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Recycled aggregate high calcium fly ash geopolymer concrete with inclusion of OPC and nano-SiO_2

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HIGHLIGHTS

- OPC and nano-SiO_2 (nS) use to improve the properties of recycled aggregate geopolymer concrete (RAGC).
- OPC-fly ash blend mixture exhibited the highest compressive strength of 48.7 MPa.
- nS showed a great potential to enhance the mechanical properties of RAGC.

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ABSTRACT

In this study, the use of ordinary Portland cement (OPC) and nano-SiO_2 (nS) to improve the mechanical and durability properties of recycled aggregate geopolymer concrete (RAGC) was evaluated. The results indicated that the inclusion of OPC enhanced the compressive strength and reduced the water absorption, porosity, as well as the penetration of chloride. Moreover, the concrete with 15% OPC-fly ash blend mixture exhibited the highest compressive strength of 48.7 MPa, which was 38% higher than that of natural aggregate geopolymer concrete (NAGC). It was also found that the addition of nS showed a great potential to strengthen the mechanical properties of RAGC. With 1% nS added, the compressive strength of RAGC was significantly higher than those of NAGC.

1. Introduction

Reusing of concrete wastes from the demolition of concrete structures is good for the environment. The transformation of these wastes into recycled aggregates for new concrete reduces the consumption of natural aggregates, creates landfill avoidance and gives additional value to resource usage [1,2]. Recycled concrete aggregate (RCA) is a composite material made of virgin natural coarse aggregates with old cement mortar adhered on the surface, which is the major cause of the differences in physical characteristics between natural and recycled concrete aggregates [3]. This adhered mortar consists of sand and cement hydration products. It also contains pores and micro-cracks which influence the mechanical and durability properties of recycled aggregate concrete (RAC) [4].

RCA has great influence on the workability of the concrete mixture. For saturated surface dry (SSD) condition, RCA contains 2.3–4.6 times higher absorbed water than that of natural aggregate (NA), which increases the excessive free water for the mix [5–7]. RAC has also been observed to lower the workability in comparison to the conventional concrete as a resulted of the roughness of RCA [8]. When hardened properties are taken into consideration, the replacement of NA with RCA causes a reduction in strengths, an increase in porosity and water absorption of concrete, leading to a decrease in durability. This is resulted from the porous nature of mortar within RCA which is weak and readily accessible by water or aggressive solutions [4,9]. In summary, RAC has lower performance than that of the natural aggregate concrete (NAC).

Geopolymer is a new cementitious material and involves less amount of CO_2 emissions compared to OPC. This material is manufactured by mixing aluminosilicate materials such as fly ash, metakaolin and red mud with alkaline solutions to form the slurry for binding coarse and fine aggregate particles in the production of concrete. Geopolymer concrete shows high early compressive strength, low shrinkage, significant resistance to creep, and good performance under acid environment [10,11]. For the geopolymer concrete prepared with coarse recycled aggregate, the negative effects of RCA on both mechanical and durability properties are similar to those of OPC concrete [12,13].

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Interesting materials used to enhance the properties of geopolymer concrete are OPC and nS [14–16]. Firstly, the influence of calcium compound plays an important role on the properties of geopolymer materials. Primarily comprised of 61–65% CaO in OPC improves the compressive strength and impermeability properties of fly ash based geopolymer concrete [10,17]. Secondly, the application of nanotechnology such as the use of nano-materials to improve the properties of concrete is a common practice. nS is one of the materials added to strengthen the properties of cement-based materials. Ghafari et al. [18] reported that the OPC concrete containing nS develops higher early compressive strength than the conventional concrete and Adak et al. [19] and Phoongernkham et al. [20] discovered the advantages of incorporating nS in geopolymer composites as well. In addition, several studies confirm that nano-particle is significant in the reduction of porosity, which makes concrete denser and stronger [21–23].

Thus, the aim of this research is to improve the properties of geopolymer concrete containing RCA by using OPC and nS. The optimal condition recycled aggregate geopolymer concrete (RAGC) with comparable or better performance than that of natural aggregate geopolymer concrete (NAGC) should be obtained.

2. Experimental program

2.1. Materials

High calcium fly ash (HCF), OPC and nS were used as the raw starting materials. HCF, the primary source of SiO_2 and Al_2O_3 for preparing geopolymer composite, was from Mae Moh power plant in northern Thailand. The specific gravity of HCF and OPC were 2.43 and 3.13, respectively. The median particle size of HCF and OPC were 21 and 15.3 μm with Blaine fineness of 2100 and 3770 cm^2/g, respectively. nS was a commercial grade with an average diameter of 40 nm, density of 0.13 g/cm^3 and BET specific area of 50 m^2/g. The chemical compositions of these materials are given in Table 1.

