Review on factors influencing thermal conductivity of concrete incorporating various type of waste materials

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Abstract. Concrete is well-known as a construction material which is widely used in building and infrastructure around the world. However, its widespread use has affected the reduction of natural resources. Hence, many approached have been made by researchers to study the incorporation of waste materials in concrete as a substitution for natural resources besides reducing waste disposal problems. Concrete is basically verified by determining its properties; strengths, permeability, shrinkage, durability, thermal properties etc. In various thermal properties of concrete, thermal conductivity (TC) has received a large amount of attention because it is depend upon the composition of concrete. Thermal conductivity is important in building insulation to measure the ability of a material to transfer heat. The aim of this paper is to discuss the methods and influence factors of TC of concrete containing various type of waste materials.

1. Introduction
In consideration of the construction cost, concrete characteristic and its availability in Malaysia, it shows that Malaysia is a country which is still depending on the concrete materials in their building constructions. However, despite of its demand, this will lead to the increasing use of natural resources such as sand and cement which has also been linked to global warming. It is essential to find a solution in order to enhance the performance of concrete in term of its properties and sustainability at the same time controls the consumption of natural resources and environmental attacks.

Till now we are facing a very common issue from waste materials that is the existing of waste disposal problem which has become one of the major environmental, economical, and social issues [1,2]. Due to this issue, some strategies have been proposed in recent years to meet environmental challenges within the building industry that is one of them is increasing the use of waste materials, especially those that are by-products of industrial processes [3].

Normally, study of concrete is more focus on the physical and mechanical properties of the materials rather than thermal properties whereas concrete is a building material that possess high thermal properties [4]. Thermal properties are mainly determined by TC, specific heat, thermal diffusivity, thermal expansion, and mass loss [5]. As the global energy issues become one of the main concern, the TC factors should be taken into the considerations. The need for energy efficient design and construction for building structure has become increasingly imperative, especially with the rising energy costs and increasing awareness on the effects of global warming [6].

It is important to have knowledge on TC of concrete and other construction materials. Since TC is a study to determine the heat transfer in a material, this aspect is crucial in construction industries [5].
Furthermore, TC of the materials used is one of the major factors affecting the heat transfer in buildings. Heats from the environment which transferred into the buildings will cause discomfort to the user [7]. Heat can be transferred in three different modes including conduction, convection and radiation [8]. TC is expressed in units of Watts per metre per degree of temperature difference (W/mK). According to Eurocode 2, the TC of a standard density concrete, at a temperature of 20°C, has a value between 1.33 W/mK and 1.95 W/m.K [9]. Since materials with high value of TC conduct heat faster than materials with low TC, they are normally used as heat sinks while low TC materials are used in thermal insulation.

2. Comprehensive review on TC of concrete incorporating various waste materials

2.1. Review on materials and method

2.1.1. Materials. The basic constituents of concrete are binder (cementitious materials), coarse and fine aggregates (or inactive mineral filler) and water [4]. Natural aggregates such as sand and gravel are commonly used in concrete. Recently, waste materials also known as by-product aggregate is widely used in concrete production that is blast-furnace slags, fly ash, plastic, etc. It is usually used as lightweight aggregate by replacing fine aggregate, coarse aggregate or as addition mixture.

Many researchers [9,10-26] have investigated the TC of concrete utilizing waste materials: recycled aggregate, fly ash, rubber, expanded perlite, oil palm shell, palm oil fuel ash, recycled glass, plastic waste, sawmill waste, polyamide etc. Main objective of this paper is to overview the effect of utilizing these waste materials on TC of concrete which later will be discussed in depth.

2.1.2. Measurement method. There are a number of practices to determine TC. To analyse thermal behaviour of materials, the methods must be clearly known and defined [18]. Generally, there are two main methods to measure TC of materials that is steady state method and transient method which also called as non-steady method. [15]. This methods is suitable for limited range of materials, depending on the temperature and thermal properties.

The steady state method performs a measurement when a tested material is in complete equilibrium while the non-steady state or transient method performs a measurement during the process of heating up [27]. The steady method makes the process of signals analysis very easy (steady state implies constant signals) however it takes a long time to reach the required equilibrium. As for non-steady method, the parameter can be measured relatively quickly.

