Relationship between Thermal Conductivity and Compressive Strength of Insulation Concrete: A Review

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Abstract: Developing insulation concrete with high strength is essential for the construction of energy saving buildings. This is important to achieve carbon neutrality in the modern building industry. This paper reviews the existing studies in the literature on insulation concrete. This paper aims to reveal the correlation between the thermal conductivity and strength of concrete and identify the most effective method to make insulation concrete with lower thermal conductivity but higher strength. The review is carried out from two perspectives, including the effects of different foaming methods and various lightweight aggregates. As for the foaming methods, the chemical and mechanical foaming methods are discussed. As for the lightweight aggregates, cenospheres, porous aggregates, aerogels, and phase change materials are assessed. It is clearly observed that the thermal conductivity and compressive strength of concrete can be fitted by a linear function. As for the foaming methods, chemical foaming using hydrogen peroxide is the most effective to produce concrete with relatively lower thermal conductivity and higher compressive strength. For concrete with lightweight aggregates, cenospheres are the best option. Finally, recommendations are made to develop concrete with lower thermal conductivity and higher strength.

Keywords: Foaming, lightweight aggregates, thermal conductivity, compressive strength, concrete.

1. INTRODUCTION

Global energy consumption is increasing, and buildings consume a large proportion of global energy [1, 2]. Thus, the energy-saving of buildings through thermal insulation has attracted much attention. There are two ways of achieving building insulation. One is to use non-structural materials with low thermal conductivity attaching to the inside or outside of the building, and the other is to use structural materials with low thermal conductivity so that they can carry the loading and save energy at the same time.

As for non-structural insulation materials, organic foaming materials and inorganic foaming materials are normally used to reduce thermal conductivity. Organic foaming materials have the advantages of higher strength and lower density than inorganic foaming materials when the thermal conductivity is the same, but their disadvantages include low fire resistance, spalling, and UV aging, which limit their applications in building insulations. In comparison, inorganic foaming materials have attracted more attention for their excellent fire resistance and durability. Inorganic foaming materials are mostly cementitious materials that are made by adding foaming agents such as hydrogen peroxide [3-8] or aluminum powder [9-11] or directly adding foam which is made through mechanical processing [12-15] into the mixture. Compared with organic counterparts, inorganic foaming materials have higher porosity and lower thermal conductivity [2].

As for structural insulation materials for building applications, low thermal conductivity is achieved by adding lightweight aggregates of low thermal conductivity in the mixture, such as microspheres [16-19] and perlite [20]. Lightweight aggregate concrete can be used as a structural material for building constructions (e.g., walls) to achieve thermal insulation

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and load carrying function at the same time. Compared with non-structural insulation materials, structural insulation materials have higher thermal conductivity and higher strength. In other words, lightweight aggregates are not as effective as foam for thermal insulation but are desirable for strength improvement.

Therefore, materials made by foaming have good insulation but are weak in strength, whereas materials made by adding lightweight aggregates may have better strength but at the cost of low insulation performance. How to obtain a balance between the insulation performance and strength becomes the key research question [2]. It is desirable to develop a material with low thermal conductivity and high strength so that it can be used as a structural material to achieve thermal insulation and load carrying at the same time. This is crucial for the cost and energy saving of buildings.

This paper presents a review of the relationship between the thermal conductivity and strength of concrete to identify the key influencing factors. This will guide the development and design of new generation insulation concrete for cost and energy saving purposes. This review focuses on two methods for achieving insulation, i.e., adding foaming and lightweight aggregates in the mixture, because they are the most adopted methods in making insulation concrete. This review is divided into two parts, with the first and second parts discuss the effects of foaming and lightweight aggregates, respectively.

2. EFFECTS OF FOAMING METHODS

Foaming is an effective method to reduce the thermal conductivity of concrete. This is because the air bubbles in the foam have lower thermal conductivity than the surrounding matrix [21]. However, the foaming in concrete will inevitably reduce the concrete strength due to the porous microstructure. The pore volume, size, and shape mainly affect thermal conductivity and strength [22-25]. Foaming can be created using either chemical agents or mechanical processing.

2.1. Chemical Foaming

2.1.1. Aluminum Powder

Aluminum power as a foaming agent has been widely used in making insulation concrete [9-11]. Aluminum powers could react with alkali in the cementitious materials and release hydrogen gas, following the reaction as:

$$Al(s) + 3H_2O(l) + OH^-(aq.) \rightarrow Al(OH)_4^-(aq.) + \frac{3}{2}H_2(g) \quad (1)$$

Generally, more aluminum powder and a higher water/binder ratio will create more pores in concrete [26, 27]. It can be seen from Eq. 1 that aluminum powders react with alkali, which produces hydrogen gas and aluminum ions. The aluminum ions will participate in the cement hydration and provide strength to the pore walls. This may affect its mechanical properties and insulation performance. The thermal conductivity and 28-day compressive strength changed with the addition of aluminum powder, so these reported data are presented in Figure **1**, and these studies are summarized in Table **1**. Figure **1** shows a linear relationship between thermal conductivity and strength. This explains why it is difficult to achieve high strength and low conductivity of the concrete simultaneously. The following function can represent this linear relationship:

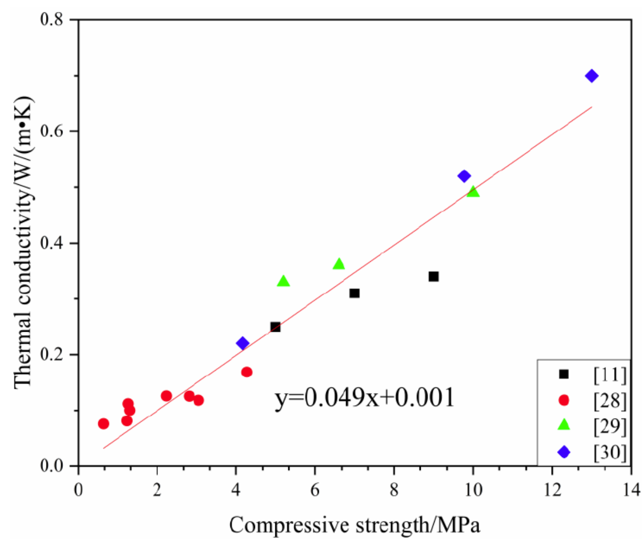

Figure 1: The relationship between thermal conductivity and 28-day compressive strength of concrete with aluminum powder as a foaming agent.

