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Bond strength of PCC pavement repairs using metakaolin-based geopolymer mortar

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ABSTRACT

In order to use geopolymer mortar as a pavement repair material, a splitting test and a slant shear test are performed to characterize the bond strength of the geopolymer and conventional cement mortar interfaces. Effect of curing time, degradation of the cement mortar under different acid conditions on the bond strength of geopolymer with conventional cement mortar, and comparison of the metakaolin geopolymer with other pavement repair materials are analyzed. It was found that curing time affects the interface bond strength greatly. Metakaolin geopolymer reaches 80% of its 28 day strength in 3 days curing, but shows low strength in 24 h curing. Curing temperature affects the strength of metakaolin geopolymer, however metakaolin geopolymer cured in ambient temperature and the bond strength of 3 days curing through splitting and slant shear tests reaches 3.63 MPa and 16.32 MPa, respectively. Degradation of cement mortar negatively affects the bond strength of geopolymer and conventional cement mortar. Possibility of using metakaolin geopolymer as a repair material is discussed by comparison of this experimental result with these of other repair materials.

1. Introduction

Cement is the world's most used construction binder material [1]. Cement production emits large amounts of CO_2 [2], and consumes significant amount of energy. Production of one ton of Portland cement releases one ton of CO_2 into the atmosphere [3]. It is a common viewpoint that finding an alternative material to the Portland cement is imminent. On the other hand, geopolymer is a new construction material which could be produced by the chemical action of inorganic molecules, without using any Portland cement. The geopolymer binder could be produced through chemical reaction between alumino-silicate materials such as fly ash or metakaolin that are rich in SiO_2 and Al_2O_3 and alkaline solutions such as Sodium Hydroxide or Sodium Silicate. Fly ash is a by-product of burnt coal that could be obtained from the thermal power plant, and it is readily available worldwide [4]. Metakaolin is produced by heating kaolin (a natural clay) at 750 °C, could be produced in a large quantity with homogeneous properties, and is considered environmentally friendly compared to Portland cement [5]. Metakaolin has been become the preferred alumino-silicate material among researchers [6–8] due to its high rate of dissolution in the reactant solution, ability to manufacture with same homogenous properties, even though it needs extensive energy to produce. It was recorded about 300,000 tonnes of locally produced calcined clay (metakaolin) were used in Amazon basin in 1960s [9].

Davidovits found the geopolymer after the reaction between alkali and source material in 1970's [10]. Shortly after Davidovits's finding, the geopolymer binder was quickly researched as the main binder to replace Portland cement [6,10,11]. Typically, synthesis of geopolymer consists of three steps. The first step is the dissolution of alumino-silicate under strong alkali solution; then the free ions re-orientate into clusters in the solution, and the last step is polycondensation. The geopolymer forms very rapidly, consequently the three steps occur almost simultaneously, which makes the kinetics in the chemical reaction inter-dependent [12].

Many researches have been focused on the mechanism of geopolymerization and how to optimize the product for better strength. Bernal et al. [13] studied evolution of binder structure in sodium silicate –activated slag–metakaolin blends, in which effect of metakaolin addition on the final strength of binder is discussed. Silva and Sagoe-Crenstil [14] researched the effect of different ratios of Al_2O_3 and SiO_2 on setting and hardening of the geopolymer

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system. It was revealed the ratio affects the setting time and the final strength of the geopolymer formed. Chindaprasirt et al. [15] studied effect of SiO_2/Al_2O_3 and Na_2O/SiO_2 on the setting time, workability, and the final strength of the geopolymer system and found the best ratio for geopolymer binder is around 2.87–4.79 for SiO_2/Al_2O_3 and 1.2–1.4 for SiO_2/Na_2O. Durability has been research in literature as well. Bernal and Provis [16] summarized durability of alkali-activated materials: progress and perspectives recently, in which accelerated degradation testing methods have been discussed including effect of elevated concentrations of CO_2, sulfates or chlorides.

In the past decade, one of the research focus areas in geopolymer is to use the geopolymer as a protective coating for marine concrete and transportation infrastructures [8,17,18]. To use the geopolymer as a repair material, the bond strength between the substrate concrete and the repair material [19,20] is critical. The properties of geopolymer concrete [21,22] such as the modulus of elasticity, Poisson's ratio, and the tensile strength are similar to those of Portland cement concrete, which shows the compatibility between the geopolymer concrete and Portland cement concrete. The geopolymer concrete can also cure at ambient temperature [23–26] as conventional concrete, however this is only proven for fly ash geopolymers, but not for metakaolin geopolymers. Furthermore, the geopolymer concrete degrades significantly less than the Portland cement concrete does when they are soaked in an acid solution [27,28]. Geopolymers also present low permeability and excellent anticorrosion, and effective bonding with cement paste and mortar [29]. Moreover, geopolymers can be implemented using the same equipment and practices used for Portland cement concrete to repair deteriorated infrastructures such as manholes, pipes and chambers [30]. Geopolymers are also an excellent alternative to epoxy resins since geopolymers are stable at high temperature [31]. In addition, production of fly ash-based geopolyermic cements release 80–90% less CO_2 than Portland cement does [32]. All these merits make geopolymer an excellent candidate for pavement repair; however the durability of these applications has not been evaluated in literature. Therefore, the aim of this research is to study the possibility of using the geopolymer as a repair material under various aggressive environments. Since one of the most critical factors impacting repair durability is the bond strength between a repair material and an existing concrete, a splitting tensile and slant shear test were employed. This paper reports the results of the conducted tests and systematically characterizes the bond strength between geopolymer mortar and mortar substrate under different aggressive environments and compares it with current repair materials in market.