Nowadays, many experimental methods were designed to measure TC according to methods as mentioned above. The experimental methods of steady state are guarded hot plate, unguarded hot plate method, heat flow meter and cylindrical probe method to name a few, while for non-steady method are hot wire method, laser flash method, step method, transient line, transient strip and transient plane method [6,9-11,13-18,20-27]. These devices have different technique, specimen size, testing time, capability and methodologies of measurement.

Guarded hot plate and hot-wire method have commonly practiced in engineering field as they are related on TC measurement of engineering applications. However, the guarded hot plate apparatus has been selected as the most accurate method for determining the TC as it was adopted by American Society for testing and Materials (ASTM) as a Standard Method [8,27].

Hot-wire method is based on dimensional radial heat flow and, TC is measured by tracking the thermal pulse propagation induced in the sample by a heating Nickel alloy wire and then the temperature is measured on the wire by thermocouples [8]. ISOMET 2114 device is adopted by hot wire method which able to directly measures, among other thermal characteristics, the TC coefficient through surface probes [9], while QTM 500 is a quick TC meter based on the modified hot-wire technique which users can expect accurate and repeatable results [23].

Gandage et al. [15] reported the test procedure for laboratory measurement of the steady state heat flux was specified through flat, homogenous specimens with their specimens in contact with solid, parallel boundaries held at constant temperature using the guarded hot plates. Basically, guarded hot...
plate method requires some equipment like battery, data logger, a device for controlling the hot and cold temperature, thermocouples to monitor the temperature at each face of the specimen and the main body or chamber where the specimens were to be kept [12,14,15,17,18]. A single specimens of material is placed symmetrically between two plates: one plate is heated and the other is cooled or heated to lesser extent as illustrated in figure 1 [27]. Temperature of the plates is observed until they are constant which is called as steady state. Various devices that using guarded hot plate method have been created which can directly measure the thermal properties precisely k-factor of a large number of materials, for instances Quick-line™-30 thermophysical properties analyser [10], Unitherm™ Model 6000 Guarded Hot Plate TC Instrument [6], and Anacon TCA-8 TC analyser [26]. The parameters obtained from the experiment that is steady state temperatures, the thickness of the specimen and the heat input to the hot plate are used to determine TC, λ by using the Fourier linear heat flow equation [6].

\[
\lambda = \left( \frac{W}{A} \right) \cdot \frac{d_1}{dT_1}
\]

Where
\[
\lambda = \text{TC of the test specimen}
\]
\[
W = \text{Electric power input to the centre heater}
\]
\[
A = \text{Main heater surface area}
\]
\[
d_1 = \text{Specimen 1 thickness}
\]
\[
dT_1 = \text{Temperature gradient from hot plate to cold plate 1}
\]

Nevertheless, different methods still can be practiced on measuring TC of concrete. Medina et al. [11] was using a high insulating house with dimension 400 x 400 x 400 mm\(^3\) to measure TC of concrete in the steady state an internal temperature of about 50°C. Thermal needle probe method has been used which the thermal probe is made with a stainless steel with 60 mm in length and 1.3 mm diameter within which the heating wire and thermistor are embedded [16]. TC measurements were performed through the transient plane source (TPS) technique as studied by Ruiz Herrero et al. [21] and Girardi et al. [24] which the technique is based on the use of a thin metal strip as a continuous plane heat source.

![Illustration diagram of guarded hot plate method.](image)

Figure 1. Illustration diagram of guarded hot plate method.

2.1.3. Specimen preparation. According to BS EN 12667 [28], the preparation of the specimens shall be accordance with the appropriate product standard. Therefore, specimen dimension for TC test on concrete shall be prepared according to concrete standard test specimen which is proper with the technique and devices that will be used. This section only focused on hot-wire and guarded hot plate technique since both are closely related on TC measurement of engineering application [8].

For hot-wire technique, Bravo et al. [9] was investigated the TC of concrete by using specimen size of 100 x 100 x 500 mm, meanwhile Demirboga and Kan [23] was applied the dimension size of 40 x 110 x 160 mm. Both are in prism dimension. Specimens were tested after cured 28 days in a dry chamber (20°C and 50% relative humidity) which the measurement range is 0.0116 to 6 W/mK.

