Comparison of the Thermal Characteristics of Portland Cement and Geopolymer Cement Concrete Mixes

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Abstract: Concrete is widely used in buildings as a structural and finish material, and mix designs for these applications are well established. The thermal properties of concrete are also embedded in a number of building envelope design strategies, but mix designs to optimize for these performance characteristics are not generally considered. In this study, specific heat capacity, thermal conductivity, and compressive strength of concrete mixes were investigated. It was determined that a broad range of thermal conductivity and specific heat capacity values can be obtained through the adjustment of mix paste percentages. Portland cement (PC) and geopolymer cement concrete (GCC) mixes were compared for this application, with the range of thermal variability found to be greater with concretes that use the geopolymer binder. **DOI: 10.1061/(ASCE)AE.1943-5568.0000240.** © *2017 American Society of Civil Engineers.*

Author keywords: Geopolymer cement concrete (GCC); Specific heat capacity; Thermal conductivity; Compressive strength.

Introduction

Maximizing Thermal Performance of Concrete through Mix Design

The malleability of concrete's performance characteristics is one of its inherent advantages as a construction material. By adjusting a variety of variables including paste percentage, water content, aggregate composition, paste characteristics, and a number of available admixtures, a variety of physical characteristics can be controlled. Typically, concrete used in buildings is divided into two categories: structural and architectural (sometimes called *finish*), with nuanced and exacting mix designs well established through a long development history to create a wide spectrum of strength, durability, and appearance performance within each category.

The binder geopolymer has added a new option to the material palette for concrete design and construction. Compared with portland cement concrete (PCC), geopolymer cement (GC) and geopolymer cement concrete (GCC) have demonstrated superior environmental performance by having a reduced carbon footprint and the potential to incorporate waste stream materials as inputs to production (Weil et al. 2009). They also feature very similar strength and elastic performance (Hardjito and Rangan 2005; Sofi et al. 2007; Tempest et al. 2009) and improved durability compared with PCC (Bakharev 2005; Reddy et al. 2011; Roy et al. 2000; Wallah et al. 2004). Despite these similarities, the physiochemical make-up of GC is very different from that of hydrated portland cement (PC). Therefore, the ability to adjust mix proportions to achieve particular performance characteristics in GCC may be different from PCC. This also gives rise to the possibility that the thermal characteristics (specific heat and thermal conductivity) of the aluminosilicate GC will be substantially different from those of the calcium silicate PC.

The thermal characteristics of concrete are critical to building design and have been availed as both thermal storage and to reduce or enhance thermal movement through and within building envelopes for thousands of years. The public Roman baths built in Ostia almost 2,000 years ago are an example of this use. The Romans used large complex masonry and concrete materials in walls and floors as storage masses for solar heat and as part of a centralized radiant heating system in which heat from a wood fire was moved under the floor and through the walls (Ring 1996). Other cultures developed similar technologies throughout the world during various epochs. In a similar fashion, long before the contemporary concept of insulation, concrete and other mass materials, such as stone, earth, and brick, have constituted the full volume of the building envelopes of a considerable portion of the world's buildings. The high mass envelope provided a small resistance to heat flow but primarily provided thermal comfort by its ability to store and release large quantities of heat with only small changes in temperature (Zhai and Previtali 2010).

Over the last 100 years, the development of discrete materials with low thermal conductivity, usually called *insulation*, have allowed considerable design control over heat movement through building envelopes. Building assemblies and configurations combining mass for thermal storage and dedicated insulation materials for thermal resistance have become common, especially in residential construction. More recently, massive insulated envelope systems suitable for large-scale commercial applications, such as continuously insulated precast concrete panels, have been developed and are gaining in popularity. One such panel featuring two wythes of concrete separated by 16 cm of rigid insulation is shown in Fig. 1. Yet, standard concrete mix design practices focus primarily on strength and durability objectives, and provisions to adjust their thermal characteristics to better suit performance in building envelopes are essentially nonexistent (ACI 1991).

By quantifying energy use through rigorous lifecycle analysis, it has been well established that the greatest proportion of a typical

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building's environmental impact is through its operation (Sartori and Hestnes 2007). Therefore, improving building operational performance will have the most significant effect on its energy and carbon impact. The next step toward more energy-efficient building envelopes is to optimize the thermal characteristics of concrete by manipulating mix designs. This would enable designers to take full advantage of the considerable thermal storage and heat transfer properties (e.g., through embedded hydronics) of concrete while consciously lowering the associated carbon footprint, the current Achilles heel of PCC in the context of sustainable design. The ubiquity with which concrete is used as a major component of the built environment generally and building envelopes specifically leads to the conclusion that there is a compelling rationale for investigating thermal optimization strategies for concrete mix designs in building envelopes.

Affecting the overall thermal characteristics of concrete can be accomplished by altering the proportions of components that have different thermal properties of specific heat (c_p) and thermal conductivity (k). These two properties determine the quantity of heat that may be stored in materials and the rate that it is transferred into and out of the material, respectively. Because various aggregate materials and cements have different values of c_p and k, their relative proportions can be adjusted to change the bulk characteristics of the composite. Further, materials could be specially selected based on their thermal characteristics. Current proportioning practices are related to producing concrete with workable fresh characteristics, desired strength and durability characteristics in the hardened form, and economy of finished product. The quantity of PC proportioned into concrete is limited by economy, required strength, and hydration processes that might affect shrinkage and durability. However, because non-PC binders may deliver a similar mechanical performance with different constraints to proportioning, they may also offer the opportunity to further tailor concrete thermal properties to building climate needs. Through physical testing of a variety of concrete mixes representing different paste percentages for specific heat capacity, thermal conductivity, and compressive strength, this study establishes that considerable variations in thermal performance can be achieved through mix design.

