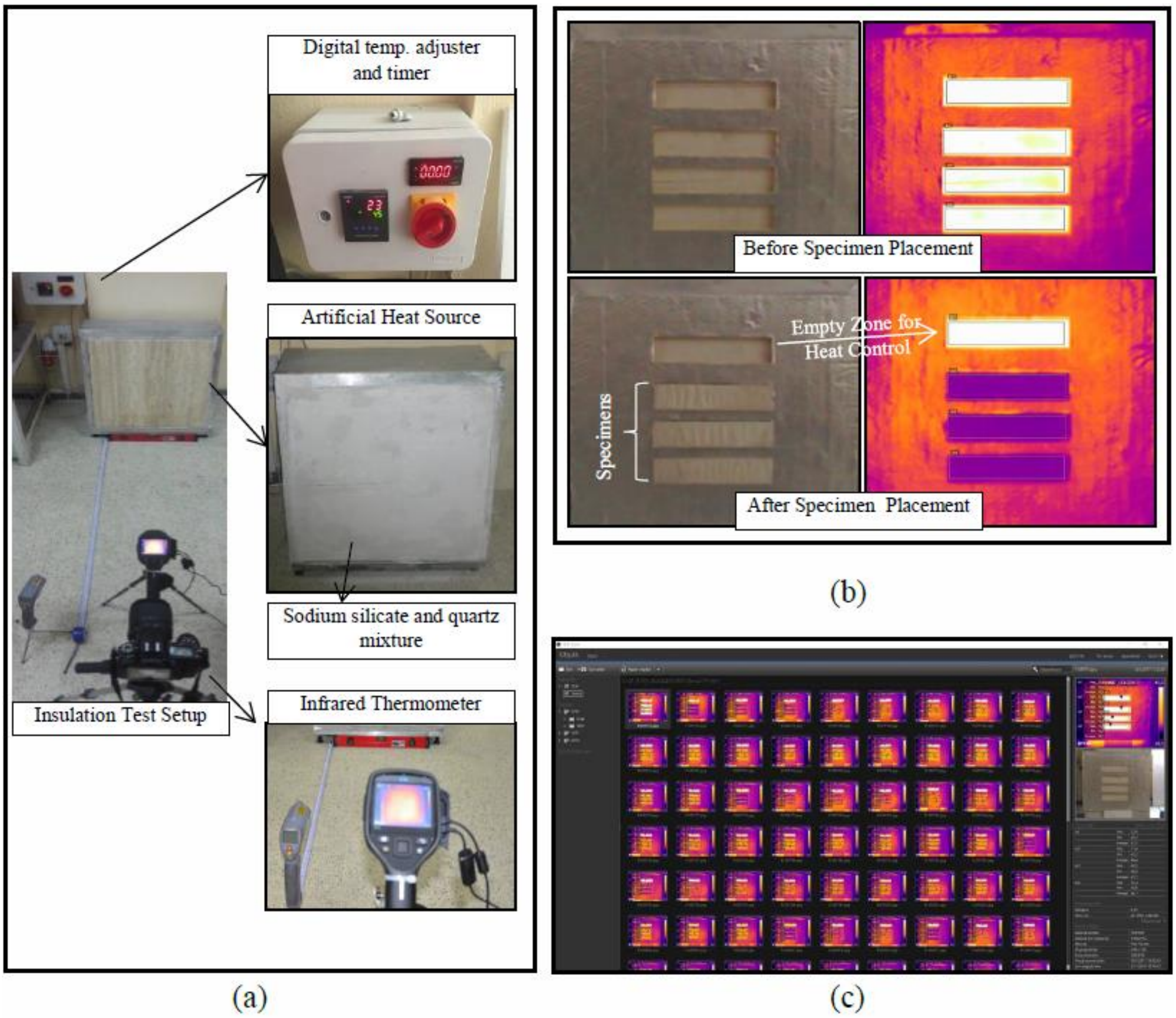


Figure 3. a) Thermal insulation test setup, b) Specimen placement to the test setup and raw images, c) Analysis of raw images by FLIR Tools.

Table 4. Technical specifications of thermal camera and heat source

Thermal Camera IR resolution	240 × 180 pixels
Thermal sensitivity	< 0.05°C @ +30°C
Field of view	25° × 19°
Focal length	18 mm
Detector type	Focal plane array, Uncooled microbolometer
Spectral range	7.5–13 μm
Object temperature range	–20°C to +120°C & 0°C to +650°C
Accuracy	±2°C or ±2% of reading for ambient temperature 10°C to 35°C
Heat Source	
Max. power	5000 W
Dimensions	70x70x30 cm
Adjusted current	5.5 A
Status	Fully insulated excluding the front side

applied and these specimens called as “failed” where major crack width increased to 5 mm (from the bottom). Flexural load-Mid-span deflection curves of composites were drawn by using the recorded data and mechanical parameters were obtained with the help of data obtained from the curves. First cracking strengths and flexural strengths were calculated by inserting the load from the point where the load-deflection relationship became non-linear and maximum flexural loads in Equation 1, respectively.

