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Development of a High Strength Geopolymer by Novel Solar Curing

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ABSTRACT

Geopolymer is a popular construction material derived from different sources of aluminosilicates known for its environmental benefits and excellent durability in harsh conditions. However, the curing of fly-ash based geopolymer normally requires a thermal treatment that increases the manufacturing cost and carbon footprint. This paper explored a new economical and environmentally-friendly alternative, i.e. solar curing, that harnesses solar radiation to achieve accelerated geopolymerization process. Geopolymer mortars coated in two different greyscales namely solar curing black (SCB) and 40% black (grey, SCG) were prepared to study the effect of solar radiation absorption ability on the strength of the specimens, along with ambient cured specimens (ATC) for comparison. Mechanical properties such as workability, compressive strength, stress-strain relationship from 1 day to 28 days were tested. The SCB specimens that can easily reach 65 °C under the sun showed a substantial improvement of the compressive strength especially at the early age, i.e. 49.2 MPa at 1-day compared with 25.5 MPa for the ATC ones. At 28-day, SCB reached 92 MPa in compressive strength which is 17.8% (13.9 MPa) higher than that of ATC. SCG showed a moderate enhancement in strength. Through in-depth physical and chemical characterizations, the structure and morphology of geopolymers were identified through X-ray diffraction (XRD), scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDS). It was found that geopolymer cured by solar radiation had more calcium aluminate silicate content hence leading to a higher mechanical strength. Furthermore, a titration study that determines the conversion rate of the activators inside geopolymers suggested a faster geopolymerization process in the solar cured specimens.

1. Introduction

Geopolymer was termed to describe the polymerization reaction of alkaline liquid (activator) and aluminosilicate of geological origin [1]. It was considered to replace the ordinary Portland cement as the third generation of cementitious materials [2]. The usage of fly ash as the source material (binder) in geopolymer composites was examined extensively for its advantages such as low cost and easy access. However, replacing the cement completely with fly ash caused new challenges such as the early age strength deficiency. Conventionally, this was resolved by elevating the curing temperature in an oven, which in turn imposed new challenges, such as high equipment cost and difficult synthesis. This negated the advantages of geopolymers in terms of cost and environment footprint. The novel solar curing method will be introduced in this paper to produce high strength geopolymers while lowering the greenhouse gases emission from the curing process.

The main constituent fly ash is the combustion residue collected from pulverized coal fired power plants. It is classified as ASTM Class C [3] to represent high calcium content and ASTM Class F [3] to represent low calcium content. Spherical fly ash particles reduce water demand and improve the workability of the geopolymer [4]. However, fly ash based geopolymer composite develops strength very slowly at early age due to the lack of calcium content. At room temperature, fly ash is not completely dissolved [5] and the low reactivity of the fly ash increases the setting time of the geopolymer. Therefore, to maintain an acceptable early age strength, methods that accelerate the curing process or modify the chemical reactions, which are heating curing and incorporating high calcium additives respectively, should be applied. Traditionally, oven curing at 60–120 °C for an extended period [6–8], was introduced to accelerate early age strength. The duration was usually 24 h [7], after which point the rate of increase in strength reduced to an uneconomical level [8]. Ultra-high strength specimens (120 MPa compressive strength) were obtained by heat curing at 115 °C for 24 h [9]. However, this

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method was only suitable for producing precast concrete structures, which were limited in size, cost and proximity to its designated location. Furthermore, despite of the slow polymerization process, the 56-day compressive strength of the ambient cured mixes is comparable to the ones that are heat cured [7]. Jang, Lee and Lee [10] produced fly ash based geopolymer in ambient environment with the binder, activator and superplasticizer only. However, the 28-day strength ambient-cured specimen was considerably lower than that of its oven-cured counterpart. More recently, to overcome the low reactivity of fly ash and reduce synthesis complexity, additives such as slag and various types of fibers were added to the geopolymer mix. Earlier researches were done to investigate the effect of adding slag on the chemical composition of the product. In 2003, Yip and Van Deventer [11] discovered that geopolymeric aluminosilicate hydrate (A-S-H) gel and calcium silicate hydrate (C-S-H) gel were formed simultaneously and independently. The feasibility of ambient curing of low calcium (Class F) fly ash was tested and it was concluded that the addition of ground granulated blast-furnace slag (GGBS), ordinary Portland cement (OPC) or $Ca(OH)_2$ accelerated early age strength development therefore enabled the method of ambient curing [12]. In the contrary, an adverse impact of adding granulated lead smelter slag (GLSS) on geopolymer strength was also discovered [13]. However, finer GLSS would reduce the impact. Ultra-high strength geopolymer mortars (108 MPa) were produced in the ambient conditions by replacing 50% of fly ash with slag [14]. Slag proved to provide additional calcium content that accelerated the polymerization process. Fast microwave curing was introduced using household microwave ovens [15]. 1 min of high microwave output (850 W) accelerated the formation of aluminosilicate bonds. Combined with higher concentration of NaOH, porous structures formation was seen in the fly ash based geopolymer paste. In Table 1, a summary of the mix designs and their curing methods are shown. Some of which only specified the mixing ratios of the constituents. Thus, the weights were adjusted based on the assumption that the geopolymer mortar had a density of 1800 kg/m^3.