Scope and Significance of Research

Specific heat capacity (c_p) and thermal conductivity (k) of a concrete mix define its thermal performance as part of a building envelope and are essential to modeling and predicting heat transfer. Research presented in this paper had two objectives. The first objective was to experimentally establish the thermal characteristics, specific heat capacity (c_p), and thermal conductivity (k) of GC paste and aggregates. Second, by way of further experimentation, GCC mixes prepared with varying proportions of aggregates were evaluated for their composite thermal characteristics. Additionally, the compressive strength was measured for all mixes. Although structural concrete design depends on more properties than only compressive strength, this measure was selected as an indicator due to its proportionality to other important parameters, such as shear strength and modulus of elasticity.

A set of PCC specimens was prepared for comparison with the GCC materials. The PCC was chosen as a material for comparison because it is the standard used by construction industries worldwide. The significance of investigating GCC is that (1) its considerably lower carbon footprint compared with PCC is well established in the literature (Duxson et al. 2007), and (2) its binder components have distinctly different physical characteristics than those for PCC mixes. Therefore, GCC could have advantages for thermal envelope construction in addition to reduced emissions and mechanical performance.

Fig. 1. Continuously insulated precast wall panel being installed as part of a net zero energy project (image by Clarke Snell)

A small number of studies into the thermal properties of geopolymer pastes and concretes exist in the literature, for example, focusing on adjustments to the aluminosilicate component (Duxson et al. 2006; Subaer and van Riessen 2007) or concerning foamed mixes (Liu et al. 2014), but none deals with a comparison of component mix ratios, as is the case with the present study. The number of studies dealing with thermal conductivity and specific heat of PCCs is larger, but still surprisingly small in relation to the important role concrete plays in the built environment generally and building envelopes specifically. Still, a perusal of this literature leads to the conclusion that the PCC mix of specific heat and thermal conductivity is dependent on core variables, such as aggregate source water/cement ratios, chosen additives (Kim et al. 2003), and especially aggregate source (Chan 2013; Waples and Waples 2004). For this reason, thermal performance comparisons between GCC and PCC mixes seem primarily useful when the mixes in question are equivalent relative to these core variables, as is the case with the current study in which aggregates were identical and other core variables were tightly controlled for both mix types as a group.

Materials and Methods

Fly Ashes

The GCs are formed by dissolving an aluminosilicate in a strong alkaline solution. For this study, coal combustion waste fly ashes

Table 1. Oxide Composition of Fly Ashes Used in GC Mixes

Oxide	% by Mass
SiO_2	56.20
TiO_2	1.46
Al_2O_3	28.00
Fe_2O_3	5.22
MnO	0.02
MgO	1.00
CaO	1.52
Na_2O	0.21
K_2O	2.74
P_2O_5	0.18
Totals	96.55
Loss on ignition	3.32

Table 2. GC Paste Mix Proportions

Component	Quantity (kg/cylinder)
Fly ash	1.87
Sodium silicate	0.46
Sodium hydroxide	0.07
Water	0.13

were the chosen aluminosilicate source. Fly ashes for GCC mixes were sourced from a steam generation station in the southeastern United States. X-ray fluorescence was used to determine the oxide composition, which is reported in Table 1, and shows a similar make-up to ashes frequently used in geopolymer production (Fernandez-Jimenez and Palomo 2003). The ashes were marketed as ASTM Class-F (ASTM 2003).

Aggregates

Most often, the aggregates in concrete are naturally occurring minerals whose thermal characteristics can vary based on geographical changes in geology (Waples and Waples 2004). The aggregates used to prepare both the PC and GC concrete mixes were the same and sized in accordance with ASTM C33 (ASTM 2013). Fine aggregate was silica sand graded for concrete use and coarse aggregate was 9.5 mm crushed granite, both sourced from the southeastern United States quarries. Aggregates were oven dried prior to mixing so that the moisture content of each batch could be more closely controlled. The measured absorption capacity of the aggregates was 0.47 and 4.82% for coarse and fine, respectively.

General Sample Description and Preparation

The PC mixes were prepared in accordance with ASTM C150 (ASTM 2012) with Type I/II PC. The 100% paste mixes had a water/cement ratio of 0.35. In batches containing aggregates, additional water equivalent to the absorption capacity of the aggregates was added to mixes so that each batch would contain the same quantity of free water for hydration after absorption, regardless of the aggregate proportion. Mixes were placed in cylinder forms 75 mm in diameter and 150 mm in depth. After 24 h, all cylinders were demolded and placed in a curing tank containing saturated lime water (3 g/L hydrated lime) for 28 days before being further processed for testing, as described next.

The GC pastes were prepared with fly ash and an activating solution mixture of sodium silicate, sodium hydroxide, and water with the proportions shown in Table 2. Mixes were placed in cylinder forms 75 mm in diameter and 150 mm deep. Two mix batches were

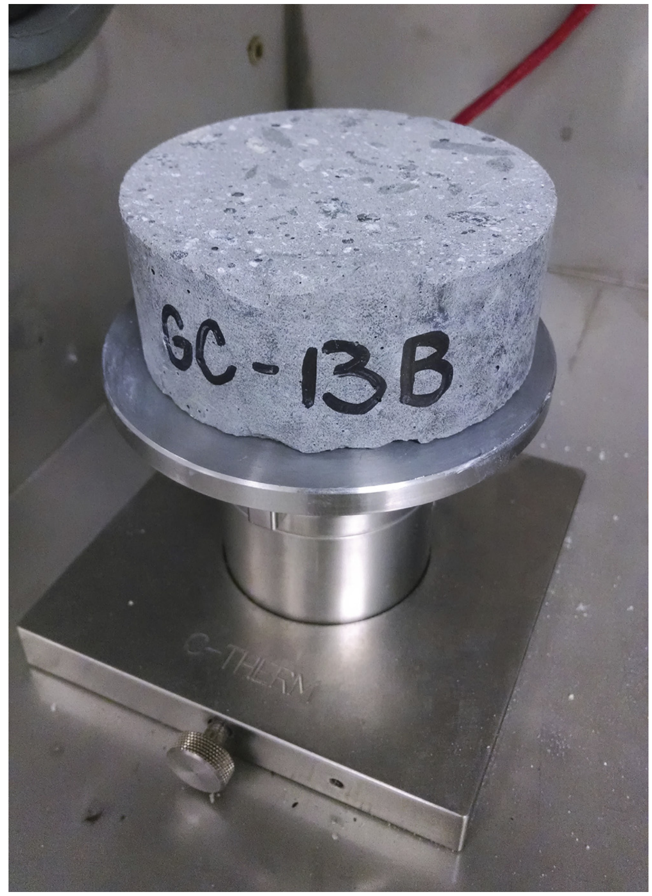

Fig. 2. GCC sample on TCi thermal sensor

prepared. In the first batch, no additional water was added to the oven-dried aggregate. In the second batch, water was added in proportions calculated to saturate the aggregate according to their measured absorption capacity. After placement in cylinders, mixes were set on a vibrating table for 1 min and then aged at room temperature for 2 days before being cured in an oven at 75°C for 48 h.