$$y = 0.049x + 0.001 \; (R^2 = 0.932) \quad (2)$$

The 28-day compressive strength of the specimen decreases with the increase addition of aluminum powder, and so does its thermal conductivity. In Table **1**, the best performance of paste foaming by aluminum powders is achieved by Novais *et al*. [28] because it has the lowest gradient. This low boundary means the same 28-day compressive strength with the lowest thermal conductivity. This result shows that the fly ash and metakaolin-based geopolymer paste is the best paste to match the aluminum powder in Table **1**. Table **1** also shows that the gradient is from 0.021 to 0.054.

Table 1: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Foaming by Aluminum Powders

Description of pastes	Linear fitting	Ref.
Metakaolin-based geopolymer	y=0.023x+0.143 (R^2=0.93)	[11]
Fly ash and metakaolin-based geopolymer	y=0.021x+0.071 (R^2=0.754)	[28]
	y=0.022x+0.066 (R^2=0.564)	
Metakaolin-based geopolymer	y=0.039x+0.134 (R^2=0.8)	[29]
Fly ash based geopolymer	y=0.054x−0.007 (R^2=0.99)	[30]

2.1.2. Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is a foaming agent which produces oxygen gas through decomposition, as shown in Eq. 3. H_2O_2 can decompose and create uniform oxygen bubbles when the temperature increases.

$$2H_2O_2(l) \rightarrow 2H_2O(l) + O_2(g) \tag{3}$$

It was reported that the 28-day compressive strength and thermal conductivity of concrete decreased with the addition of H_2O_2 [3-8]. The data of thermal conductivity and 28-day compressive strength of concrete foaming by different amounts of H_2O_2 in each study are fitting and summarized in Table **2**, and these data are presented in Figure **2**. The data points in Figure **2** scatter in a wide range because they are from different concrete mixtures with different H_2O_2 amounts. The majority of lower boundary data are obtained from [31], which is the best performance in Figure **2**.

To investigate which paste is better for application, Table **2** summarizes the reported concrete foaming by H_2O_2 and the fitting function of thermal conductivity and 28-day compressive strength in each corresponding literature, similar to that foamed by aluminum powder in Table **1**. The range of gradient is 0.003-0.130.

2.1.3. Other Foaming Agents

Silica powder was also used as a foaming agent in some research [48, 49], and it was not only a foaming agent but also a binder. The foaming is obtained by:

$$Si(s) + 4H_2O(l) \rightarrow Si(OH)_4(aq) + 2H_2(g) \tag{4}$$

Silica carbide sludge also contains some silica powder, which is also used as a foaming agent [50]. In addition, other materials have also been used as foaming materials, like Na_2O_2 [51], sodium perborate [52], sodium carbonate [53], and recycled aluminum foil powder [29]. The reported thermal conductivity and the strength with different foaming agents content in each corresponding literature fit using linear regression, and the fitting function is summarized in Table **3**. The gradient of the linear function from 0.009 to 0.099. The lowest gradient of these data points in these cited references is achieved by [54] and the highest gradient is achieved by [55] with Silicon powder as a foaming agent and Fly ash and expanded clay-based geopolymer as the paste.

2.2. Mechanical Foaming

Mechanical foaming is to use of foaming equipment to process plant or animal proteins to create foam which is directly added to the concrete mixture [12-15]. In general, mechanical foaming will reduce thermal conductivity and 28-day compressive strength at the same time. The reported thermal conductivity and 28-day compressive strength of concrete with different mechanical foaming methods are presented in Figure **3**. The relationship between the thermal conductivity and strength is best described with a linear function which is presented in Table **4**, that shows the gradient of the linear function from 0.004 to 0.121. It can be seen in Figure **3** that the best performance of mixtures is obtained from the fly ash and blast furnace slag-based geopolymer foamed by a diluted aqueous surface-active concentrate [56].

3. EFFECTS OF LIGHTWEIGHT AGGREGATES

Using lightweight aggregates is another effective way to reduce the thermal conductivity of concrete to improve its insulation performance. Generally, concrete with lightweight aggregates may have greater strength than foamed concrete, given the same thermal conductivity [2]. This section will analyze the effects of various lightweight aggregates on concrete's thermal conductivity and strength.

3.1. Cenospheres

Cenospheres are suitable as lightweight aggregates because they are high in shell wall strength and low in

Table 2: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Foaming by Hydrogen Peroxide

