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Thermal Transmission Properties of Sustainable Concrete with Supplementary Cementitious Materials

Ahmad Khartabil[1,a] and Samer Al Martini[2,b]

[1]Transgulf Ready Mix Concrete Company, Dubai, UAE

[2]Correspornding Author, Abu Dhabi University, Abu Dhabi, UAE

[a]ahmad.khartabil@tgrmcc.com, [b]samer.almartini@adu.ac.ae

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Abstract. Understanding the thermal properties of a construction material is necessarily to evaluate its heat transfer resistance that has a major contribution to the energy-efficiency required to achieve sustainable structure. Thermal properties are evaluated through three main parameters namely: thermal conductivity, thermal resistivity and thermal transmittance. The aforementioned parameters are commonly referred as K-value, R-value, and U-value respectively. Recent regulations by Dubai municipality enforced to use sustainable concrete in construction. This is by replacing cement with supplementary cementitious materials (SCMs), such as grand granulated blast furnace slag (GGBS) and fly ash. The use of grand granulated blast furnace slag (GGBS) at relatively high percentage replacement became a typical practice in ready-mixed concrete industry in Dubai. As such, it is essential to characterize the thermal properties of this sustainable concrete. The current paper investigates the thermal properties of sustainable concrete mixtures incorporating supplementary cementitious materials, air entrainment additives, polypropylene and hybrid synthetic fiber. K-value, R-value and U-value are evaluated in accordance with ASTM C518. Additionally, hardened density of all investigated mixtures are measured. The results show that the foamed concrete has better heat transfer resistance than that for the non-air entrained mixture.

Introduction

The main typical properties of concrete are accounted for during design and construction are mechanical properties and durability performance. This is to ensure that the projected service life of a structure will be attained [1]. When used in non-load bearing elements, concrete is mainly validated for fire rating, adhesion’s pull-off strength, and thermal transmission. Recently, sustainability become a major concern, and the thermal properties of concrete used in load bearing structural elements have also to be evaluated. For instance, thermal transmission property is one of the most important properties that affect the construction stages including design and planning.

Concrete could be part of either the exterior envelop of structures or the interior face of the envelop. Thus, it would be the main thermal insulation barrier of a structure.Uunderstanding and improving the thermal properties of concrete can contribute to the development of energy-efficient thermal insultation system solely or along with other involved materials in the system [2]. This can lead ultimately to economically optimized system.

The need for energy-efficient system that has great capabilities to insultate structure has been emerging as an environmental friendly action against the features of global warming, and especially in areas affected by urban heat islands (UHI) phenomenon. Such areas which are mostly the busy and business hub cities, where population is higher compared to the suburban areas. The temperature of such urban areas can reach up to 12 ºC higher at night than that for the surrounding towns [3]. Concrete plays significant part in that difference, as it is not generally an excellent thermal insulator and it absorbs heat [4]. Ultimately, having a low thermal conductivity concrete is beneficial for reducing temperature gradients in strcutures [5].

Foam concrete is one of the lowest thermal conductivity mixtures among other normal concrete mixtures. The amount and size of the homogenous pores in foam concrete generated by the foaming agent - causing its low density - reduces the thermal conductivity of the concrete. Jhatial, et al., [6] studied improving the foam concrete thermal properties at three different densities by incorporating 0.80% of polypropylene fiber. It was found by Jhatial, et al., [6] that polypropylene fiber reduces thermal conductivity of 1400 kg/m^3 and 1600 kg/m^3 foam concrete slightly by 1.4% and 3.0% respectively. Jhatial, et al., [6] also reported a 2.4% increase in thermal conductivity, when the foam concrete density increased to 1800 kg/m^3. Mydin, et al., [7] investigated the effect of fly ash on thermal resistivity of foam concrete. Their study reported that incorporating flyash could reduce the pore size and amount resulting in uniform distribution of voids. They also documented that the low hydration helped in the slight reduction of the thermal conductivity. This reduction was as low as 0.46% when flyash replaced the Portland cement by 15%. Yet, thermal conductivity increased by 3.4% when flyash replaced Portland cement by 30%.

