CONCRETE PAVEMENT

CPTP

TECHNOLOGY PROGRAM

Geopolymer Concrete

Geopolymer concrete—an innovative material that is characterized by long chains or networks of inorganic molecules—is a potential alternative to conventional portland cement concrete for use in transportation infrastructure construction. It relies on minimally processed natural materials or industrial byproducts to significantly reduce its carbon footprint, while also being very resistant to many of the durability issues that can plague conventional concrete. However, the development of this material is still in its infancy, and a number of advancements are still needed. This TechBrief briefly describes geopolymer concrete materials and explores some of their strengths, weaknesses, and potential applications.

INTRODUCTION

Geopolymer materials represent an innovative technology that is generating considerable interest in the construction industry, particularly in light of the ongoing emphasis on sustainability. In contrast to portland cement, most geopolymer systems rely on minimally processed natural materials or industrial byproducts to provide the binding agents. Since portland cement is responsible for upward of 85 percent of the energy and 90 percent of the carbon dioxide attributed to a typical ready-mixed concrete (Marceau et al. 2007), the potential energy and carbon dioxide savings through the use of geopolymers can be considerable. Consequently, there is growing interest in geopolymer applications in transportation infrastructure.

Although geopolymer technology is considered new, the technology has ancient roots and has been postulated as the building material used in the construction of the pyramids at Giza as well as in other ancient construction (Davidovits 1984; Barsoum and Ganguly 2006; Davidovits 2008). Moreover, alkali-activated slag cement is a type of geopolymer that has been in use since the mid-20th century.

WHAT IS A GEOPOLYMER?

The term geopolymer was coined by Davidovits in 1978 to represent a broad range of materials characterized by chains or networks of inorganic molecules (Geopolymer Institute 2010). There are nine different classes of geopolymers, but the classes of greatest potential application for transportation infrastructure are comprised of aluminosilicate materials that may be used to completely replace portland cement in concrete construction (Davidovits 2008). These geopolymers rely on thermally activated natural materials (e.g., kaolinite clay) or industrial byproducts (e.g., fly ash or slag) to provide a source of silicon (Si) and aluminum (Al), which is dissolved in an alkaline activating solution and subsequently polymerizes into molecular chains

TechBrief

The Concrete Pavement Technology Program (CPTP) is an integrated, national effort to improve the long-term performance and cost-effectiveness of concrete pavements. Managed by the Federal Highway Administration through partnerships with State highway agencies, industry, and academia, CPTP's primary goals are to reduce congestion, improve safety, lower costs, improve performance, and foster innovation. The program was designed to produce user-friendly software, procedures, methods, guidelines, and other tools for use in materials selection, mixture proportioning, and the design, construction, and rehabilitation of concrete pavements.

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and networks to create the hardened binder. Such systems are often referred to as alkali-activated cements or inorganic polymer cements.

As stated by Rangan (2008), "the polymerization process involves a substantially fast chemical reaction under alkaline conditions on silicon-aluminum minerals that results in a three-dimensional polymeric chain and ring structure…." The ultimate structure of the geopolymer depends largely on the ratio of Si to Al (Si:Al), with the materials most often considered for use in transportation infrastructure typically having an Si:Al between 2 and 3.5 (Hardjito et al. 2004; Davidovits 2008). This type of geopolymer will take one of the following three basic forms (where "sialate" is an abbreviation for silicon-oxo-aluminate) (Davidovits 2008):

- Poly (sialate) Si:Al = 1, which has [-Si-O-Al-O-] as the repeating unit.
- Poly (sialate-siloxo) Si:Al = 2, which has [-Si-O-Al-O-Si-O-] as the repeating unit.
- Poly (sialate-disiloxo) Si:Al = 3, which has [-Si-O-Al-O-Si-O-Si-O-] as the repeating unit.

Although the mechanism of polymerization is yet to be fully understood, a critical feature is that water is present only to facilitate workability and does not become a part of the resulting geopolymer structure. In other words, water is not involved in the chemical reaction and instead is expelled during curing and subsequent drying. This is in contrast to the hydration reactions that occur when portland cement is mixed with water, which produce the primary hydration products calcium silicate hydrate and calcium hydroxide. This difference has a significant impact on the mechanical and chemical properties of the resulting geopolymer concrete, and also renders it more resistant to heat, water ingress, alkali–aggregate reactivity, and other types of chemical attack (Davidovits 2008; Lloyd and Rangan 2009).

Conceptually, the formation of geopolymers is quite simple. In the case of geopolymers based on aluminosilicate, suitable source materials must be rich in amorphous forms of Si and Al, including those processed from natural mineral and clay deposits (e.g., kaolinite clays) or industrial byproducts (e.g., low calcium oxide ASTM C618 Class F fly ash or ground granulated blast furnace slag) or combinations thereof. In the case of geopolymers made from fly ash, the role of calcium in these systems is very important, because its presence can result in flash setting and therefore must be carefully controlled (Lloyd and Rangan 2009). The source material is mixed with an activating solution that provides the alkalinity (sodium hydroxide or potassium hydroxide are often used) needed to liberate the Si and Al and possibly with an additional source of silica (sodium silicate is most commonly used).