Specific Heat Capacity

It has been well established that the c_p of a composite such as concrete can be accurately described as a linear combination of the heat capacity of its discrete (aggregate) and continuous (paste) elements (Bergman et al. 2011; Waples and Waples 2004). Aggregate and paste elements used in the concrete mixes considered for this study were prepared and tested as described in this section with the results used to derive the specific heat capacity of a concrete mix (composite) using the following equation:

$$c_{\text{composite}} = \sum_{i=1}^{x} c_i m_i \tag{1}$$

where $c_{\text{composite}}$ = specific heat of composite; c_x = specific heat of material x; and m_x = mass of material/mass of composite x.

Samples were prepared and tested through differential scanning calorimetry in accordance with ASTM E1269 (ASTM 2005b). In this method, a crucible containing the sample and an empty crucible are heated at a controlled rate in a controlled atmosphere, and the difference in heat flow between the two is measured as a function of time and temperature change.

The PC and GC pastes were prepared as previously described. These pastes, as well as samples of fine and coarse aggregate, were then ground separately in a ring mill, creating powders with particle sizes of 0.7 mm or less. These powders were then oven dried at 105°C for 24 h and stored in airtight containers until testing. Samples were placed in 270-μL aluminum crucibles and tested in a SENSYS evo TG-DSC apparatus (Setaram, Inc., Hillsborough, New Jersey) over a temperature range of −50 to 50°C. The calibration standard used was synthetic sapphire.

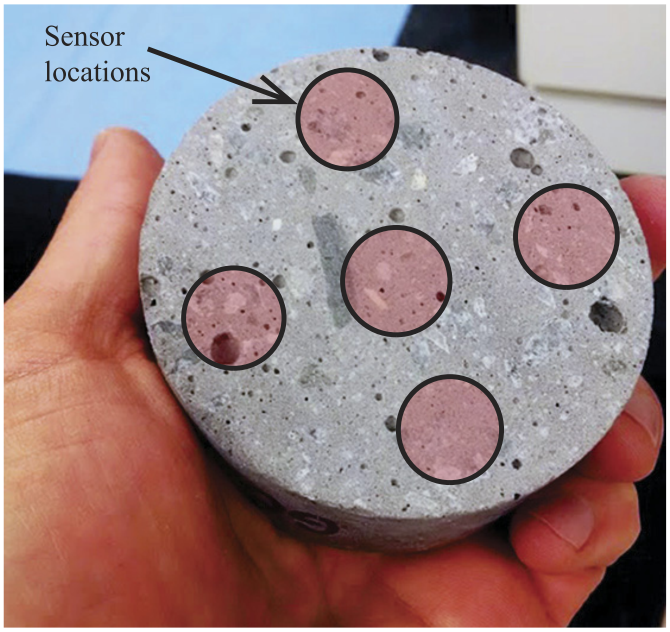

Fig. 3. Sampling pattern for thermal conductivity testing; the number of locations was chosen based on the size of the sensor to ensure no overlap between measurements

Thermal Conductivity

Unlike specific heat capacity, heat flow through a composite is much more difficult to model based on the characteristics of the discrete components. For this study samples representing a variety of paste percentages were prepared, and the thermal conductivity of each sample was determined experimentally. Paste percentage is defined as $P/(P+A)$, where P = mass of the paste; and A = sum of the masses of all aggregates in a given concrete mix.

The PCC and GCC samples were prepared having the following paste percentages: 1.0, 0.85, 0.65, 0.45, 0.25, 0.15, and 0.10. The aggregate blend was comprised of a 50/50 mix of fine and coarse aggregates. A wet saw was used to cut three 40-mm-thick disks out of each cylinder. These samples were then conditioned in accordance with ASTM C870 (ASTM 2011) by being stored in open containers for two weeks in a climate-controlled environment with ambient conditions approximating 20°C and 50% relative humidity.

Samples were tested with a thermal conductivity analyzer [TCi version 2.0 (C-Therm Technologies Ltd., Fredericton, NB, Canada)] using the modified transient plane source method in which the rate of temperature change is measured by a sensor and used to calculate the resistance of the sample to heat flow. The middle 40-mm sample of the three cut from each cylinder was tested in a thermal chamber at 20°C and then a subset at 40°C (Fig. 2). Five test locations were selected on each disk using a layout pattern, as illustrated in Fig. 3, to collect a representative sampling of aggregate-dominated and paste-dominated regions. This methodology was chosen because the size of the coarse aggregate in the mixes is large compared with the size of the sensor; therefore, each test location may have a different thermal conductivity.

Six measurements were made at each of the five locations, and the mean value of these six was taken as the thermal conductivity of the given location. In turn, the mean of these five measurements was reported as the thermal conductivity of the sample.