Composition of mixtures		Linear fitting	Ref.
Type	Matrix		
Paste	Metakaolin-based geopolymer	y=0.018x+0.387 (R^2=0.87)	[5]
	10 wt.% glass-metakaolin-based geopolymer	y=0.016x+0.39 (R^2=0.99)	
	20 wt.% glass-metakaolin-based geopolymer	y=0.008x+0.452 (R^2=0.44)	
	30 wt.% glass-metakaolin-based geopolymer	y=0.019x+0.413 (R^2=0.94)	
	40 wt.% glass-metakaolin-based geopolymer	y=0.016x+0.392 (R^2=0.76)	
Mortar	Fly ash-metakaolin-based geopolymer	y=0.041x+0.087 (R^2=0.40)	[8]
Paste	Slag-based geopolymer	y=0.003x+0.120 (R^2=0.98)	[31]
		y=0.003x+0.134 (R^2=0.999)	
		y=0.003x+0.123 (R^2=0.80)	
		y=0.006x+0.116 (R^2=0.99)	
Paste	Fly ash-rice husk-based geopolymer	y=0.015x+0.088 (R^2=0.98)	[32]
Paste	Kaolinite-based geopolymer	y=0.025x+0.044 (R^2=0.976)	[33]
Concrete (sawdust biomass)	Metakaolin-based geopolymer	y=0.003x+0.109 (R^2=0.909)	[34]
Paste	Magnesium phosphate cement	y=0.011x+0.135 (R^2=0.95)	[35]
Paste	Fly ash and cement	y=0.034x+0.041 (R^2=0.946)	[36]
Paste	Metakaolin and fly ash-based geopolymer	y=0.048x+0.032 (R^2=0.95)	[37]
Paste	Metakaolin-based geopolymer	y=0.015x+0.091 (R^2=0.98)	[38]
Paste	Metakaolin-based geopolymer	y=0.006x+0.110 (R^2=0.95)	[39]
Paste	Fly ash-based geopolymer	y=0.038x+0.023 (R^2=0.68)	[40]
		y=0.019x+0.044 (R^2=0.998)	
		y=0.021x+0.041 (R^2=0.90)	
Concrete (hollow glass bubbles)		y=0.012x+0.039 (R^2=0.979)	
		y=0.010x+0.043 (R^2=0.884)	
Paste	Fly ash-blast furnace slag-based geopolymer	y=0.010x+0.179 (R^2=0.95)	[41]
Paste	Fly ash and cement	y=0.049x+0.121 (R^2=0.795)	[42]
Paste	Pitchstone-based geopolymer	y=0.008x+0.060 (R^2=0.956)	[43]
Paste	Metakaolin-based geopolymer	y=0.012x+0.105 (R^2=0.34)	[44]
Paste	Perlite wastes-based geopolymer	y=0.011x+0.076 (R^2=0.70)	[45]
		y=0.007x+0.090 (R^2=0.997)	
Paste	Metakaolin-based geopolymer	y=0.130x−0.009 (R^2=0.211)	[46]
Paste	Calcined phosphogypsum	y=0.123x−0.478 (R^2=0.951)	[47]

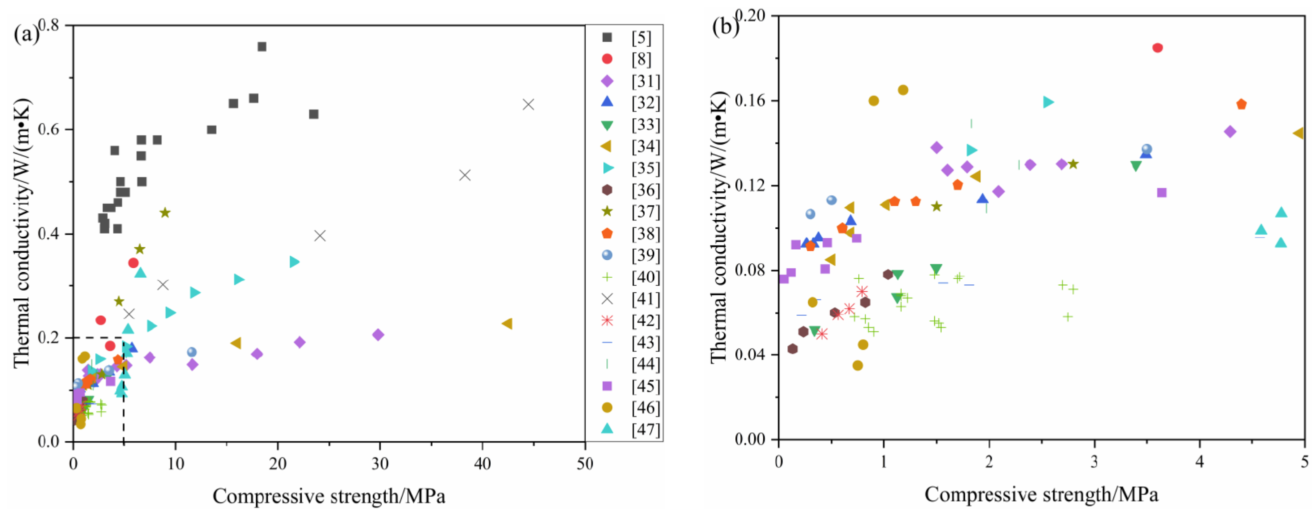

Figure 2: (**a**) the relationship between thermal conductivity and 28-day compressive strength of concrete with hydrogen peroxide as a foaming agent, (**b**) zoomed in from 0 to 5 MPa.

Table 3: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with other Different Foaming Agents

Composition of pastes	Foaming agents	Linear fitting	Ref.
Metakaolin-based geopolymer	Municipal solid waste incineration bottom ash	y=0.040x+0.147 (R^2=0.7)	[29]
Metakaolin-based geopolymer	Na_2O_2	y=0.032x+0.064 (R^2=0.678)	[51]
Fly ash-based geopolymer	Sodium bicarbonate	y=0.009x+0.118 (R^2=0.97)	[54]
Fly ash-based geopolymer	Silicon powder	y=0.062x+0.130 (R^2=1)	[55]
Fly ash and expanded clay-based geopolymer	Silicon powder	y=0.099x−0.043 (R^2=0.984)	

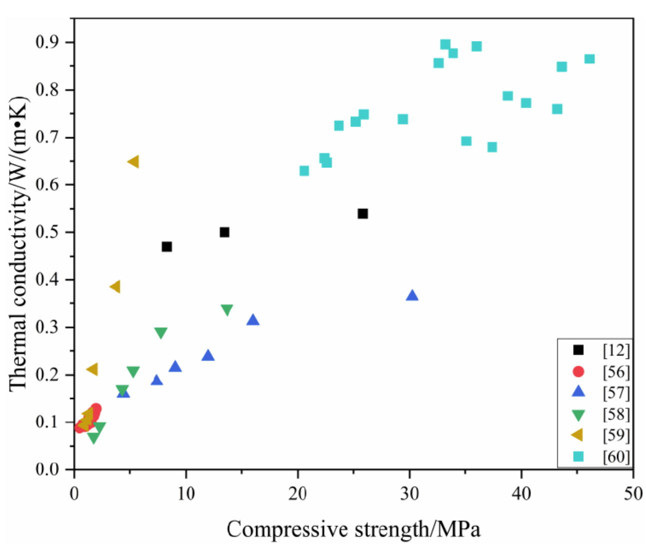

Figure 3: The relationship between thermal conductivity and 28-day compressive strength of concrete with different mechanical foaming materials.