Another approach to reduce the thermal conductivity of concrete mixture is by replacing coarse aggregates or sand partially with aggregates with better thermal resistivity. This approach was adopted by [7, 8, 3]. Mydin, et al., [7] replaced sand with 30% raw lime filler. The reported a decrease in thermal conductivity from 0.5851 W/mk to 0.5297 W/mk for the foam concrete mixture investigated. Mydin, et al., [7] attributed it to the increase in percentage of porosity as was observed by the electron microscopic scanning. Nevertheless, Wang et al., [8] used ceramsite light weight aggregate that has high porosity of 74% and 40% as coarse aggregate in foam concrete mixture. It was confirmed by Wang et al., [8] that the higher the dry density and compressive strength of the mixture, the higher conductivity. Also, the lowest achieved thermal conductivity was 0.137 W/m.k for the mixture of 498 kg/m^3 dry density. Expanded slate light weigth aggregate was the aggregate considered by Cavalline, et al., [3] to improve thermal properties' of concrete mixture. Cavalline, et al., [3] reported that the effects of total voids content of concrete mixtures, including air content of fresh concrete, on thermal resistivity of concrete is much more than that for mixture's design proportions such as total cementitious content and water to cement ratio. When light weigth aggregates replaced the sand, thermal conductivity of concrete dropped by 23% compared to the control normal weight concrete mixture. This percentage reduction increased to 60% for light weight concrete mixture. It was concluded that the increase light weigth aggregate content in the mixture reduce the thermal conductivity.

This paper studies the thermal properties of different sustainable concrete mixtures. The investigated mixture incorporated relatively high supplementary cementitious materials. The mixtures design took into consideration the green concrete regulations -for the structural control mixture - enforced by Dubai municipality. The use of GGBS at high percentages becomes very common to fulfil both durability and sustainability approaches as well as projects' service life parameters. Other additives such as fibers and air entrainment are also used to prepare sustainable mixtures with high thermal resistivity. Effects of concrete density and incorporated constituents on thermal properties are investigated. ASTM C518 was considered for evaluating thermal conductivity (K-value), thermal resistivity (R-value) and thermal transmittance (U-value) for the investigated mixtures.

Experimental Program

A total of five concrete and mortar mixtures were designed, prepared, and evaluated for thermal properties. The first mixture was a typical sustainable concrete mixture (TC) with a 28 day target mean cube compressive strength of 50 MPa. This mixture had a 60% GGBS as replacement to the portland cement by weight and total cementitious content of 430 kg/m^3 with water-to-cementitious materials ratio of 0.35. The second mixture (FoC) is a common standard used foam concrete mixture in UAE concrete industry. This mixture is usually recommended to by the ready-mixed concrete company for low thermal conductivity concrete. The FoC consists of ordinary Portland cement incorporating SCMs with total cementitious materials content of 420 kg/m^3 and water-to-cement ratio of around 0.45.

Further, three concrete mortar mixtures were designed to have good thermal resistivity. These three mortar mixtures contained 50% class F flyash conforming to ASTM C618 and either air-entrainment or foam agent additive at various dosages for different concrete densities. The water-to cementitious materials for these mixtures was 0.45. Additionally, 6 kg/m^3 of 12 mm long and 18 microns in diameter monofilament polypropylene fiber was added to two of these mixtures. The third one was considered a hybrid mixture in terms of fiber incorporated. The two types of fibers incorporated were 12mm polypropylene fiber (2 kg/m^3) and 2.3 kg/m^3 of 54 mm macro-synthetic chemical bonded fiber known as MAC 2200CB. Flyash and polypropylene fiber were considered in this investigation, because it was reported elsewhere [7] that they can help in reducing concrete's thermal conductivity.

The superplasticizer used for all of the aforementioned concrete mixtures was a low range polycarboxylate base admixture conforming to ASTM C494 as type G. The aggregates used for the mixtures in this investigation were crushed limestone obtained from Ras Al Khaima, United Arab Emirates with nominal maximum size of 20 mm for typical concrete mixture and 5 mm for the four thermal resistivity mixtures. All aggregates conforms to BS 882 limits.

The four thermal resistivity mixtures (including the typical foam mixture) were compared to each other and to the control typical sustainable concrete for thermal conductivity, resistivity and transmittance values. ASTM C518-15 standard which is titled as "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus" is followed to measure the aforementioned values for the mixtures. Therefore, 40 mm thick plates with dimensions of 300 mm for length and width from each of the mixtures were cast and tested for the thermal values after moisture stabilization at the age of 7 days.