$$\sigma = \frac{P.L}{b.h^2} \quad (1)$$

where, σ is the first crack or flexural strength, P is the first crack or maximum flexural load, L is the mid-span length (290 mm), b and h are the width and height of the specimen, respectively. The deflection capacity was considered as the abscissa of maximum flexural load. The area under the load-deflection curve up to maximum flexural load was calculated and accepted as "Peak Toughness". Besides, the multiple cracking behavior of composites and crack properties (width and number) were examined by using a digital hand microscope after the removal of applied load.

RESULTS AND DISCUSSION

Thermal Conductivity of Composites

Thermal conductivity test results of HTPP-ECCs were presented in Tab. 5. Conductivity values of specimens were ranged between 0.255-0.307 W/m.K. By considering the conductivity of air is 0.024 W/m.K, the fluctuation of conductivity values in the same specimen but different regions (Fig. 2b - left, middle, right) can be correlated with the presence of air voids due to the natural pore structure of composite. The average thermal conductivity of HTPP-ECC was calculated as 0.274±0.003 W/m.K.

In Fig. 4, the density and conductivity values of prepared composites were compared with the literature data of conductivity obtained from recently published papers for different kinds of ECCs (researchers referred to Fig. 4), ordinary fiber reinforced cementitious composites (FRCC) and concrete, respectively. All ECCs have lower thermal conductivity when compared to ordinary concrete and FRCC. HTPP-ECC prepared in this study showed 86 and 80% less conductivity compared to ordinary concrete and ordinary FRCC. In addition, lower conductivity values than PVA-ECCs which ranging between 28-69%, have been obtained. By considering the Fig. 4, it is clear that HTPP-ECCs (CK and SFR-ECC) appears as heat resistant compared to PVA-ECCs (GL-ECC, TES-ECC, HSL-ECC) with relatively lower conductivity values. The conductivity values of HTPP-ECCs (HTPP-ECC prepared in this study and SFR-ECC) were close to each other, relatively. However, it is remarkable that HTPP-ECC has higher density value (1646±31 kg/m^3) than SFR-ECC (550 kg/m^3, Zhang and Li, 2015). As commonly known, there are strong correlations between the density and the mechanical properties of concrete (Iffat, 2015). A denser concrete generally provide higher mechanical properties owing to less porosity. Due to this reason, HTPP-ECC may be advantageous for meeting the strength requirements when compared to SFR-ECC.

Table 5. Thermal conductivity values of composites

(W/mK)	Left	Middle	Right	Average	Standard Deviation
CK (1)	0.265	0.261	0.267	0.264	0.003
CK (2)	0.302	0.298	0.307	0.302	0.005
CK (3)	0.255	0.256	0.255	0.255	0.001
HTPP-ECC*	0.274				0.003

*The mean conductivity value of HTPP-ECC used in comparison in Figure 4.

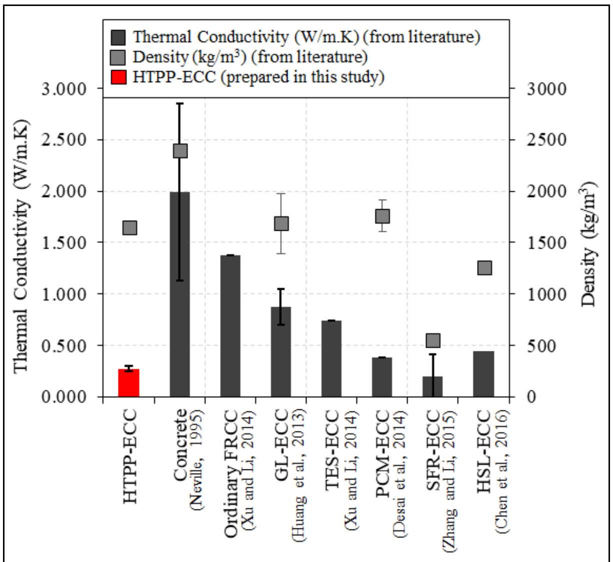


Figure 4. Comparison of Thermal conductivity values of HTPP-ECC with various composites (unloaded, "virgin" state) (GL-ECC: Green lightweight engineered cementitious composites, TES-ECC: thermal energy storage engineered cementitious composites, PCM-ECC: Phase change material engineered cementitious composite, SFR-ECC: Spray applied fire resistive engineered cementitious composites, HSL-ECC: High strength lightweight engineered cementitious composites).