The temperature during curing is very important, and depending upon the source materials and activating solution, heat often must be applied to facilitate polymerization, although some systems have been developed that are designed to be cured at room temperature (Hardjito et al. 2004; Davidovits 2008; Rangan 2008; Tempest et al. 2009). Figure 1, for example, shows the compressive strength of two geopolymer mixtures, illustrating the importance of curing temperature on 7-day strength development (Hardjito et al. 2004).

EXISTING APPLICATIONS

To date, there are no widespread applications of geopolymer concrete in transportation infrastructure, although the technology is rapidly advancing in Europe and Australia. One North American geopolymer application is a blended portland-geopolymer cement known as Pyrament® (patented in 1984), variations of which continue to be successfully used for rapid pavement repair. Other portland-geopolymer cement systems may soon emerge. In addition to Pyrament®, the U.S. military is using geopolymer pavement coatings designed to resist the heat generated by vertical takeoff and landing aircraft (Hambling 2009).

In the short term, there is potential for geopolymer applications for bridges, such as precast structural elements and decks as well as structural retrofits using geopolymer-fiber composites. Geopolymer technology is most advanced in precast applications due to the relative ease in handling sensitive materials (e.g., high-alkali activating solutions) and the need for a controlled high-temperature curing environment required for many current geopolymer

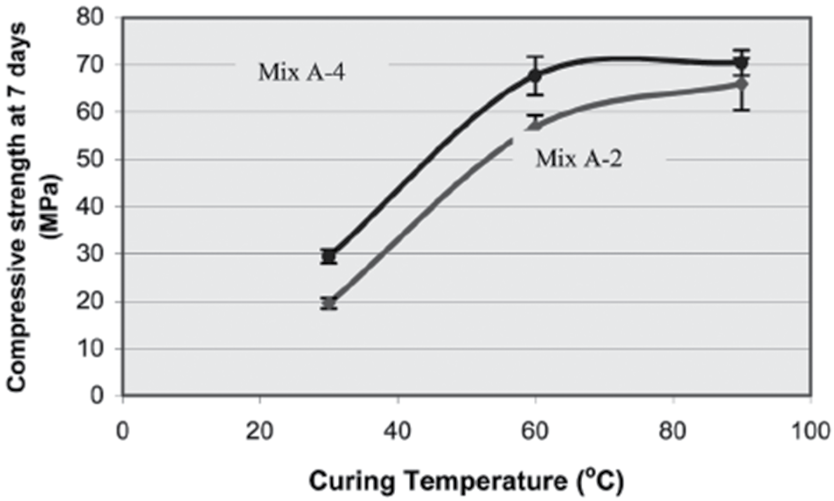

Figure 1. Effect of curing temperature on 7-day compressive strength for two geopolymer concretes. (Hardjito et al. 2004, p. 469, © 2004 American Concrete Institute. Reprinted by permission.)

systems. To date, none of these potential applications has advanced beyond the development stage, but the durability attributes of geopolymers make them attractive for use in high-cost, severe-environment applications such as bridges. Other potential near-term applications are precast pavers and slabs for paving.

CURRENT LIMITATIONS

Although numerous geopolymer systems have been proposed (many are patented), most are difficult to work with and require great care in their production. Furthermore, there is a safety risk associated with the high alkalinity of the activating solution, and high alkalinity also requires more processing, resulting in increased energy consumption and greenhouse gas generation. In addition, the polymerization reaction is very sensitive to temperature and usually requires that the geopolymer concrete be cured at elevated temperature under a strictly controlled temperature regime (Hardjito et al. 2004; Tempest et al. 2009; Lloyd and Rangan 2009). In many respects, these facts may limit the practical use of geopolymer concrete in the transportation infrastructure to precast applications.

Considerable research is under way to develop geopolymer systems that address these technical hurdles, creating a low embodied energy, low carbon dioxide binder that has similar properties to portland cement. In addition, current research is focusing on the development of user-friendly geopolymers that do not require the use of highly caustic activating solutions.

FUTURE DEVELOPMENTS

User-friendly geopolymer cements that can be used under conditions similar to those suitable for portland cement are the current focus of extensive worldwide research efforts. These cements must be capable of being mixed with a relatively low-alkali activating solution and must cure in a reasonable time under ambient conditions (Davidovits 2008). Until such cements are developed, geopolymer applications in transportation infrastructure will be limited. The production of versatile, cost-effective geopolymer cements that can be mixed and hardened essentially like portland cement would represent a "game changing" advancement, revolutionizing the construction of transportation infrastructure.

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