thermal conductivity [16]. Glass microspheres and fly ash are two typical examples of cenospheres [17-19]. Glass microspheres and fly ash have pozzolanic activity, especially in alkaline condition under high temperature, while the reactivity is limited when the temperature is low [61]. Adding a small number of cenospheres in the concrete mixture helps reduce the thermal conductivity, and they have a filling effect, so they can also improve the strength. However, after the amount of cenospheres exceeds a certain limit, the concrete strength will decrease because these cenospheres increase the voids in concrete. On the other hand, more cenospheres can yield lower thermal conductivity, although the strength decreases. There is also research on replacing sand with cenospheres in concrete [62] which suggested that the cenospheres with higher crushing strength and smaller wall thickness were more helpful in achieving higher concrete strength and lower thermal conductivity.

The experimental studies with cenospheres are reviewed, and the reported thermal conductivity and 28-day compressive strength of concrete in different

Table 4: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Different Mechanical Foaming Materials

Composition of mixture		Materials used to produce mechanical foaming	Linear fitting	Ref.
Type	**Matrix**			
Concrete (oil palm shell)	Low-calcium fly ash and palm oil fuel ash-based geopolymer	Sika AER-50/50	y=0.004x+0.442 (R^2=0.954)	[12]
Paste	Fly ash and blast furnace slag-based geopolymer	A diluted aqueous surface active concentrate	y=0.008x+0.139 (R^2=0.889)	[56]
Paste	Phosphogypsum: fly ash: cement: hydrated lime(49: 20: 25:6)	A locally available plant-based foaming agent	y=0.023x+0.061 (R^2=0.863)	[57]
Paste	Blast furnace slag-based geopolymer	Protein with enzymatic active components	y=0.031x+0.067 (R^2=0.935)	[58]
	Fly ash and blast furnace slag-based geopolymer		y=0.022x+0.073 (R^2=0.781)	
	Blast furnace slag-based geopolymer		y=0.052x+0.036 (R^2=0.908)	
Paste	Fly ash-based geopolymer	Animal protein	y=0.121x−0.033 (R^2=0.98)	[59]
Concrete	Cement	Protein-based foam agent	y=0.019x+0.240 (R^2=0.970)	[60]
			y=0.020x+0.224 (R^2=0.970)	
			y=0.020x+0.220 (R^2=0.946)	
	Cement and silica fume		y=0.008x+0.512 (R^2=−0.461)	
			y=0.018x+0.055 (R^2=0.968)	
			y=0.020x−0.089 (R^2=0.857)	

references are shown in Figure **4**. It can be seen that the lower boundary corresponds to metakaolin-based geopolymer composites with fly ash cenosphere [19]. The lower boundary means the same 28-days compressive strength with the lowest thermal conductivity, so metakaolin-based geopolymer composites mixed with fly ash cenosphere has the best performance in Figure **4**. Generally, the relationship between thermal conductivity and 28-day compressive strength can be fitted using a linear function as summarized in Table **5**. The gradient is from 0.003 to 1.59, and the highest gradient is 1.59, obtained from [63]. This indicates that the expanded glass granules can be the best choice in these cenospheres in Table **5** when applied in insulation concrete. This is because the high gradient means that the thermal conductivity decreases faster than the 28-day compressive strength.

3.2. Inorganic Porous Aggregates

Inorganic porous aggregates can effectively reduce the thermal conductivity of concrete because of their high porosity. Another benefit of the inorganic porous aggregates is that they have a better bond with the concrete matrix than the organic aggregates. Common inorganic porous aggregates include clay [65], perlite [20], pumice [66], vermiculite [67], and bentonite [68].

These reported data are fitted with linear functions as summarized in Table **6**. The gradient of these

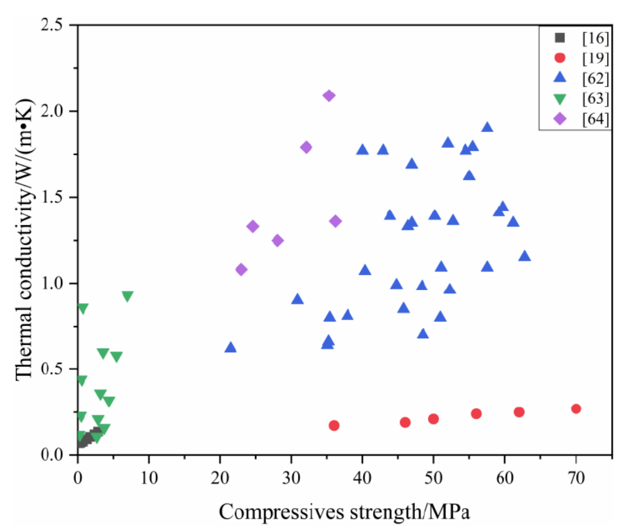

Figure 4: The relationship between thermal conductivity and 28-day compressive strength of concrete with different cenospheres.