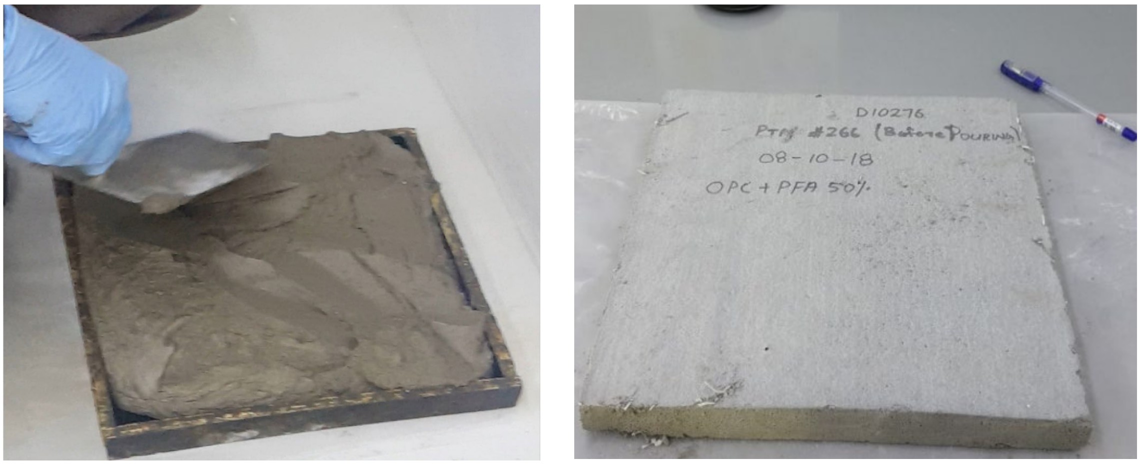

Figure 1. Thermal test specimen preparation: (a) Casting 40 X 300 X 300 mm plate for an investigated mixtures for thermal properties testing in accordance with ASTM C518-15, (b) Hardened mixture plate specimen for thermal testing.

Table 1. Details of Investigated mixtures.

Mixture	Symbol	GGBS (%)	Flyash (%)	Fiber (kg/m^3)		Fresh Density (kg/m^3)	Dry Density (kg/m^3)
				Polypropylene	**Macro Synthetic**		
C50 Typical Concrete	TC	60%	-	-	-	2,450	2,350
Light Weight Foam Concrete	FoC	-	-	-	-	690	533
Air Entrained Concrete + FA and PP	AEFaP	-	50%	6.0	-	1,560	1460
Foam Concrete + FA and PP	FoCFaP	-	50%	6.0	-	990	940
Air Entrained Concrete + FA, PP and Synthetic	AEFaPS	-	50%	2.0	2.3	1,450	1,410

The investigated mixtures can be divided into three categories: typical sustainable concrete mixture, air-entrained mixtures and foam generated mixtures. Density of the mixtures was measured. Table 1 shows various details of the five examined mixtures.

Results and Discussion

Thermal Properties of Conventional Sustainable Structural and Foam Concrete. Figure 2 presents results of the thermal conductivity (K) and density for the two mixtures: a typical sustainable concrete mixture (TC) and a typical foam concrete mixture (FoC) used in the ready-mixed concrete and construction industry. The TC mixture has 60% GGBS with 50 MPa and the light weight foam concrete (FoC) has a target dry density of 600±100 kg/m^3. It is widely known that foam concrete is a mixture that usually used in a non-structural elements that require low conductivity concrete. This is due to its low density that can reach as low as 500 kg/m^3. Thus, the dry density of conventional concrete (TC) is 4.5 times higher than that for the foam concrete mixture (FoC).

As shown in the figure, TC mixture has dry density of 2450 kg/m^3 and FoC has a dry density of 533 kg/m^3. It can be observed that foam concrete mixture (FoC) has a thermal conductivity value (K) of 0.1567 W/m and TC mixture has K value of 0. 0.4225 W/m W/m. Thus, the FoC mixture has K value almost 3 times less compared to the conventional concrete (TC). This can be related to the fact that the lower the density of material the lower its thermal conductivity, and accordingly the higher the resistivity.