Recently, more questions were posed on the actual environment benefits of the geopolymers. A study stated that a mere 9% margin existed between the carbon emission between OPC and fly ash based geopolymers [16]. A huge proportion of emission occurred in elevating the curing temperature and the use of the alkaline solutions. On average 12.5% of CO_2 was released during the curing phase for the geopolymer in contrast to less than 1% for the OPC. The activator solution accounted for up to 59.4% of the total emission [16]. The addition of slag proved to reduce the demand for the activator solution [17]. The novel solar curing method is aiming to reduce the cost and carbon emission by raising temperature. Utilizing the solar energy as a replacement of high temperature curing of geopolymers can provide a green way to produce high strength concrete at almost no additional cost. Combining the two approaches, the fly ash based geopolymer will have an accelerated strength development as well as reduced carbon emission. Another important advantage of this mix design that cannot be overlooked is the utilization of waste materials such as slag and fly ash. The risk of toxic leakage and the cost of disposal can be significantly reduced [17]. This method is potentially beneficial to the production of structures that have large surface areas such as airport runways, rigid pavements for industrial floors [18], wall panels and floor slabs in regions with large solar energy reserves. The fast acceleration in strength development from the solar heat can potentially benefit various applications. Similarly, the outcomes from this study will also benefit the study of geothermal curing, e.g. shotcrete in hot and humid deep underground mine sites.

2. Testing program

2.1. Material properties

In this study, the main constituent fly ash was acquired from Gladstone Power Plant, QLD Australia. GGBS was from Builder's

Table 1
A review of mix designs and their curing methods.

Author	Binder	Activator	SP	Water	CA	FA	n/s	M_{NaOH}	Curing	Max Comp Strength (MPa)	Comments
Lloyd, N. A., & Rangan, B. V. (2010)	408	144	6	0	1294	554	2.50	8	HC 60 24 h	–	
Albitar, M., Visintin, P., Mohamed Ali, M. S., & Drechsler, M. (2014)	424.8	158.4	0 – 48	0 – 60	1168.8 – 1200	580.8 – 600	1.50	14	HC 70 24 h	3-day: 74.5	
Albitar, M., Mohamed Ali, M. S., Visintin, P., & Drechsler, M. (2015)	424.8	156.7	31.2	9.84	1180.8	595.2	1.50	14	HC 70 24 h	7-day: 66.78	Binder FA GLSS, Fine aggregates WRS GLSS
Jang, J. G., Lee, N. K., & Lee, H. K. (2014)	1176.6 – 1291.1	588.3 – 645.6	0 – 51.6	0	0	0	2.00	4	AC 20 24 h	28-day: 61	SP: naphthalene-based and polycarboxylate-based
Chindaprasirt, P., & Chareerat, T. (2010)[a]	415.7	207.9	0	33.3	0	1143.2	1	10	HC 30–90 48 h, delayed for one hour	28-day: 84	Fine high-calcium fly ash
Khan, M. Z. N., Shaikh, F. uddin A., Hao, Y., & Hao, H. (2016)[a]	562.5	337.5	0	0	0	900	2.5	12	AC 23 24 h	28-day: 108	Fly ash, Slag, Ca(OH)2, UFFA
Onutai, S., Jiemsirilers, S., Thavorniti, P., & Kobayashi, T. (2016)[b]	–	–	–	–	–	–	2.5	2–15	Microwave 200 – 850 W, Heat Curing 80 24 h	–	
Atiş, C. D., Görür, E. B., Karahan, O., Bilim, C., İlkentapar, S., & Luga, E. (2015)	450	–	0	150	0	1350	–	–	HC 45 – 115 24 – 72 h	1-day: 120	Na is 14% of mix weight

*SP: superplasticizer; CA: coarse aggregate; FA: fine aggregate; n/s sodium silicate to sodium hydroxide ratio; M_{NaOH}: molar concentration of NaOH; HC: heat curing; AC: ambient curing; GLSS: granulated lead smelter slag; WRS: washed river sand; UFFA: ultra-fine fly ash.

[a] Mix design adjusted based on the assumption that geopolymer mortars have a density of 1800 kg/m^3.

[b] Mix design not disclosed.