Table 3. Mean Measured Specific Heat Values of Aggregates and Cement Pastes

	c_p (J/kg·K)				Aggregate c_p/paste c_p ratio	
Temperature (°C)	Fine aggregate silica sand	Coarse aggregate granite	PC paste	GC paste	Fine/PC paste	Fine/GC paste
−50	498.4	491.1	686.4	549.9	0.73	0.91
0	627.2	623.3	828.5	685.6	0.76	0.91
20	666.9	663.5	877.9	730.1	0.76	0.91
50	735.6	722.1	931.3	790.8	0.79	0.93

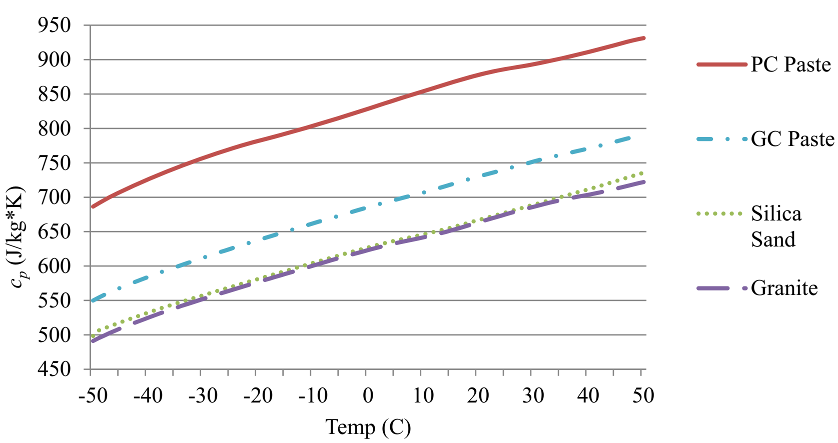

Fig. 4. Specific heat of concrete components as measured over a range of ambient temperatures

Compressive Strength

Cylinders from each batch described earlier for the thermal conductivity testing were analyzed for compressive strength in accordance with ASTM C39 (ASTM 2005a). After curing for 28 days in a water bath, a universal testing machine (UTM) was used to apply a compressive axial force until failure, and then the compressive strength of the sample was calculated per the standard. Three cylinders of each paste percentage were tested in this fashion.

Results

General Observations

The thermal testing temperature range (−50 to 50°C) for this study was chosen to approximate temperatures that materials in a building envelope might encounter. Within this range, the relationship of c_p and k values to changes in temperature were essentially linear, which means that there were no data spikes or troughs. These results match published trends for specific heat and thermal conductivity in a wide variety of materials that do not experience a component change of phase through the testing temperature range. There are a number of examples of studies that establish this trend in PCC mixes (Khan 2002).

Specific Heat Capacity

Discrete Components

The measured specific heat of discrete concrete constituents at −50, 0, and 50°C are presented in Table 3 and Fig. 4. Fig. 4 provides data that were measured over the range of −50 to 50°C in 1°C increments. Table 3 provides a few discrete values at −50, 0, 20, and 50°C from the full data set. Fine and coarse aggregate sample mean values were essentially identical, ranging from 500 J/kg·K at −50°C to 735 J/kg·K at 50°C. At 20°C both measured about 665 J/kg·K. Paste values were higher than aggregates with the differences decreasing as temperatures rose. The GC pastes ranged from 9.5% higher than aggregates at −50°C to 7% higher at 50°C. The PC pastes ranged from 27.5% higher than aggregates at −50°C to 21% higher at 50°C. The ratio of c_p for fine aggregate to PC paste was lower than the ratio of fine aggregate to GC paste.

Standard deviations for PC paste, coarse aggregate, and GC paste were 2, 6, and 9, respectively, with value ranges (minimum/maximum) between 1 and 4%. Silica sand fine aggregate samples had a wider range with a standard deviation of 26 and min/max ranges of 11%. Although this result is worth noting, all values were within published ranges for similar materials (Waples and Waples 2004).

Concrete Mixes

By using the discrete component specific heat measurements and Eq. (1), the specific heat of aggregate-binder systems was estimated and is shown in Table 4 and Fig. 5. For both mix types specific heat was highest with the 100% paste mixes and decreased in linear fashion as aggregate percentages increased. The 100% PC pastes had a c_p of 877.9 J/kg·K, which is 17% higher specific heat than GC pastes. At a paste percentage of 10% the two concrete types had almost identical specific heat values. Specific heat of the mixes decreases as the ambient temperature increases, but the relationship describing the rate of change relative to paste percentage was essentially identical across temperature ranges considered in this study. The ratio of specific heat of GCC to that of PCC (Table 4) illustrates that although GC paste has a significantly lower c_p than PC paste, as the proportion of aggregate in the concrete increases, the c_p of the PCC becomes very similar to that of GCC. This relationship is also clear in Fig. 5.

Table 4. Calculated Specific Heat of Concrete Mixes Using Eq. (1) and Measured Mean Values of Discrete Components at 20°C

	c_p (J/kg·K)		
Paste (%)	PCC	GCC	GCC/PCC (%)
100	877.9	730.1	83
85	846.0	720.3	85
65	803.4	707.4	88
45	760.9	694.4	91
25	718.4	681.4	95
15	697.1	674.9	97
10	686.5	671.7	98

Thermal Conductivity

As shown in Table 5 and Fig. 6, the trend for thermal conductivity was the opposite of that for specific heat. The 100% paste mixes of both concrete types had the lowest k values and increased in a generally linear fashion as aggregate percentage rose. The PC pastes had approximately twice the thermal conductivity of GC pastes. As the aggregate percentage in the mix increased, the relative difference in thermal conductivity between GCC and PCC mixes decreased. GCC mortars with less than 25% paste content had too

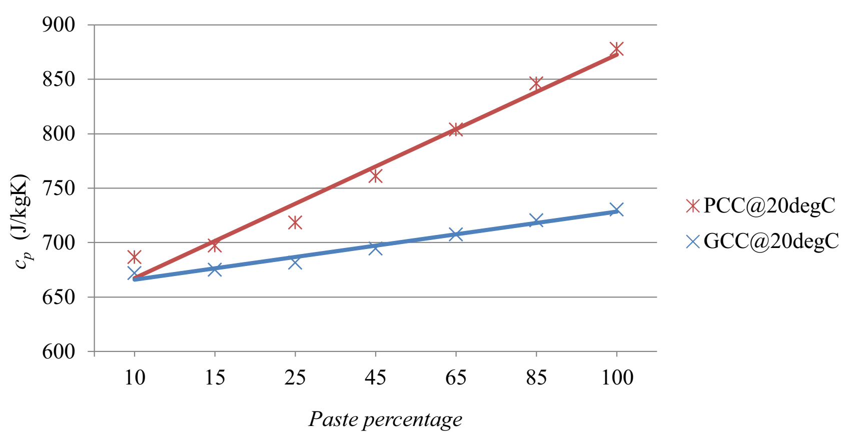

Fig. 5. Specific heat capacity of concrete mixes at 20°C

many voids to allow for k value measurements with the sensor used for this study. The GCC mixes prepared with saturated aggregate had lower thermal conductivity than those with oven dry aggregate.