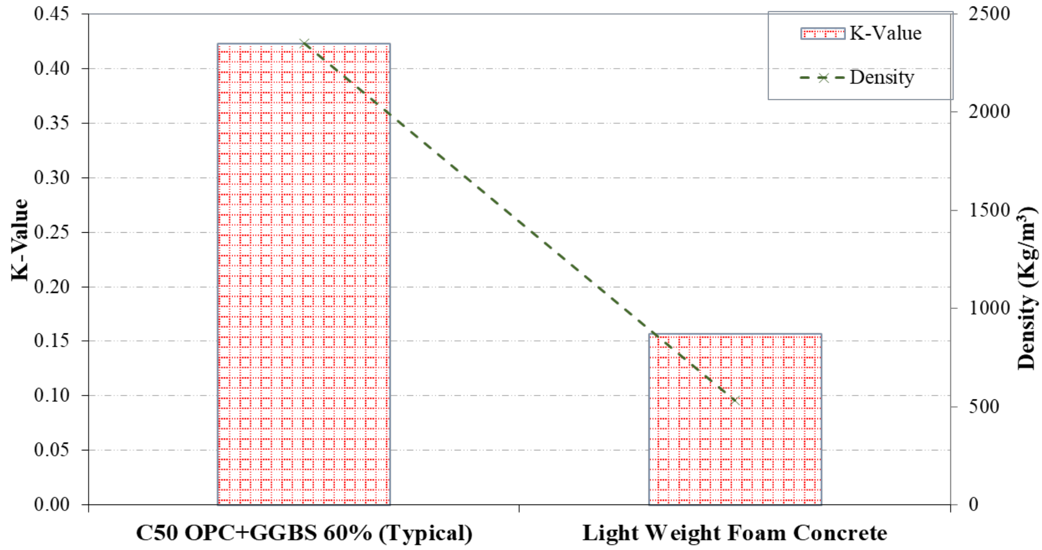

Figure 2. Thermal conductivity in W/m.K of conventional concrete (TC) and light weight foam concrete (FoC).

Thermal Properties of Sustainable Foam Concrete Mixtures. Based on the discussed findings, a sustainable improved light weight foam concrete mixture referred as FoCFaP is investigated. The Portland cement was replaced by 50% flyash and polypropylene fiber was introduced to the concrete mixture at a dosage of 6 kg/m^3. As shown in Table 1, the new foam concrete mixture that is presented herein showed a higher density than the earlier discussed foam concrete mixture. However, it is still within the category of light weight foam concrete that has a dry density below 1000 kg/m^3.

Figure 3 shows thermal properties of the typical sustainable structural mixture (TC) and the two foam concrete mixtures (FoC) and FoCFaP. Thermal properties are K-value, R-value and U-Value. It can be noticed that although a thermal conductivity reducing additives were added to the foam concrete mixture (FoCFaP), yet the mixture achieved higher thermal conductivity and subsequently lower resistivity compared to the standard control foam mixture (FoC). Both the K-value and U-value of FoCFaP mixture increased by 34%, while the value representing the resistivity (R-value) reduced by 29% for the set thickness of the plate.

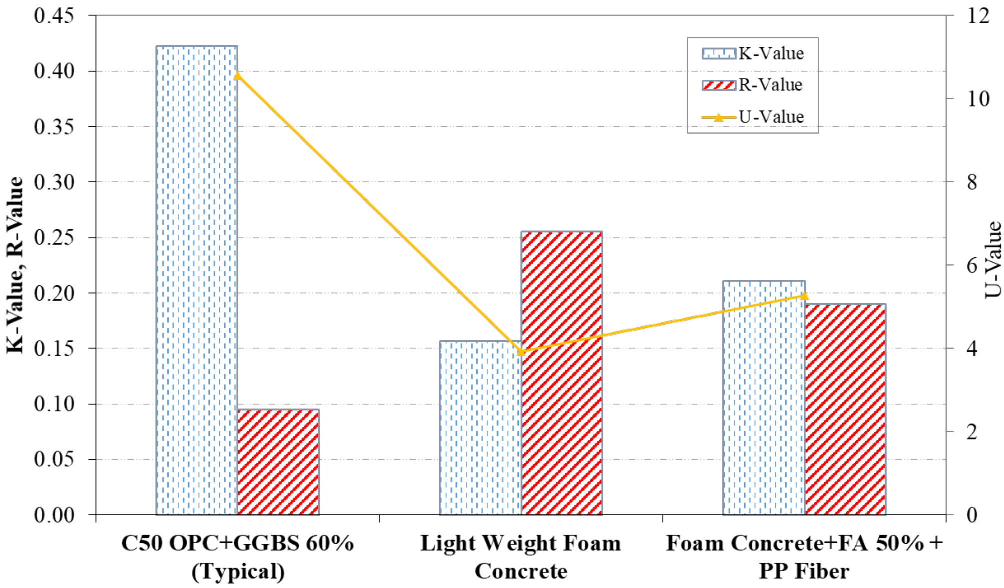

Figure 3. Thermal properties (K-value in W/m.K, R-value in K.m^2/W , and U-value in W/m^2K) of foam concrete mixtures in comparison with typical structural conventional concrete.