Flexural Test Results of Composites

Flexural load-Mid-span deflection graphs of composites have been presented in Fig. 5. Mechanical properties of HTPP-ECCs were also given in Table 6.

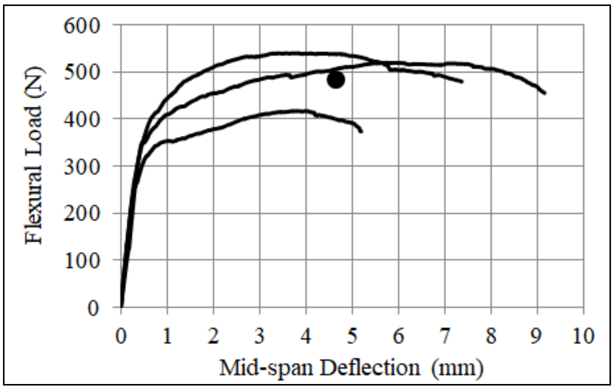


Figure 5. Flexural load-Mid-span deflection curves of composites (black point represents the averages of flexural loads and their corresponding deflection values).

All HTPP-ECCs produced in the study showed deflection hardening behavior with multiple micro-cracks (Fig. 5a). Flexural strength and deflection capacity of HTPP-ECCs ranged between 3.22-4.18 MPa and 3.82-5.75 mm, respectively. Their average crack number and width values were measured as 18 and 30 µm, respectively.

Table 6. Mechanical performances of composites

Specimen	First Crack Strength (MPa)	Flexural Strength (MPa)	Deflection Capacity (mm)	Peak Toughness (N.mm)	Crack Number	Crack Width (μm)
CK (1)	2.71	4.02	5.75	2577.66	24	43
CK (2)	1.97	3.22	4.00	1441.72	15	18
CK (3)	2.11	4.18	3.82	1764.34	14	29
Average	2.26	3.81	4.52	1927.91	18	30
Std. Dev.	0.28	0.36	0.75	413.92	3.90	8.86

Thermal Insulation Test Results of Composites

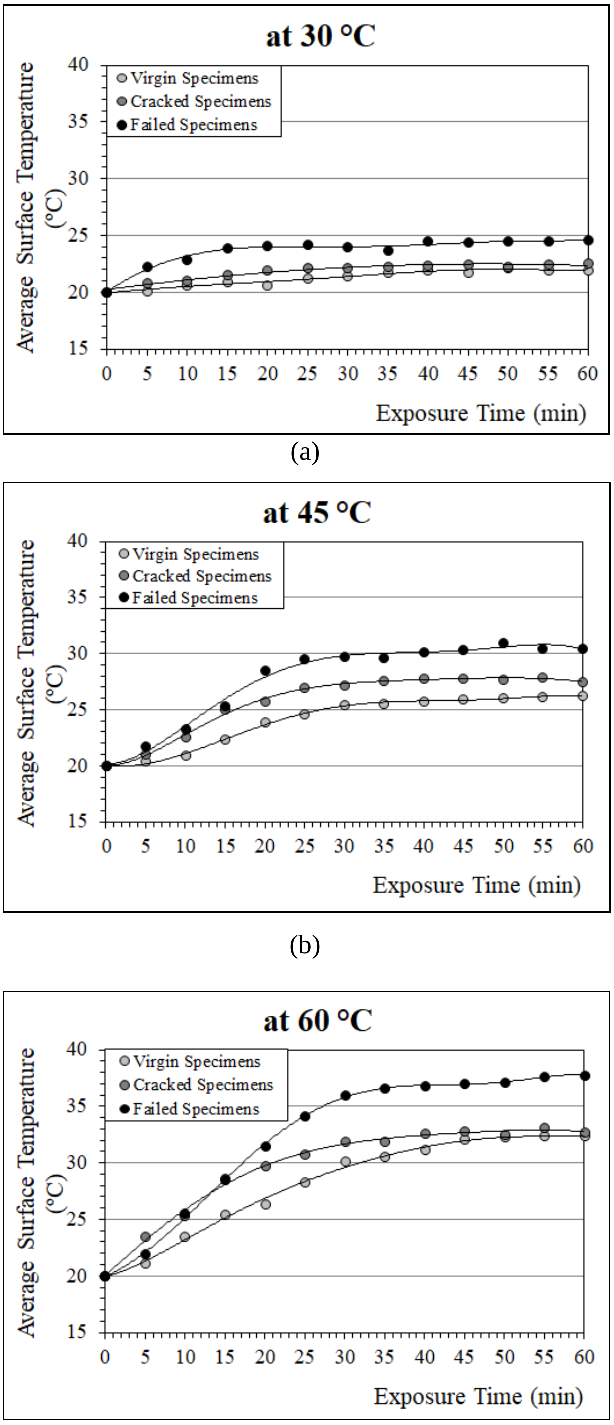
Thermal insulation test results of virgin, cracked and failed state HTPP-ECCs at 30, 45 and 60°C were presented in Fig. 6. The aim of testing at different temperatures was to compare their performance at different service conditions.