As for guarded hot plate technique, the specimens size of 150 x 150 x 150 mm were tested in the variation temperature of 20 ± 2°C, 150, 250, 350, 450 and 550°C to investigated the influence of high temperature of fly ash concrete [10]. However, most research have been adopted square slab specimens
with dimension of 300 x 300 x 50 mm, 300 x 300 x 30 mm, 500 x 500 x 100 mm and 200 x 200 x 40 mm were prepared by Alengaram et al. [14], Liu et al. [17], Akcaozoglu et al. [25] and Sayadi et al. [26], respectively. According to BS EN 12664, all specimens were cured under a temperature of 20 ± 2°C before testing at the age of 28 days in dry state [14,18].

2.2. Review on influence factors of thermal conductivity

The TC value is not variably continuous. It may varies due to some factors like mix proportioning, aggregate types and sources, as well as moisture status and unit weight in the dry state [29]. With increasing density, moisture and temperature, the TC increases too. Many research have been conducted to determine TC of concrete using different types of waste materials. Table 1 lists some of result findings about factors that affects TC of concrete with various types of waste materials from these researches.

Bravo et al. [9] was investigated the effect of using recycled aggregate (RA) on TC of concrete. These RA was obtained from construction and demolition waste which consists of waste concrete, ceramics, glass, wood and etc. They found that replacement of natural aggregated with these RA reduces the TC value of concrete. This may due to TC of materials used, considering that these waste materials have different TC, concrete mixes with different thermal properties [9,11,18,22,24].

Table 1. Influence factors on TC of concrete incorporating various types of waste materials.

| Authors | Type of waste materials | Influence Factors |
|---------|------------------------|-------------------|
| [9]     | Recycled aggregate from construction and demolition waste | TC of materials, density |
| [10]    | Class F fly ash        | Temperature, micro-environment relative humidity, porosity |
| [11]    | Rubber aggregate & fibre | TC of materials, amount of aggregate, porosity |
| [13,15] | Expanded perlite       | Density, temperature, porosity |
| [14]    | Oil palm shell         | Density |
| [16,17] | Palm oil fuel ash      | Replacement of aggregate and glass bubbles, density |
| [18]    | Hybrid RCA             | Amount of RCA, TC of materials, porosity, density |
| [6]     | Recycled glass         | W/C ratio, amount of replacement |
| [20]    | Pumice, expanded polystyrene beads | Density, porosity |
| [21]    | Polyethylene and PVC residues from electric cable protective sheath (plastic waste) | Amount of replacement, porosity |
| [22]    | Sawmill waste: wood    | Amount of materials, TC of materials, porosity |
| [23]    | Waste polystyrene      | Density, amount of materials |
| [24]    | Polyamid fibres from post-consumer textile carpet waste | Type of materials, temperature |
| [25]    | Waste PET              | Amount of replacement, bulk density |
| [26]    | Expanded polystyrene (EPS) | Volume percentage of materials |

Density are greatly influences the TC of concrete. Gandage et al. [15] conclude that the lower TC of concrete is due to the lower density which is comparable to the results reported by other researchers [9,14,17,20,23,25]. Marie [18] reported that the density does not considerably affect the conductivity of ordinary concrete. However, it is known that TC of air is lower than TC of concrete, therefore, the low conductivity of air entrapped on the surface of RA or RCA and the rubber itself, the conductivity decreased with the increase of the percentage of RCA in the RARC which directly relate the density to the TC [18]. TC is a function of density as a lower density results in a lower TC value, thus, the reduction of TC is mainly contributed from density [26].

Porosity is one of the factors affecting the TC of concrete and enclosed pores reduce the conductivity due to low TC of air. Medina et al. [11] concluded that air entrapment in concrete is increased with CR,
because during the mixing and curing of fresh rubberized concrete air bubbles are entrapped, hence, TC values are reduced due to higher porosity produced from entrapped air in concrete. Air entrainment might have also contributed to reduce the thermal diffusivity of all the mixtures [13]. It is observed that the higher the porosity and pore size are, the decreases the TC is, which mean if the porosity and pore size increased, the pores in concrete would be filled in more air, and fundamentally, the TC of the gas is much smaller than the solid [10]. The same observation also reported in other studies [18,20-22].