Table 5: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Different Cenospheres

Matrix of concrete	Types of cenosphere	Linear fitting	Ref.
Cement	Vitrified microspheres	y=0.027x+0.059 (R^2=0.998)	[16]
Metakaolin-based geopolymer	Fly ash cenosphere	y=0.003x+0.059 (R^2=0.96)	[19]
Cement	Hollow glass microsphere (HGM) bubbles K25	y=0.034x−0.157 (R^2=0.969)	[62]
	HGM S32	y=0.067x−1.817 (R^2=0.863)	
	HGM S38HS	y=0.041x−0.691 (R^2=0.188)	
	HGM H50	y=0.056x−1.901 (R^2=−0.034)	
	HGM S60	y=0.059x−2.015 (R^2=0.17)	
	Fly-ash cenospheres(FAC) E106	y=0.02x+0.164 (R^2=−0.276)	
	FAC E160	y=0.002x+1.168 (R^2=−0.498)	
	FAC E200/600	y=0.094x−2.552 (R^2=0.579)	
Lime	Expanded glass granules	y=1.590x−0.397 (R^2=0.834)	[63]
Natural hydraulic lime		y=0.568x−1.1447 (R^2=0.989)	
Lime-cement		y=0.235x−0.711 (R^2=0.998)	
Cement and fly ash	Glass bubble	y=0.069x−0.389 (R^2=0.977)	[64]
		Y=0.021x+0.633 (R^2=0.874)	

Table 6: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Different Inorganic Porous Aggregates

Matrix of concrete	Types of aggregate	Linear fitting	Ref.
Concrete	Expanded perlite	y=0.026x+0.209 (R^2=0.711)	[20]
Concrete	Expanded clay	y=0.031x+0.116 (R^2=0.847)	[65]
Magnesium oxychloride cement and fly ash	Expanded perlite	y=0.019x−0.228 (R^2=0.844)	[69]
Cement	Expanded perlite	y=0.184x−0.177 (R^2=0.391)	[70]
		y=1.495x−1.258 (R^2=0.911)	
Cement and silica fume	Non-graded expanded perlite with aerogel	y=0.036x+0.401 (R^2=0.970)	[71]
		y=0.098x+0.108 (R^2=0.246)	
	Graded expanded perlite with aerogel	y=0.076x−0.140 (R^2=0.847)	
		y=0.094x+0.111 (R^2=0.439)	
	Non-graded expanded perlite	y=0.154x−0.145 (R^2=0.792)	

functions is from 0.019 to 1.495, with the lowest gradient from [69] and the highest gradient from [70]. It shows that the expanded perlite is the best choice in these inorganic porous aggregates in Table **6** to be applied in insulation concrete.

3.3. Organic Porous Aggregates

Similar to inorganic porous aggregates, organic porous aggregates can also reduce the thermal conductivity of concrete through porosity. Common organic porous aggregates include polyurethane [72, 73], polyethylene terephthalate (PET) [9, 74, 75], polystyrene [76, 77], polycarbonate [78], recycled packaging foam [79], crumb rubber [80], recycled polyvinyl chloride [81]. The reported thermal conductivity and strength data of concrete with various organic porous aggregates are plotted in Figure **5** and summarized in Table **7**. Figure **5** presents that the data

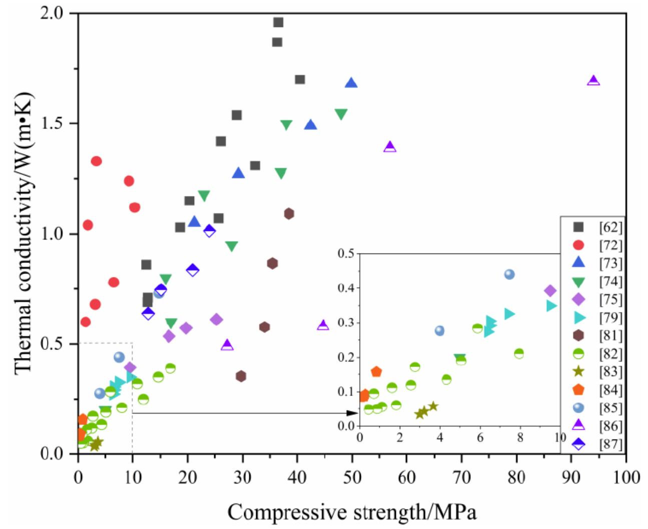

Figure 5: The relationship between thermal conductivity and 28-day compressive trength of concrete with different organic porous aggregates.

scatter different from those in Figure **5** for inorganic porous aggregates. This may be because the strength of concrete with different inorganic porous aggregates depends not only on the porosity but the bond between aggregates and matrix, for the bond between organic porous aggregates and concrete may be less consistent than that of inorganic porous aggregates. The low boundary data are mostly from [82], and this best performance concrete is a mixture of waste expanded polystyrene as aggregate with cement and resin.

Table **7** shows the linear fitting functions of these data. The gradient of the function is from 0.014 to 0.313. The highest gradient (i.e., 0.313) in this table is achieved by [72], and the best performance of organic porous aggregate is rigid polyurethane foam wastes in Table **7**.

3.4. Aerogel

Aerogel has attracted increasing attention for making insulation materials for its low thermal conductivity and lightweight property [88]. The most commonly used aerogel is silica aerogel [89, 90]. It is found that [91] when the aerogel is less than 1 wt.% in

Table 7: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Different Organic Porous Aggregates