As shown in Fig. 7, k values were a function of temperature, decreasing as temperature increased. This trend was more pronounced with GC paste than with PC paste. When the ambient temperature was increased from 20 to 40°C, thermal conductivity of the PC paste dropped by 19%, whereas the GC paste fell 38%.

Compressive Strength

As shown in Table 6 and Fig. 8, PCC mixes had higher compressive strengths when compared with GCC mixes with the same paste percentage. Pastes had higher strengths than mixes with aggregates. The GCC mixes with oven dry aggregate (and therefore less water) were stronger than mixes with saturated surface dry aggregate. This trend increased as aggregate percentage increased. Compared with GCC mixes with saturated aggregate, oven dry aggregate GCC mixes were 9% stronger as pastes, 20% stronger with 55% aggregate, and 67% stronger with 85% aggregate content. Most of the GCC mixes tested had a compressive strength of between 22 and 60 MPa, which is suitable for a range of structural and nonstructural applications in building construction.

Analysis and Discussion

The cementitious material in concretes provides the strength in the hardened state and contributes workability in the fresh condition. However, an excess of PC might cause a range of problems related to shrinkage and cost of production (the cost of PC paste is at least 10 times that of aggregate). Therefore, traditional concrete mix design strategies are processes of proportioning cement and aggregates with an emphasis on economizing cement as much as possible, while still achieving the strength and workability (flow, slump, finishability, etc.) required for the given application. Even if costs were not a factor, there are also physical limits on feasible paste percentages for PCCs. Volume changes of hydration products and loss

Table 5. Mean Measured Thermal Conductivity Values of Concrete Mixes at 20°C

Paste (%)	k (W/m·K) PCC	GCC1[a]	GCC2[b]	GCC1/PCC (%)	GCC2/PCC (%)
100	1.07	0.57	0.47	54	44
85	1.29	0.75	0.59	58	46
65	1.25	0.92	0.88	74	71
45	1.48	1.02	0.89	69	61
25	1.56	1.26	0.92	81	59
15	1.62	1.49	—	92	—
10	1.63	—	—	—	—

[a]Dry aggregate.
[b]Saturated surface dry aggregate.

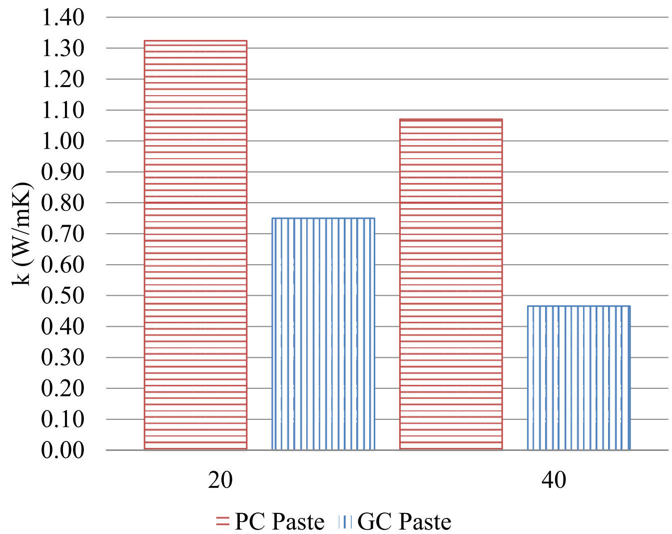

Fig. 7. Thermal conductivity of 100% cement pastes at 20 and 40°C

Table 6. Measured Compressive Strength of Concrete Mixes

Cement (%)	GCC1[a] (MPa)	GCC2[b] (MPa)	PCC (MPa)	GCC1/PCC (%)	GCC2/PCC (%)	GCC2/GCC1 (%)
100	53.67	48.79	60.45	89	81	91
85	43.08	38.58	57.15	75	67	90
65	35.74	31.54	55.94	64	56	88
45	31.28	25.09	41.69	75	60	80
25	21.95	12.19	33.80	65	36	56
15	10.89	3.61	29.16	37	12	33
10	0.00	1.73	12.67	—	14	—

[a]Dry aggregate.
[b]Saturated surface dry aggregate.