The aforementioned finding doesn't meet the expected thermal performance of mixture (FoCFaP) that incorporated flyash and polypropylene fiber. This unexpected result may be attributed to the higher density (76%) of FoCFaP mixture compared to the standard foam concrete mixture (FoC) Figure 4 shows that there is strong linear relationship between the density and thermal conductivity for the three mixtures with $R^2 = 0.9995$. This confirm the earlier explanation of the unexpected results of FoCFaP.

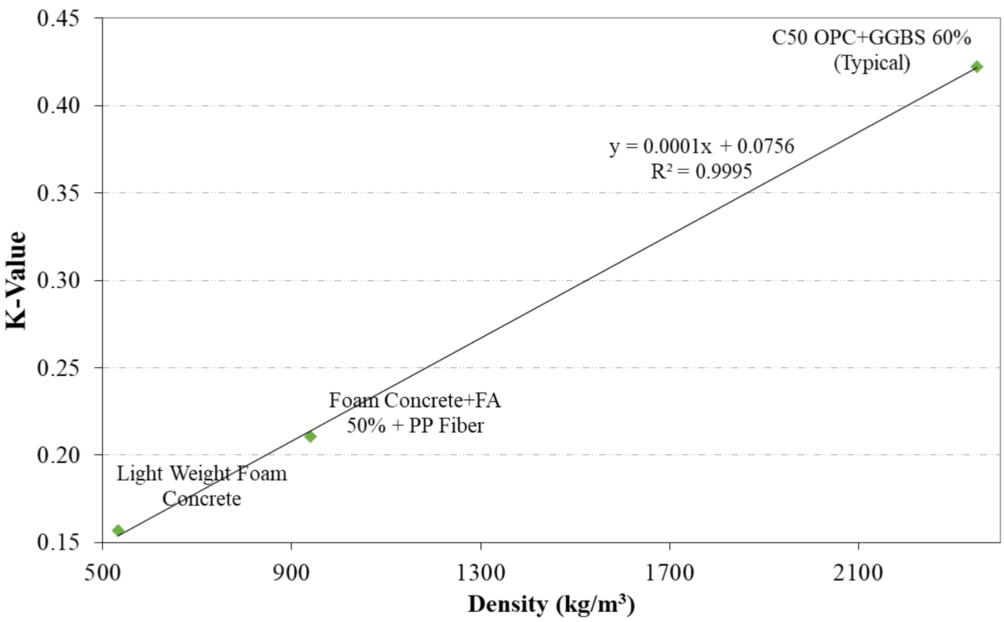

Figure 4. Linear regression between thermal conductivity in W/m.k and dry density of foam concrete mixtures (FoC, FoCFaP) and the typical structural mix (TC).

Thermal Properties of Sustainable Air Entrained Mixtures. The thermal properties of the mixtures with air entrainment additive (AEFaP and AEFaPS) were investigated in this section. The effects of incorporating flyash and polypropylene fiber were also investigated. The used air entrainment additive herein is based on vinsol neutralised resin admixture that reacts and generates uniformly distributed micro-air bubbles in the mixture. This used air entrainment agent conforms to the requirements of ASTM C260. As illustrated in Table 1, both mixtures contain 50% flyash however, AEFaPS has a reduced dosage of polypropylene fiber yet referred as hybrid fiber mixture due to the incorporation of the synthetic fiber.

Figure 5 shows that AEFaP mixture recorded an almost identical thermal conductivity value to the TC mixture despite the 38% difference decrease from the dry density of TC to AEFaP mixture. The reported k-values were 0.4225 W/m.k and 0.4330 W/m.k for AEFaP and TC, respectively. Furthermore, the presence of flyash at high percentage and polypropylene fiber at relatively high dosage didn't assist in reducing the thermal conductivity of the mixture, and subsequently didn't improve its thermal resistivity. However, it may be caused an adverse effect that offset the low dry density effect of AEFaP mixture in reducing the thermal conductivity.