Matrix of concrete	Organic porous aggregates	Linear fitting	Ref.
Cement	Expanded polystyrene (2.5 mm)	y=0.046x+0.256 (R^2=0.989)	[62]
Cement	Expanded polystyrene (1mm)	y=0.049x+0.103 (R^2=0.996)	
Cement	Thermoplastic microsphere (35-55 μm)	y=0.036x+0.199 (R^2=0.976)	
Cement	Rigid polyurethane foam wastes	y=0.076x+0.399 (R^2=0.742)	[72]
Cement and limestone filler		y=0.313x+0.302 (R^2=0.619)	
Cement	Polyurethane foam waste	y=0.021x +0.621 (R^2=0.986)	[73]
Cement	Polyethylene terephthalate (0.1 mm, density: 214 kg/m^3)	y=0.039x+0.115 (R^2=0.915)	[74]
	Polyethylene terephthalate (1mm, density: 547 kg/m^3)	y=0.031x+0.084 (R^2=0.991)	
Cement	Waste PET lightweight aggregate	y=0.014x+0.278 (R^2=0.907)	[75]
High calcium fly ash-based geopolymer	Recycled packaging foam (2.36-4.75 mm, 215 kg/m3)	y=0.020x+0.162 (R^2=0.73)	[79]
Cement	Recycled polyvinyl chloride	y=0.086x−2.236 (R^2=0.918)	[81]
Cement	Waste expanded polystyrene	y=0.021x+0.029 (R^2=0.973)	[82]
Cement and 0.5 % resin		y=0.021x+0.048 (R^2=0.983)	
Cement and 1.0 % resin		y=0.025x+0.052 (R^2=0.959)	
Cement and 1.5 % resin		y=0.041x+0.049 (R^2=0.964)	
Metakaolin-based geopolymer	Polystyrene particles	y=0.035x−0.072 (R^2=0.997)	[83]
Cement and fly ash	Expanded polystyrene particles (<6.5 mm, density: 16.6 kg/m3)	y=0.099x+0.069 (R^2=0.932)	[84]
Cement	Expanded polystyrene	y=0.042x+0.116 (R^2=0.996)	[85]
Cement and silica fume	Expanded polystyrene	y=0.019x−0.031 (R^2=0.751)	[86]
Fly ash geopolymer	Recycled Non-Biodegradable polyethylene terephthalate waste	y=0.030x+0.266 (R^2=0.904)	[87]

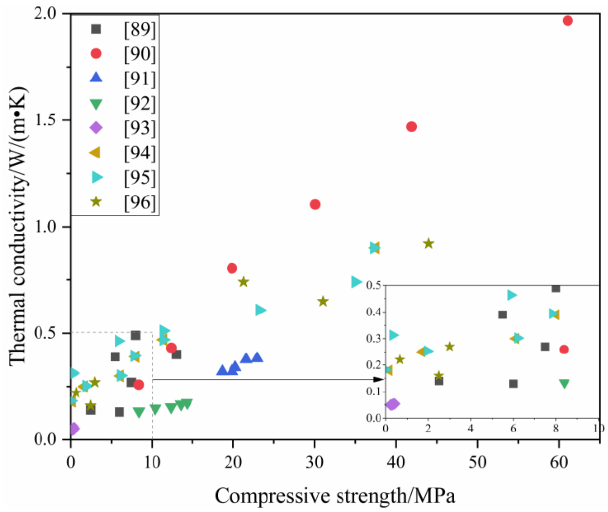

Figure 6: The relationship between thermal conductivity and 28-day compressive strength of concrete with different aerogels.

the concrete mixture, it has a negligible effect on the 28-day compressive strength, but the strength significantly drops if more aerogel is added. Currently, there are not many studies on concrete with aerogel for insulation purposes. The reported thermal conductivity and strength data of concrete with aerogel are plotted in Figure **6** and summarized in Table **8**. The low boundary of these data is achieved by [92], which has the best matrix for aerogel made by fly ash, cement, α-hemihydrate gypsum, and lime (1:3:9:0.6). Table **8** shows the gradient of the fitting function is from 0.006 to 0.064. The best performance of silica aerogel in Table **8** is achieved in [89] for its highest gradient.

3.5. Phase Change Materials

Phase change materials can also be used for making insulation concrete [97]. Insulation is achieved through a phase change, i.e., from liquid at high temperature and absorbing heat, to solid at low temperature and releasing heat [98-101]. Phase change materials are also used to fill the pores of the porous aggregates to reduce thermal conductivity [102]. In general, phase change materials have a negative effect on the 28-day compressive strength of concrete [103-107]. The reported thermal conductivity and strength data of concrete with phase change materials are summarized in Table **9**. The low boundary data is obtained from [108], which shows that this concrete has the lowest thermal conductivity at the same strength. In Table **9**, the gradient of the fitting function is from 0.008 to 0.025. The highest gradient is achieved by [109] which has the best performance of phase change materials.

3.6. Other Lightweight Aggregates

Many other types of materials can be used as lightweight aggregates to reduce the thermal conductivity of concrete, such as clay [110], glass [110], oil palm shells [111], and waste rubber [88, 112]. The reported thermal conductivity and strength data of concrete with these aggregates are summarized in Table **10** and plotted in Figure **7**. In Figure **7**, the low boundary is obtained from [34], which is the best-performance concrete using metakaolin-based

Table 8: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Different Aerogels

Matrix of concrete	Type of aerogel	Linear fitting	Ref.
Cement	Silica aerogel	y=0.034x−0.038 (R^2=0.778)	[89]
80 wt.% cement and 20 wt.% pozzolan		y=0.064x−0.003 (R^2=0.929)	
Cement	Hydrophobic aerogel granules	y=0.032x+0.076 (R^2=0.983)	[90]
Cement and silica fume	Silica aerogels	y=0.017x−0.004 (R^2=0.841)	[91]
Fly ash:cement: α- hemihydrate gypsum: lime = 1:3:9:0.6	Silica aerogel	y=0.006x+0.079 (R^2=0.954)	[92]
Fly ash-based geopolymers	Silica aerogel	y=0.025x+0.043 (R^2=0.938)	[93]
Cement and silica fume	Hydrophobic aerogel	y=0.019x+0.212 (R^2=0.982)	[94]
Ultra-high performance concrete	A hydrophobic aerogel	y=0.011x+0.358 (R^2=0.937)	[95]
Cement and silica fume		y=0.019x+0.214 (R^2=0.982)	
Cement	Micro-sized aerogel powder	y=0.009x+0.494 (R^2=0.021)	[96]
Cement and 3 wt.% hydrogen peroxide		y=0.007x+0.203 (R^2=−0.954)	

Table 9: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with Phase Change Materials