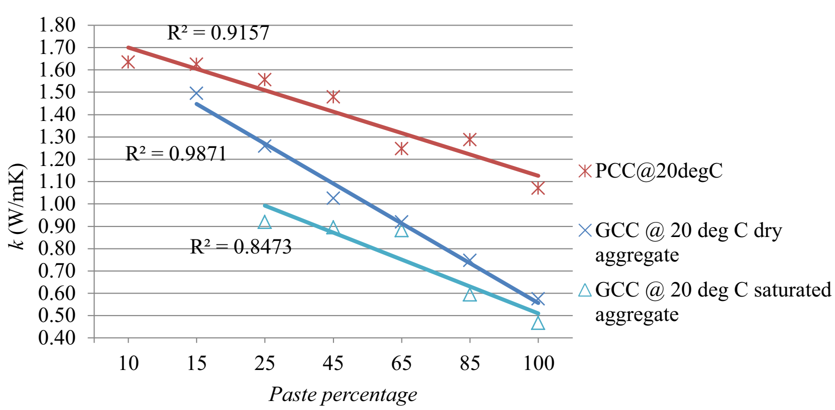

Fig. 6. Thermal conductivity of concrete mixes at 20°C

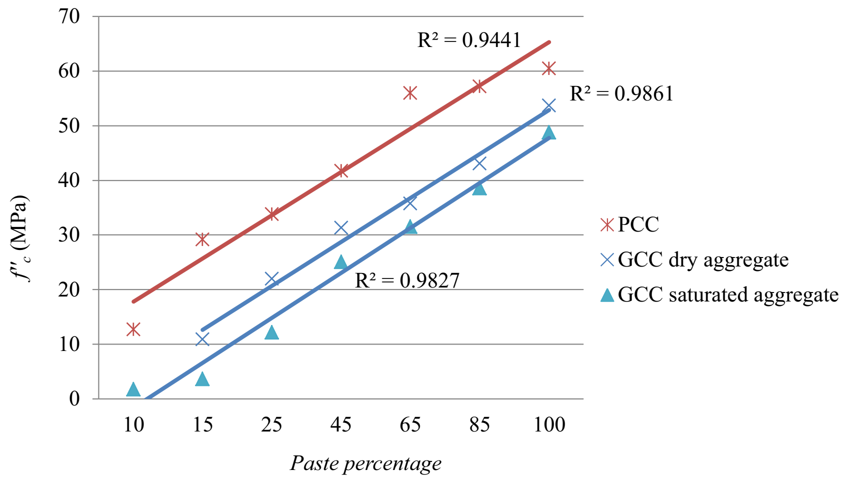

Fig. 8. Compressive strength of concrete mixes at 20°C

of water from mix pore structure through the curing process cause shrinkage. Some percentage of aggregates are required in the mix to restrain shrinkage cracking, which can range in effect from an aesthetic nuisance to the cause of durability problems and, in the rare case, structural failure.

Because aggregates used for both mix types can be identical, price differences between GCC and PCC are confined to the binding cements. Cost comparisons between geopolymers and PCs are inconclusive in the literature because they depend on many factors that are not easily generalized. An Australian study found that GC pricing in that country fell between 7% lower and 39% higher than PC (McLellan et al. 2011). In Fig. 9, the approximate material costs to produce GCC and PCC on a laboratory scale are reproduced from Snell (2014) and are reflective of the cost ratios for the mixes produced for this study. In this case, GC proved to be over double the price of PC. For mixes that have similar compressive strength, the cost differences are greater. For instance, the GCC mix with 85% paste content and the PCC mix with 45% paste content both developed a compressive strength of approximately 43 MPa. As is shown in Fig. 9, the cost to manufacture this mix is approximately \$56/t for PCC and \$198/t for GCC. In both cases, as aggregates are added to mixes, the cost of materials becomes more similar. It is important to acknowledge that GCC has not been widely commercialized; therefore, it has not benefited from the efficiencies that will come with producing it on a large scale.

In Fig. 10, the economical zone represents the range of concrete mixes defined as typical by the Portland Cement Association and encompasses most of the concrete being poured as part of buildings and other hardscape (Kosmatka and Panarese 2002). As shown in Fig. 10, there is only a potential to adjust thermal performance parameters of PCC by less than 5% for both specific heat and thermal conductivity within this paste percentage range. Although there are many factors that determine whether a mix will have sufficient durability and strength for its specific application, the feasible zone in Fig. 10 is an approximation of paste percentages that could be applied from a mechanical properties standpoint, discounting cost.

In contrast to PCC, a basic description of the make-up of the GC mixes used in this study can be found in an earlier section of this paper. The main ingredient of GC, an alumina silicate, can be sourced from many raw materials including certain naturally occurring clays and industrial by-products, such as burnt rice husks or, as in the case of the mixes used in this study, fly ash produced as a waste product in coal combustion. Although the ashes are not expensive,

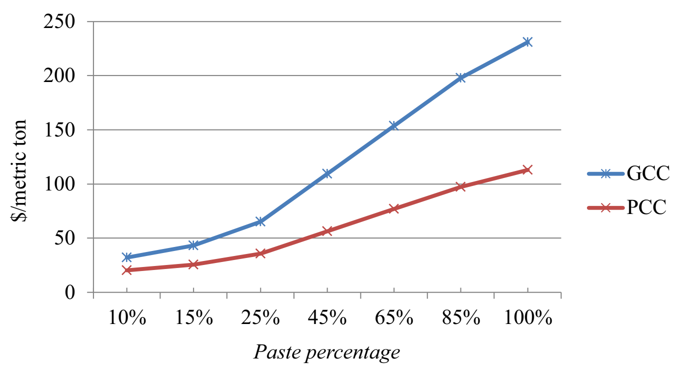

Fig. 9. Cost of concrete mixes (Snell 2014)

the materials required to activate their cementitious properties are, as is apparent in Fig. 9. With costs aside, the feasible zone for GCC encompasses all paste percentages covered in this study (Fig. 11). In other words, mixes between 15 and 100% paste content are physically feasible. This is because of limited autogenous shrinkage observed in GCC and insusceptibility to durability challenges that are typical of PC binders. The possibility of incorporating more GC paste provides the full thermal design range expressed by the data, as summarized in Figs. 5 and 6. Table 7 shows that the combined economical and feasible zones for GCC mixes allow for a range of about 8% in specific heat values and over 217% in thermal conductivity values. This degree of adjustability for these properties could make them both variables to be manipulated in thermal envelope design. It is also apparent that higher thermal conductivity is associated with lower paste content and, therefore, lower strength. This could also have implications for selecting appropriate usage locations within the building envelope.

To make a baseline for comparison, the 15% paste PCC mix, which was found to have a compressive strength of 29 MPa (Table 6), may be used. Such a mix would be typical of general purpose structural concrete; therefore, it is representative of the thermal performance of concrete mixes used presently in building envelopes. As seen in Table 7, the 15% paste mix would have a specific heat capacity of 697.1 J/kg·K and a thermal conductivity of 1.62 W/m·K.