At 30°C, ultimate surface temperatures (UST) of composites were ranged between 22.0-24.5°C depending on the state of composites. UST of virgin composites were measured as 22.0°C (Fig. 6a). After flexural tests, cracked composites were re-heated and their UST value slightly increased to 22.4°C. However, after the failure of composites (enlargement of the major crack up to 5 mm) the ultimate surface temperature of composites increased by 21% and reached to 24.5 °C.

At 45°C, UST of composites increased due to increasing temperature and ranged between 26.1-30.6°C (Fig. 6b). Virgin composites reached to a UST of 26.1°C. At the cracked state, UST increased by 6% and reached to 27.7°C. After the failure of composites, UST value measured as 30.6°C with a 17% increment.

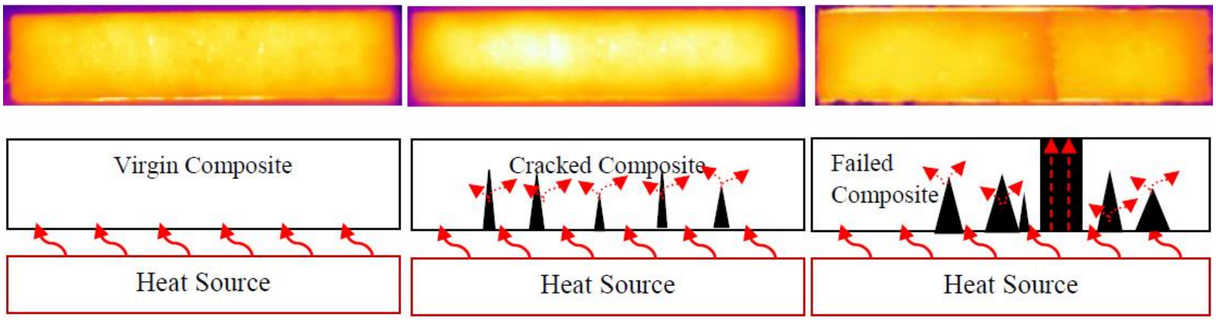
At the highest exposure temperature (60°C) (Fig. 6c), UST of composites ranged between 32.3-37.5°C. UST of virgin composites were found as 32.3°C. Even at the cracked state, the UST of composites increased only slightly to 32.7°C. UST of failed composites showed the highest value and measured as 37.5°C.

It is obvious that the micro-cracked composites exhibited similar thermal resistance results with the virgin HTPP-ECCs when compared to failed ones. This behavior may be attributed to the steady state multiple cracking behavior of composites and presence of tight micro size cracks. Mechanisms supporting this hypothesis are schematically presented in Fig. 7. Virgin composites may have acted as a blockage and isolated the environments (Fig. 7a). With any breakage in the insulation material, heat leakage may occur and insulation property may negatively be affected. Therefore, the heat leaking from the failed crack section of composite and causing the loss of thermal insulation efficiency in Fig 7c may be explained as such. It must be noted that such a wide crack width cannot be observed in HTPP-ECC under plastically deformed specimens at practical loading conditions. In the case of micro-cracked ECC composite, heat leakage can be blocked



(c)

Figure 6. Average surface temperature values obtained from the thermal insulation test results at a) 30 °C, b) 45 °C, c) 60 °C.



(a) (b) (c)

Figure 7. Schematical heat insulation and leakage mechanisms of composites a) Virgin state, b) Cracked state, c) Failed state.

owing to small micro sized crack widths and temperature lost can easily be prevented even at highly plastically deformed conditions (Fig. 7b). This property of ECC can also be accepted as an eco-efficient advantage for increasing the service life and reducing the repair cost with preserving thermal insulation performance of building.

CONCLUSION

In this paper, long-term thermal conductivity and thermal insulation properties of special type of ECC named as HTPP-ECC have been investigated at unloaded (virgin) and plastically deformed (micro-cracked and failed major crack) conditions.

Results showed that, HTPP-ECC have better performance in terms lower of thermal conductivity (0.274 W/m.K) when compared to PVA-ECCs (0.380-0.875 W/m.K) and other types of cement-based materials in the existing literature (0.863-1.990 W/m.K). Besides, HTPP-ECC exhibited an effective thermal insulation efficiency even in micro-cracked state when compared to failed state composites. HTPP-ECC can provide an efficient insulation property to the buildings even after even plastically deforming (in damaged state) by preserving its insulation property due to heat being unable to penetrate through micro-cracks (rather than large cracks). Therefore, HTPP-ECC can be accepted as an eco-efficient material, which has advantage for reducing the energy release, repair cost and increasing the insulation service life of building.

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