Type of compositions	Type of phase change material	Extracted correlation	Ref.
Cementitious mortar	A novel paraffin/hydrophobic expanded perlite composite phase change material	y=0.020x+0.747 (R^2=0.935)	[107]
Cementitious composite	Microencapsulated phase change materials	y=0.008x+0.680 (R^2=0.904)	[108]
Cementitious concrete	Micro-encapsulated phase change materials	y=0.024x+0.883 (R^2=0.975)	[109]
Cementitious mortar		y=0.025x+0.506 (R^2=0.894)	

Table 10: Linear Relationship between the Thermal Conductivity and 28-Day Compressive Strength of Concrete with other Different Aggregates

Composition of Concrete		Linear fitting	Ref.
Matrix	Type of aggregates		
Metakaolin-based geopolymers	Sawdust biomass	y=0.003x+0.123 (R^2=0.858)	[34]
Cement and 5% Class-F (low calcium) and 10% silica fume	Oil palm shell	y=0.012x+0.348 (R^2=0.731)	[111]
Cement	Waste rubber	y=0.017x+0.577 (R^2=0.90)	[112]
Cement	Virgin cork	y=0.169x+0.027 (R^2=0.988)	[113]
Cement and 20% silica fume	Vegetable synthetic sponge wastes	y=0.019x+0.316 (R^2=0.86)	[114]
Cement and clay	Wood	y=0.046x+0.017 (R^2=0.914)	[115]
Cement and fly ash	Expanded cork granules and expanded clay	y=0.031x+0.046 (R^2=0.998)	[116]
Metakaolin-based geopolymers	Cork	y=0.029x+0.076 (R^2=0.98)	[117]
Fly ash-based geopolymer	Multifunctional cork	y=0.028x+0.075 (R^2=0.995)	[118]
Cement	Bio-based lightweight aggregate (indirect carbonization of plant residues from agriculture productions)	y=0.075x−0.949 (R^2=0.978)	[119]
Clay and cement	Wood aggregates	y=0.053x+0.080 (R^2=0.881)	[120]
5 wt.% silica fume and 95 wt.% cement	Waste rubber powder	y=0.023x+1.134 (R^2=0.877)	[121]
10 wt.% silica fume and 90 wt.% cement		y=0.028x+0.897 (R^2=0.974)	
15 wt.% silica fume and 85 wt.% cement		y=0.049x+0.229 (R^2=0.826)	
20 wt.% silica fume and 80 wt.% cement		y=0.039x+0.651 (R^2=0.994)	
Cement	Rubber particles	y=0.010x+0.397 (R^2=0.941)	[122]
Sulfur aluminate cement	Waste wood chips	y=0.009x+0.119 (R^2=0.911)	[123]
Ordinary Portland cement		y=0.011x+0.145 (R^2=0.75)	
Granulated blast furnace slag		y=0.008x+0.126 (R^2=0.933)	

geopolymers as the matrix and sawdust biomass as lightweight aggregate. In Table **10**, the gradient of the function is from 0.003 to 0.169. Virgin cork in [113] has great potential as a lightweight aggregate for its highest gradient in these aggregates. The highest gradient means that the aggregate can reduce the thermal conductivity with minimum decrease in compressive strength.

4. SUMMARY AND DISCUSSIONS

Generally, foaming can be obtained through chemical agents or mechanical processing. As for chemical agents, there are aluminum powder, hydrogen peroxide, and other foaming agents. Foaming reduces the thermal conductivity of concrete to improve its insulation performance, but it also reduces the compressive strength of concrete. The best insulation concrete should have the lowest thermal conductivity at the same 28-day compressive strength. The best chemical foaming concrete by aluminum powder, hydrogen peroxide, and other foaming agents are made by fly ash and metakaolin-based geopolymer, slag-based geopolymer, and fly ash-based geopolymer foamed by sodium bicarbonate, respectively. The best mechanical foaming concrete is fly ash and blast furnace slag-based geopolymer foamed by a diluted aqueous surface-active concentrate.

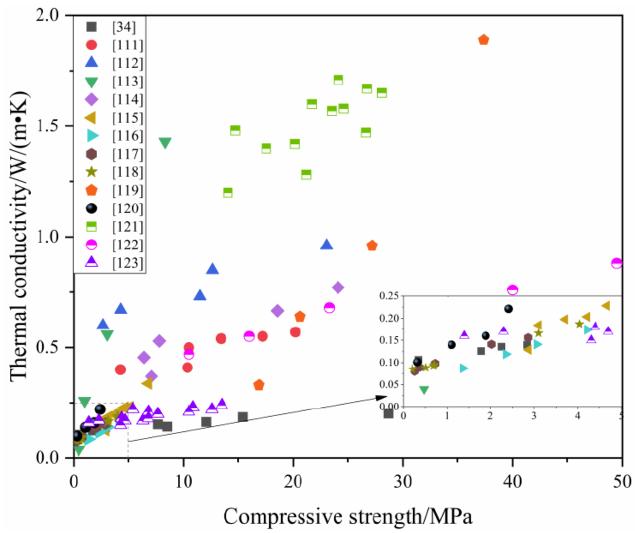

Figure 7: The relationship between thermal conductivity and 28-day compressive strength of concrete with different aggregates.

The thermal conductivity and strength of foamed concrete in cited references are fitted using a linear function to evaluate the effect of the foaming method. As seen from Tables **1** to **4**, the gradients range of the linear functions of the thermal conductivity and strength are 0.021-0.054, 0.003-0.130, and 0.009-0.099 for aluminum powder, hydrogen peroxide, or other foaming agents, respectively. The gradient of mechanical foaming is from 0.004 to 0.121. Therefore, it indicates that hydrogen peroxide had the highest gradient and is the best foaming agent in these foaming methods.