Because this standard baseline mix has the highest k value of all mixes, GCC materials with k values more than 2 times lower (or R

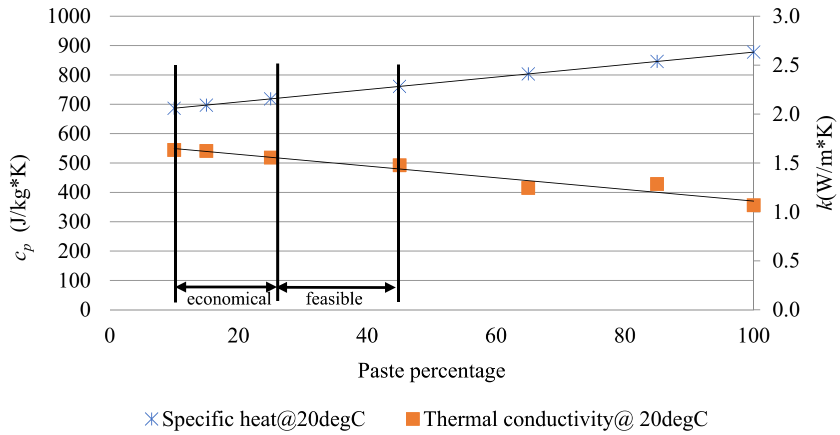

Fig. 10. c_p and k of PCC mixes at 20°C

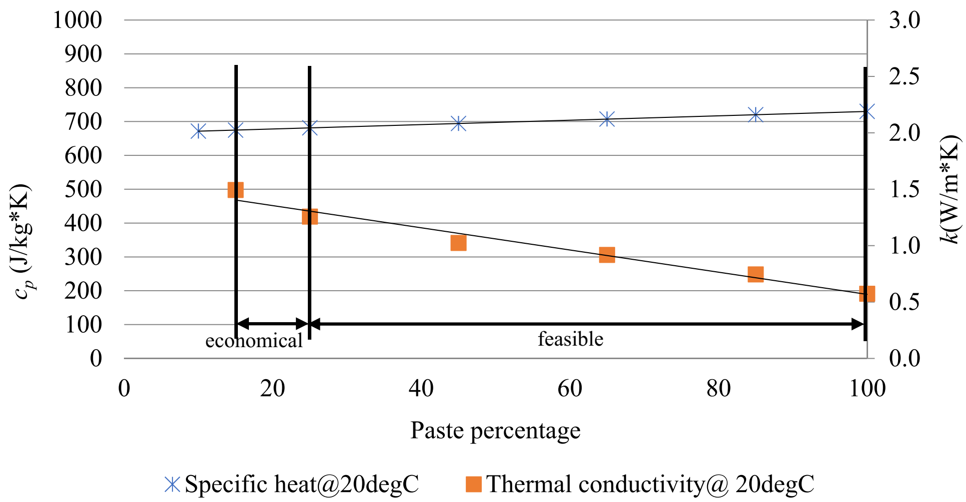

Fig. 11. c_p and k of GCC mixes at 20°C

Table 7. Thermal Performance Ranges of Feasible Concrete Mixes in This Study

	Maximum/minimum		Range (low to high)	
Mix [*P*/*A* (%)]	c_p (J/kg·K)	k (W/m·K)	c_p [% (J/kg·K)]	k [% (W/m·K)]
PCC 15	697.1	1.62	9.1 (63.8)	9.4 (0.14)
PCC 45	760.9	1.48		
GCC 15	674.9	1.49	8.2 (55.2)	217 (1.02)
GCC 100	730.1	0.47		

values more than 2 times higher) than that of the norm can be produced through paste percentage adjustment. Although these k values would not bring associated concrete mixes into the realm of current low conductivity materials used as insulation in building assemblies, such performance malleability could be of value for adjusting the rate of thermal release for thermal storage masses, adjusting thermal conductivity profiles of embedded hydronics, increasing fire protection, or to define a baseline mix for existing concrete thermal conductivity adjustment methodologies, such as foaming. Although less impressive as a ratio, the fact that GCC mixes with c_p values 5% higher and 3% lower than the norm could be produced would further augment the range of outcomes for the envelope adjustments previously mentioned.

One example of this customization potential is the wall section pictured in Fig. 12. The interior concrete wythe is conceived as having two distinct thermal zones. The zone closest to the insulation contains embedded hydronics and is involved in the thermal transfer of heat in and out of the wall. In this area, concrete having higher thermal conductivity, such as the mixes with low paste percentage, are desirable. The zone closest to the interior is intended for thermal storage. In this area, mixes that balance higher specific heat and higher thermal conductivity are desirable, such as the mixes with moderate paste percentage. Using existing precast concrete methodologies, each zone could be made up of a discrete concrete mix designed to optimize the specific intended thermal performance profile. The actual mix designs could not be generalized and would be a function of many variables including local climate and microclimate, building siting, building size and form, and many others. As a result, exacting project-specific performance modeling and design inputs would be needed. Such an exercise is outside the scope of this current study, but the results presented here suggest that such modeling is worth investigating because ranges of thermal properties for concrete mixes are potentially significant.