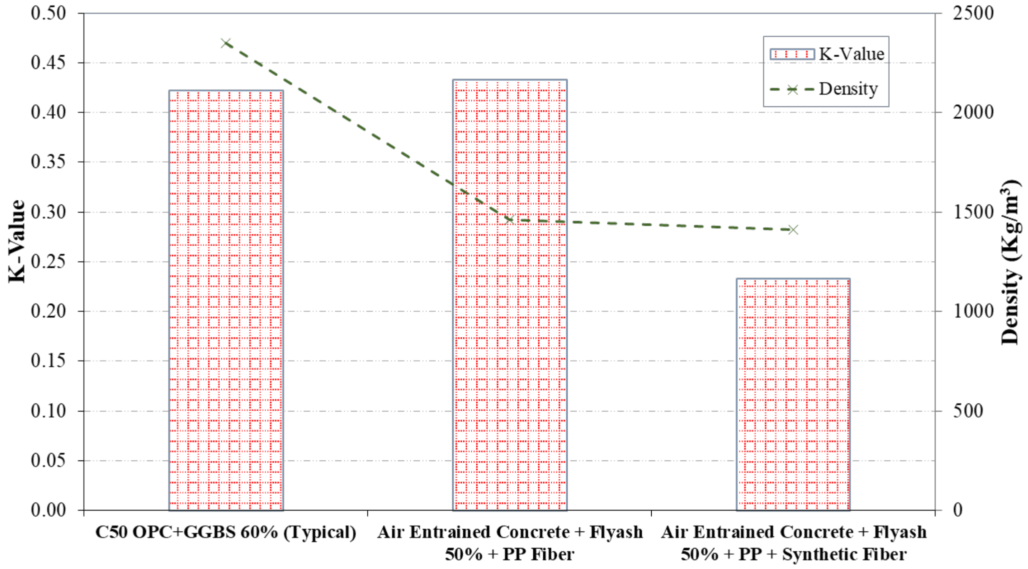

Figure 5. Thermal conductivity in W/m.K and dry density of air-entrained concrete mixtures in comparison with typical structural conventional concrete.

On the other hand, AEFaP and AEFaPS have similar dry density that falls within the same category for light weight concrete mixture as shown in Table 1. Despite the similar density for the two air-entrained concrete mixtures, AEFaPS mixture expressed an improved thermal resistivity property by around 86% and a drop in thermal conductivity of around 46% compared to AEFaP. This is since the reported R-value for AEFaP and AEFaPS are 0.0924 K.m^2/W and 0.17167 K.m^2/W, respectively and the reported K-value for AEFaP and AEFaPS are 0.4330 W/m.K and 0.2330 W/m.K, respectively (Figs. 5 and 6). This can be related to the thermal combined effect of the additives of mixture AEFaPS, specifically the fibers incorporated.

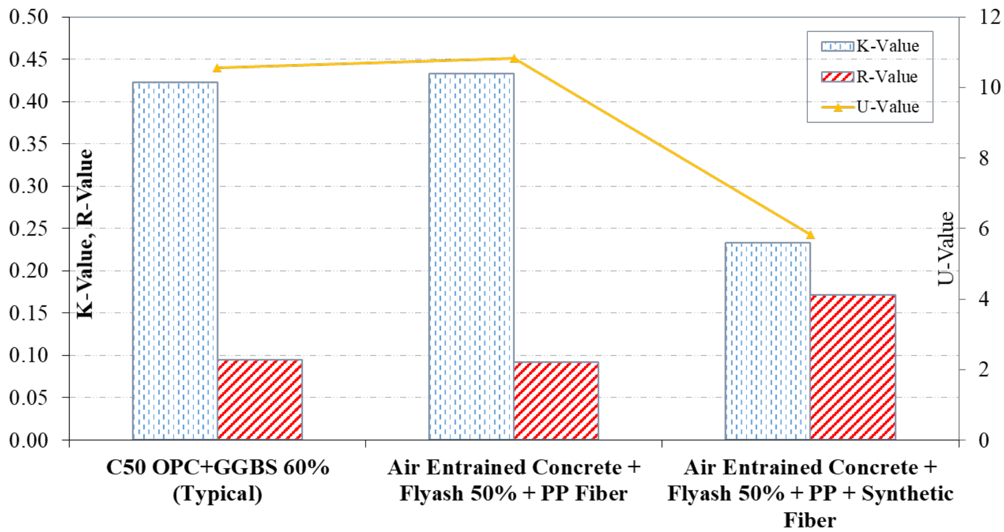

Figure 6. Thermal properties (K-value in W/m.K, R-value in K.m2/W , and U-value in W/m2K) of air-entrained concrete mixtures in comparison with typical structural conventional concrete.