Aggregates account for a large proportion of concrete mixture, so they significantly affect the thermal conductivity and strength of concrete. As for the aggregates in this section, the gradients range of the linear fitted functions in the cited reference is 0.003-1.59, 0.019-1.495, 0.014-0.313, 0.006-0.064, and 0.008-0.025 for concrete mixed with cenospheres, inorganic porous aggregates, organic porous aggregates, aerogels, and phase change materials, respectively. Cenospheres that had the maximum gradient may be the most suitable lightweight aggregates for making insulation concrete with relatively lower thermal conductivity but higher strength. It can also be seen that the maximum gradient of lightweight aggregates is higher than foaming methods.

It can be seen from the above review that foaming and porous aggregates can be used to reduce the thermal conductivity of concrete. However, these methods may have a negative effect on concrete strength. Figure **8** present all data from the above figures, and it gives us the best performance under

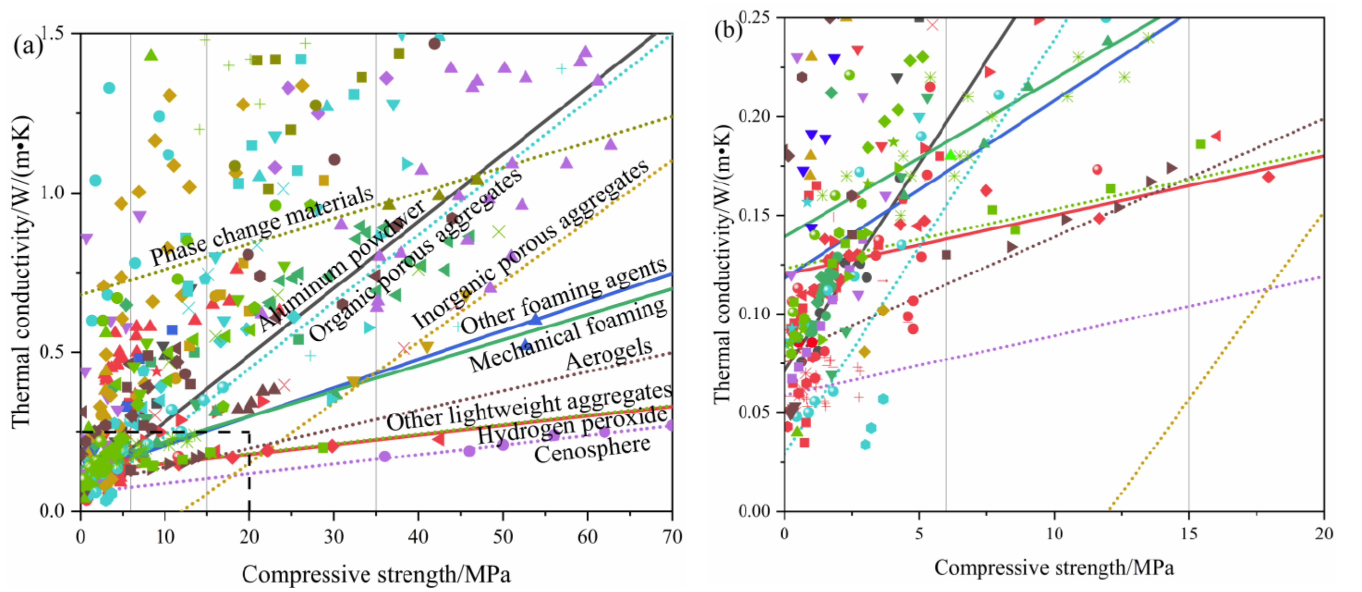

Figure 8: (**a**) The relationship between thermal conductivity and 28-day compressive strength of the best performance compositions, (**b**) zoomed in from 0 to 20 MPa.

different strength required. When the strength of insulation material is needed to be lower than 6MPa, organic porous aggregate is the best, and at the range of 6-15MPa, 15-35MPa, and more than 35MP, the best is aerogel, hydrogen peroxide, and cenosphere, respectively. It may help guide the development and design of new insulation concrete with low thermal conductivity and high strength.

5. CONCLUSIONS

The compressive strength and thermal conductivity are two important parameters of insulation concrete. Theoretically the compressive strength and thermal conductivity is not directedly related. But a clear trend has been observed from this review that the thermal conductivity increases with strength. Perhaps higher strength means denser microstructure, less voids making the material a better thermal conductor. But the discussion of the underlying mechanism of this observation is beyond the scope of this paper. This work focuses more on the relationship of these two parameters, and looks at how to improve the insulation property of concrete while maintaining its strength. The effects of foaming methods and lightweight aggregates are analyzed by correlating the thermal conductivity and strength of concrete. Based on the review, the following conclusions can be drawn:

1. Generally, the relationship between thermal conductivity and 28-day compressive strength of concrete can be fitted by a linear function, regardless of directly introducing more bubbles through a foaming agent or by adding more lightweight aggregate. In other words, it is difficult to achieve simultaneously low thermal conductivity and high strength of concrete. For this reason, it is recommended to emphasize the methods in the literature, which yield a higher gradient of the linear function of the thermal conductivity and strength because these results indicate concrete mixtures with relatively lower thermal conductivity and higher strength.

2. As for the foaming methods, chemical foaming using hydrogen peroxide is the most effective to produce concrete with relatively lower thermal conductivity and higher compressive strength. Its perfect performance also needs matching with constituent materials such as slag based geopolymer.

3. For concrete with lightweight aggregates, cenospheres are the best option. Lightweight aggregate contributes more in decreasing the thermal conductivity and maintaining the strength than foaming methods.

The following research gaps are also identified from this review:

1. The interaction mechanism of strength development and thermal insulation from the perspective of hydration kinetics should be investigated and clarified.

2. The pore parameters, like the shape and size of various foaming methods, should be characterized and correlated to the thermal insulation and strength of concrete.

3. New lightweight and porous aggregates need to be developed to achieve better insulation and strength of concrete simultaneously. This is because aggregates account for the most significant proportion of concrete, whose properties are greatly determined by the aggregates.

4. It is recommended that the underlying mechanism of the relationship between compressive strength and thermal conductivity be analyzed in future research.

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