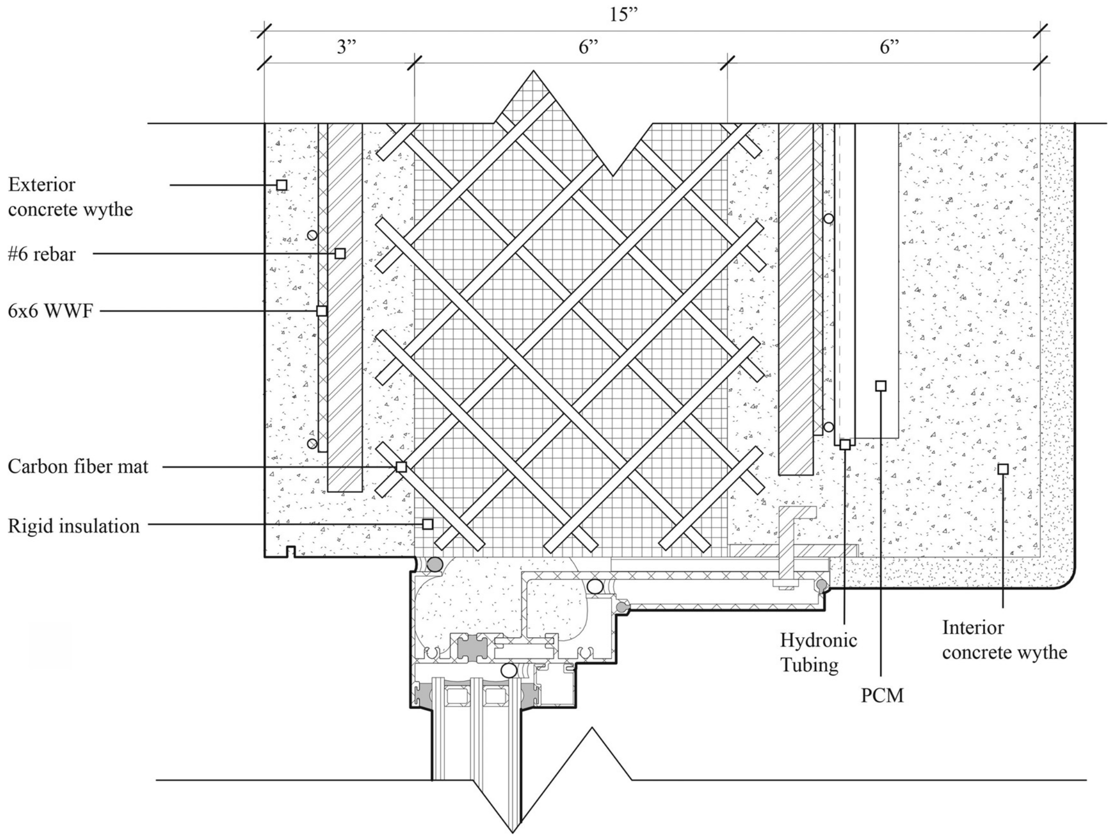

Fig. 12. Section of a high-performance precast concrete wall system under study at the University of North Carolina, Charlotte (Note: PCM = phase change material)

Although the feasible zone identified in the previous analysis is wholly a practical consideration, the boundaries of the economical zone are also important to discuss. Mixes emulating paste percentages in the economical zone for GCC would be more expensive than their PCC counterparts if manufactured using the material sourcing used for this study (Snell 2014). However, although the current production costs of GCC are high in the United States, this need not be the case. The expense of GC is a result of the reagents, sodium silicate and sodium hydroxide. Sodium silicate in particular is responsible for more than 85% of the materials cost to manufacture the GCs for this study (Snell 2014). This is true only because GCs are still mostly products of the research laboratory, even though they have been in development for several decades. As such, they have not yet been value engineered to compete in the market. If GCs are to compete with PCs, then soluble silicate and alkalinity alternatives must be identified that lead to costs typical of high mass materials produced at the scale of concretes used in buildings.

The largest mass fraction of the cementitious portion of GCC is the fly ash. Fly ash stored in ponds and landfills is an acknowledged environmental hazard. At the time of this writing one of the largest fly ash spills in history occurred in the southeastern United States (Morrison 2014). The EPA has recently released guidelines that encourage the beneficial use of fly ashes in concrete applications (EPA 2014). Fly ash is an abundant, inexpensive commodity because it is a waste product that often requires no additional processing for use in concrete than what is typical to prepare it for disposal. Therefore, if reagent production can be successfully value engineered, fly ash GCs will have a cost advantage over PC, the economy of which is linked closely to energy prices because kiln firing of limestone is required for PC production.

Conclusions: Concrete Mix Design to Optimize Thermal Performance

Results presented from this study indicate that the specific heat of geopolymer paste is lower than the specific heat of PC paste and more similar to the specific heat of granite and silica sand. The thermal conductivity of geopolymer paste was also found to be significantly lower than that of PC paste. GCC mixes with acceptable compressive strength for structural and cladding applications showed an adjustment range (high to low) of about 8% in specific heat values and over 217% in thermal conductivity.

When discussing general characteristics, such as the fact that concrete is dense and therefore a good storage medium for heat, such nuances are unimportant. However, in the context of investigations attempting to optimize thermal properties of high-performance building envelopes using concrete, these differences become more meaningful. The data in this study establish a clear difference in thermal characteristics when comparing cement pastes with aggregates. This relative difference is greater with concretes that use geopolymer binders. Such a relationship could be used to optimize thermal mix design through careful aggregate selection based on measured c_p and k values and, more fundamentally, through the adjustment of paste percentage in concrete mixes. This will allow the further integration of structure and building energy performance in design. It can also add energy use reduction strategies to the existing options available to designers.

As a first step toward determining whether this fact can be exploited to generate meaningful thermal benefits in building envelopes using concrete, at least four areas of inquiry need to be pursued, that is, (1) quantification of potential benefits for a variety of building envelope scenarios through modeling, (2) identification of the portion of the potential paste percentage mixes that are practical for implementation, (3) detailed comparison of PCC and GCC thermal mix performances in this context, and (4) physical testing of built assemblies in a guarded hot box to allow for test results to be compared with modeled results.

As a mix design methodology that considers thermal characteristic development, it will become important to begin to classify aggregates based on c_p and k values as well as to investigate production-related testing methodologies that would allow for mix-specific thermal testing at the batch plant. Such a testing regimen would be analogous to the present practice of breaking cylinders to corroborate mix compressive strength. The methodology would also need to incorporate other constraints and limitations to very high and very low paste percentages, such as strength parameters other than compressive strength, durability, and economy.

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Notation

The following symbols are used in this paper:

cp = specific heat capacity (J/kg·K);

k = thermal conductivity (W/m·K); and

$P/(P+A)$ = percentage paste of the sum of the masses of paste (P) and all aggregate (A) components in a concrete mix.

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