2. Experimental study

The objective of this research is to evaluate the bond strength of the metakaolin-based geopolymer mortar to mortar substrate using split tensile and slant shear test with line interface at 30° and 45°. In order to reduce the number of influence factors and focus the research on the bond strength of geopolymer and conventional mortar, the effect of coarse aggregates is excluded temporarily.

Since all concrete pavements will subject to degradation at some level during their usage life and hydration products decompose in acid environment, an experiment to submerge the mortar substrate into a 0.5 M (Molar per liter) solution of HCl for different duration is chosen to represent different stage of pavement degradation. Different level of degradation of concrete specimens can be obtained in laboratory experiments in different ways. One way is through accelerated tests that can be performed by increasing the concentration of the aggressive medium. For instance, geopolymer soaked in 0.5 M (Molar per liter) HCl solution for 10 days is used to evaluate the durability of geopolymer in acid media [33], and the acid resistance of fly ash geopolymer mortar was evaluated by immersion of the geopolymer specimens in a pH = 0.6 environment for eight weeks [26]. The acidity in municipal and industrial sewers could reach pH values of 2 or 3, and in some extreme cases 0.5 [34]. However there is no standard test for acid attack on concrete [35]. In order to accelerate the degradation in concrete specimens, concrete specimens are immersed in a very low pH value (0.5 M HCl in this case) for different durations [36], which corresponds to a pH = 0.3 strong acid environment. In order to assess the feasibility of using geopolymer mortar for degraded concrete pavement repairs, bond strength of geopolymer mortar and degraded conventional mortar substrate is characterized.

3. Materials

Usually in industry, a sodium silicate solution is characterized by its SiO_2/Na_2O weight ratio in a range of between 2 and 3.75. The SiO_2/Na_2O ratio greater than 2.85 will classify solution as neutral [47]. A solution with SiO_2/Na_2O ratio less than 2.85 is alkaline. Popular solutions produced in industry are with a range of SiO_2/Na_2O ratio from 1.6 to 3.3. Additionally, it is well known that SiO_2/Na_2O ration between 2 and 3 optimizes the polymerization after dissolution and formation of oligomers. However, as previously mentioned, Chindaprasirt et al. [15] found the best SiO_2/Na_2O ratio for geopolymer binder is 1.2–1.4. In the market, alkaline solution with low ratio less than 1.5 is not available for Authors to purchase. Therefore, authors used a previously approved method of mixing sodium hydroxide with sodium silicate [46] to obtain low ratio of alkaline solution. The metakaolin was supplied by Fishstone Studio Inc. Elgin, IL. The sodium silicate solution (water glass) was supplied by The Science Company, Denver, CO. The chemical composition of the metakaolin is presented in Table 1 which is obtained from the supplier's data sheet. The chemical composition of sodium silicate solution supplied consists of 9.2% Na_2O, 28.67% SiO_2, and 63.39% H_2O with SiO_2/Na_2O ratio of 3.21, which is in the normal range of neutral solution. Then, the sodium hydroxide (NaOH) in flakes of 98% purity was supplied by Alfa Aeser, Ward Hill, MA. Type I cement and river sand were used to prepare the mortar substrate. Alkaline silicate solution was prepared 24 h prior to use by dissolving sodium hydroxide pelts (Flake, 98.0%) in sodium silicate (water glass). Sodium hydroxide pelts were stirred in water glass until they were completely dissolved in water glass. This process produces extensive heat, however no crystallization is observed.

3.1. Specimen preparation

The specimen of splitting tensile test was prepared by casting a 50 × 100 mm (2 × 4 inch) cylinder for bond strength testing. The cylinder was longitudinally divided in half. One half contained cement mortar with mix ratio of 1(cement):3(river sand) at water/cement ratio of 0.5, and cured for 28 days at room temperature = 20 °C with relative humidity = 16%. The cement mortar portion has the same mix design for all specimens. The cured cement mortar resulted in a compressive strength of 35.0 MPa. After the halves of cement mortar specimens cured for 28 days, they were put back in the molds and the other empty halves of the mold were filled with geopolymer mortar with mix

Table 1
Chemical composition of materials.

Component%	Al_2O_3	SiO_2	K_2O	Na_2O	CaO	MgO	Fe_2O_3	TiO_2	LOI
Metakaolin	40.94	55.01	0.6	0.09	0.14	0.34	0.55	0.55	1.54