The investigated set of mixtures did not demonstrate a strong linear relationship between the dry density and thermal conductivity of the mixtures, and subsequently a very low R^2= 0.25 that (Fig. 7).

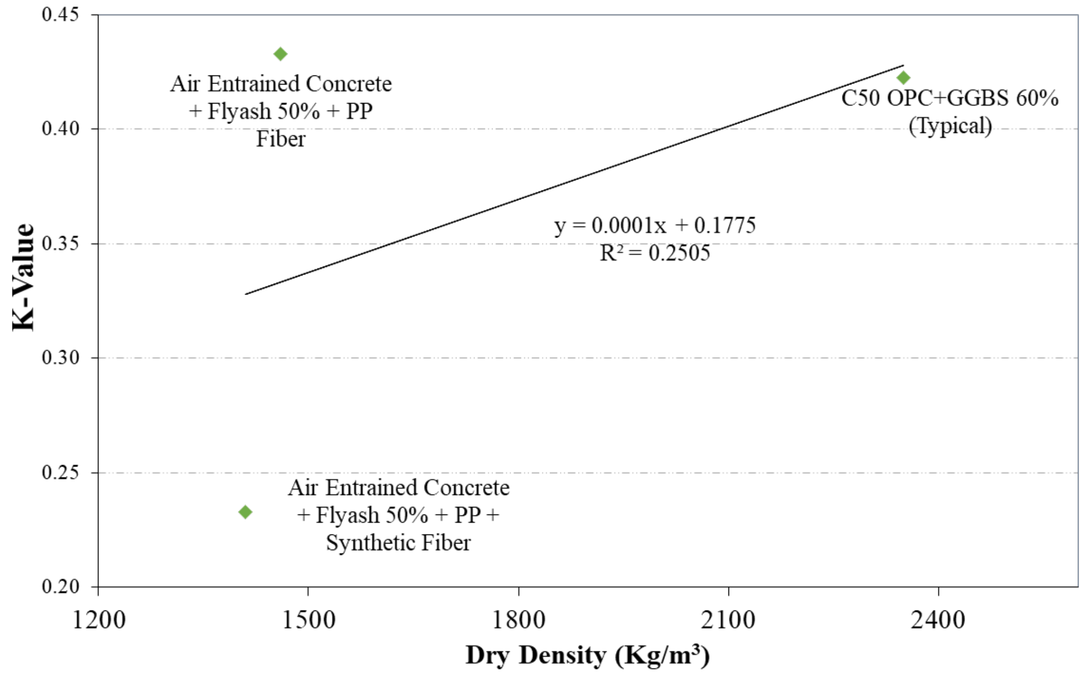

Figure 7. Relationship between thermal conductivity (W/m.k) and dry density (Kg/m^3) of air-entrained concrete mixtures (AEFaP, AEFaPS) and the typical structural mix (TC)

Conclusions

As concrete is considered main construction material, developing concrete mixtures with improved thermal parameters (i.e., low thermal conductivity and high thermal resistivity) can result in energy-efficient structures. The following can be concluded from the study:

- The results show that the investigated typical foam concrete mixture is 3 times less thermal conductivity than the conventional concrete. This is related to wide difference between both mixtures' dry density as the measured density of typical foam concrete is 23% of the conventional structural concrete.
- The foam concrete mixture with 50% flyash and polypropylene fiber had higher K-value and U-value than the typical one. This can be related to its higher dry density (around 76%) than the typical one.
- The relationship between thermal conductivity and dry density of the foam mixtures is linear. It is observed that the higher the dry density, the higher the thermal conductivity of concrete.
- The air-entrained mixtures incorporating 50% flyash and polypropylene fiber showed similar thermal conductivity to the conventional mixture, despite its lighter dry density (900 kg/m3) to the conventional mixture.
- The mixture with hybrid combination of polypropylene and synthetic fiber had 46% less thermal conductivity than the conventional one.
- The air entrained concrete mixtures did not show strong linear relationship between concrete dry density and its thermal conductivity.
- Flyash and polypropelene fiber showed marginal effect on concrete thermal property of concrete mixture.
- It is recommended that further study should be carried out to investigate the effects of polypropylene fiber on thermal properties of air-entrained concrete.

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