Sodium hydroxide (NH) and sodium silicate (NS) were used as alkaline activators with NS to NH ratio of 1.5. NH was prepared by dissolved sodium hydroxide pellets in distilled water to obtain a concentration of 12 M. The commercially available NS contained 12.3% Na_2O, 30.3% SiO_2, and 57.3% H_2O.

Table 2 shows the properties of fine and coarse natural aggregates used in this study. Normal graded river sand with fineness modulus of 2.6 was used as fine aggregate. Crushed limestone was used as natural aggregate (NA) and RCA with a single particle size of 4.5–9.5 mm were used as recycled coarse aggregate. RCA was obtained by crushing of tested concrete specimens in laboratory with compressive strength in the range of 30–40 MPa. After crushing, recycled aggregate was sieved and washed to remove the fine particles. The values of specific gravity and compacted dry density of RCA were 2.30 and 1270 kg/m^3, respectively which were lower than those of crushed limestone. While the water absorption and mass loss due to Los Angeles abrasion were 5.97% and 35.7%, respectively which were higher than those of natural aggregate. These findings were supported by Pandurangan et al. [1] who suggested that the weaker and more brittle RCA compared to natural aggregate are caused by the presence of old cement mortar, which adhered on the surface of RCA.

Table 2
Properties of natural aggregates and RCA.

Aggregate	Specific gravity (SSD)	Compacted dry unit weight (kg/m^3)	Water absorption (%)	Los Angeles abrasion (%)
Limestone (NA)	2.65	1511	0.61	33.9
RCA	2.30	1270	5.97	35.7
Sand	2.63	1764	1.07	–

2.2. Mixing and sample preparation

The mix proportions and identifications of geopolymer concretes are shown in Table 3. For all geopolymer concrete mixtures, the alkaline solution to fly ash ratio was held constant at 0.6. The control concretes were made with HCF and NA or RCA. HCF was partially replaced with OPC at 5%, 10% and 15% by weight, while nS was added to the mixture at 1%, 2% and 3% by weight of fly ash.

The mixing procedure was divided into three main steps, which took around 15 min. NH solution was added into the dry mixture of HCF and OPC or nS and mixed for 5 min. Then, the coarse and fine aggregates in saturated surface dry (SSD) state were added to the mixture and mixed until uniform mixture was obtained. The NS solution was put in and final mixing was done for another 5 min. The fresh concrete was cast into molds and compacted by rodding. The specimens were wrapped with plastic film and stored at room temperature of approximately 28 °C for 1 h before heat-cured at 60 °C for 2 days. Next, the samples were demoulded, wrapped with plastic film and stored in controlled room temperature of 23–25 °C and 50% relative humidity until the age of testing.

2.3. Detail of testing

At the age of 7 days, the properties of geopolymer concrete were tested in accordance with the references shown in Table 4. Slump flow test was used for measuring the workability of geopolymer concrete. While the mechanical properties, water absorption, porosity and sorptivity were tested at the age of 7 days according to ASTM standard test methods [24–31].

The resistance to sulfuric acid was tested with method modified from ASTM C267 [31] using $10 \times 10 \times 10$ cm^3 cube specimens and 3% concentrated sulfuric acid with immersion at the age of 7 days. The weight loss was measured after immersion for 7, 14, 28, 56, 84, and 120 days with the refreshment of new acid solution.

The chloride penetration resistance was tested by immersion in sodium chloride solution as described in Somna et al. [32] and Rerkpiboon et al. [33]. The cylinder specimen (10 cm diameter × 20 cm height) was cut into two pieces of 10 cm in diameter and 10 cm in height. The top end of the cut cylinder and its side were coated with epoxy. The coated specimens were placed in plastic containers leaving the bottom surface exposed to 3% NaCl solution (Fig. 1). The fresh NaCl solution was replaced monthly. The chloride penetration into geopolymer concrete was measured every month for 4 months by spraying silver nitrate ($AgNO_3$) solution on the freshly split surfaces of sample. The visible depth of white silver chloride precipitation which was a result of the chemical reaction between $AgNO_3$ and chloride ions was measured.

Table 1
Chemical composition and percentage retained on No. 325 sieve of HCF, OPC, and nS.

Materials	SiO2	Al2O3	CaO	FeO3	MgO	K2O	SO3	LOI (%)	% retained on No. 325 sieve
HCF	36.2	19.9	14.2	11.9	1.88	2.41	3.57	0.4	34.8
OPC	17.2	4.02	63.1	3.11	0.94	0.64	3.85	0.9	5.0
nS	99.8	0.08	–	0.01	0.03	–	–	<1	<0.2