The other parameter that affects the TC of concrete is temperature. TC is a specific characteristic of each material, and strongly be influenced by temperature of the material [9]. Wang et al. [10] concluded that after high temperature exposure (550°C) on concrete specimens, the TC were markedly reduced. At lower temperature, the TC values are higher as compared to the TC value at higher temperature that may attributed to the fact that, the residual moisture present in the concrete specimen gets dried up with increase in temperature [15]. Hence, the TC values decrease with the increase in temperature which is in line with other researches [13,24].

Amount or volume percentage of waste materials used also play an important role in determining TC. The results of experiment by Medina et al. [11] have shown that the larger the amount of rubber used as aggregate in concrete, the lower TC value is achieved. Meanwhile for Liu et al. [16], the most effective insulating additive in their study is Stalite aggregates whose TC of ∼1.25 W/mK when 20–30% of glass bubbles are added, compared with the normal concrete. Liu et al. [17] investigated that foamed and non-foamed concrete containing palm oil fuel ash and glass bubbles exhibited lower TC compared to the conventional materials. Research studied by Marie [18] found that the TC values decrease when the amount of RCA increase and concluded that the use of 10% RA and 20% RCA to produce RARC can improve the TC over RCA mixes of the same RCA percentage of 20%. Krishnamoorthy and Zujip [6] was studied the use of recycled glass as fine aggregate replacement and they found that the TC values decreased gradually with the increased of recycle glass content in specimens. The recycled glass is capable to reduce the ability of concrete to transfer heat. Taoukil et al. [22] found that the addition of wood shavings in the concrete can reduces the TC of the composite and consequently increases its thermal insulation capacity. It is observed that the TC of a material depends on those of aggregates which constitute it. On the other hand, TC of concrete was drastically decreased with increase of modified waste expanded polystyrene (MEPS) aggregate and the reduction value was 70% [23]. A study using waste PET (WLPA) as aggregate replacement in concrete has been done by Akcaozoglu [25]. The study found that PET replacement caused a reduction in TC values that is lowest TC value measured was 0.3924 W/m K for concrete with 60% replacement of WPLA which is 58% lower compared to TC value of control concrete. The results of all researches done as described above prove that type or volume percentage of waste materials used is one of the contribution of changes on TC values of concrete which in line with previous study [26].

TC is also revealed affecting by water cement ratio of concrete [6], micro-environment relative humidity [10] and mineralogical characteristics of aggregates [26,30] that greatly influences the TC of concrete. Experiment results done by Krishnamoorthy and Zujip [6] shows that TC coefficient of cement increased when the w/c increased, thus, this proved that the TC is easily influenced by the constituents of concrete. For a given micro-environment relative humidity, Wang et al. [10] found that with an increase in fly ash replacement, the pore water saturation of concrete decreased which led to reduction of the TC of concrete. TC of concrete also greatly influenced by mineralogical characteristic of the aggregate [30]. Type of aggregate can cause nearly twice an increase in TC of concrete and this is strongly depends on the aggregate composition and its degree of crystallization as well. Aggregate with crystalline structure is expected to have higher heat conduction than both of amorphous and vitreous aggregate of the same composition.

3. Conclusion

This exploration is a contribution to the improvement and the control of waste materials which led to disposal problem and global warming. Thus, this paper intended to investigate the influence of utilization of waste materials in concrete through a comprehensive review, in aspect of thermal
properties since global energy is one of the major issue in the world. From the review, the following conclusions may be drawn:

1. The utilization of waste materials such as plastic waste, construction waste, fuel ash etc. in concrete can be studied extensively due to the continuous generation of waste materials.

2. There are various method of determining TC, however, Guarded Hot Plate is selected as the most accurate method to determine the TC of concrete as it was related on TC measurement of engineering applications.

3. There is no standard method for specimen preparation. According to BS EN 12667, the preparation of the specimens shall be accordance with the appropriate product standard. Hence, specimens preparation are strongly depends on type of products, materials and devices used.

4. TC depends upon the composition of concrete which greatly influenced by density, porosity, temperature, amount or volume percentage of materials, type of materials, water cement ratio, micro-environment relative humidity and mineralogical characteristics of aggregate.

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