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Original Research Paper

High strength geopolymer binder based on waste-glass powder

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ABSTRACT

This paper presents a study on the synthesis of geopolymers based on alkaline activation of waste-glass powder using aqueous solutions of sodium hydroxide and sodium silicate with different Na_2O contents as alkali activators. Three types of calcium aluminate cements were also incorporated into the dry binder at levels up to 24% by weight in order to modify the chemical composition of the geopolymer source materials. The prepared mortars were tested for workability, setting time, compressive strength, free-alkali content and tendency towards efflorescence formation. FTIR and SEM analyses were also performed to characterize the morphology and structure of the produced geopolymer. The optimized geopolymer mortar exhibited a remarkable maximum compressive strength of 87 MPa. The results showed that inclusion of calcium aluminate cements in the silica-rich waste-glass powder leads to release high amounts of reactive alumina into aluminosilicate gels, improving the geopolymerization reactions and resulting in the formation of a more cross-linked network that exhibits higher compressive strength. High alumina cement Secar 71 showed the greatest effect in strength enhancement due to the higher amount of reactive alumina releasing into the reaction medium. The findings demonstrate a new potential of value-added reuse application for waste-glass powder by adding a suitable amount of materials that are rich in reactive alumina.

1. Introduction

It is a great challenge to handle the enormous amount of waste-glass produced annually throughout the world and sustainable efforts are necessary to reduce the amount of this waste in municipal solid waste stream due to environmental and resource management issues. Depending on its type and quality, waste-glass may be recycled or landfill disposed. Although it seems that all waste-glass is recyclable and can be reused in glass factories, but main problem is the difference between quality and color of the glass collected. Mixed glasses of different colors and origins result in an uncontrollable color and properties in the new glass and cannot be recycled, which means disposal to landfill [1]. It is estimated that approximately 740 thousand tons of waste-glass are discharged in the municipal waste stream in Iran each year, while only less than 5% of which is recycled [2]. Due to rising economic and environment consequences of land filling, the recycling of waste-glass is of increasing interest worldwide. The concrete industry is among the most attractive options to reuse the waste-glass either as aggregate in concrete or as supplementary cementitious material [3]. The use of waste materials in the production of geopolymer binder is another potential solution to overcoming the aforementioned waste management problems, which recently has been successfully introduced [4–8]. Ecological or environmental benefits of use of geopolymer technology for recycling of waste-glass include (1) the increased diversion of waste material from landfills for useful applications, (2) the reduction in the use of energy and CO_2 emission attributed to Portland cement production, (3) the conservation of natural resources.

Geopolymer binders are a class of inorganic polymers synthesized by the reaction of an aluminosilicate material with a concentrated alkali hydroxide and/or alkali-silicate solution, having an amorphous three-dimensional structure [9]. In the geopolymerization process, the nature and chemical composition of the aluminosilicate precursor plays a key role in determining mechanical performance. In general, in order to meet a desirable strength development in geopolymer binders, an optimum proportion of reactive silica and alumina contents should be present in starting materials [10]. Since glass powder contains a high content of reactive silica and is relatively poor in alumina content, it is necessary

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Table 1
Chemical composition and physical properties of raw materials.

	WGP	Calcium aluminate cement		
		Fondu	Secar 71	Secar 80
Chemical composition (%)				
SiO_2	72.10	3.75	0.50	0.40
Al_2O_3	0.50	39.90	69.80	80.50
Fe_2O_3	0.20	16.15	0.30	0.20
CaO	10.20	38.20	28.30	17.50
MgO	3.00	1.5	0.40	0.50
SO_3	–	–	0.10	0.10
$K_2O + Na_2O$	13.90	0.40	0.50	0.70
Mineralogical phase composition (%)				
Monocalcium aluminate (CA)	–	46	70	35
Monocalcium dialuminate (CA_2)	–	0	17	30
Tetracalcium aluminoferrite (C_4AF)	–	24	2	0
Corundum (α-alumina)	–	0	0	33
Other	–	30	11	2
Physical properties				
Specific gravity (g/cm^3)	2.90	3.20	2.98	3.25
Blaine specific surface area (m^2/kg)	450	315	410	1000
Mean diameter size (μm)	11	18	12	6

Table 2
Mix design of WGP-CAC geopolymer mortars and the conducted tests.

Mix No.	Dry binder		Na_2O (%)	Water/dry binder			Conducted test on specimens			
	WGP[a] (%)	CAC[b] (%)		WGP-Fondu	WGP-Secar 71	WGP-Secar 80	CS[c]	FTIR	SEM	EFE[d]
1	100	0	8	0.525	0.525	0.525	×			
2	100	0	10	0.520	0.520	0.520	×	×	×	×
3	100	0	12	0.510	0.510	0.510	×			
4	92	8	8	0.515	0.520	0.530	×			
5	92	8	10	0.510	0.510	0.525	×			×
6	92	8	12	0.500	0.500	0.515	×			
7	84	16	8	0.500	0.505	0.545	×			
8	84	16	10	0.495	0.500	0.545	×			×
9	84	16	12	0.495	0.495	0.540	×			
10	76	24	8	0.495	0.505	0.555	×			
11	76	24	10	0.490	0.500	0.550	×	×	×	×
12	76	24	12	0.485	0.490	0.540	×			

[a] Waste-glass powder.
[b] Calcium aluminate cements (Fondu, Secar 71 and Secar 80).
[c] Compressive strength.
[d] Efflorescence formation evaluation.

to modify the composition of its reactive contents by addition of a certain amount of materials that are rich in reactive-Al to guarantee the geopolymer formation. Calcium aluminate cements (CACs) as alumina rich materials are potentially capable of being added to glass powder to compensate for the lack of reactive alumina content in the initial raw mix composition.

CACs are a type of special cements, containing alumina contents ranging from ~38% up to ~80%, which depending on the application and the purity of the aluminum source have a wide range of mineral composition. In All CACs, monocalcium aluminate (CA) is the main reactive alumina phase and other calcium aluminates as well as less reactive phases form the secondary constituents [11]. Despite the differences in the chemical and mineral composition, all types of CACs can be used as supplementary alumina sources for geopolymer production [12,13].

Very limited studies have been reported on geopolymerization of waste-glass powder in combination with known precursors [14–17]. The achieved highest compressive strengths however, were low due to the relatively low reactivity of the used precursor materials. Redden and Neithalath produced geopolymer mortars by using mixtures of glass powder and fly ash as source materials. They concluded that geopolymer mortar containing 50% fly ash and 50% glass powder synthesized with 8 M NaOH solution and cured hydrothermally at 75 °C for 48 h, exhibited the highest compressive strength of 35 MPa [15]. Pascual et al., who studied the geopolymerization of mixtures of glass powder and metakaolin, evaluated the highest 28 days compressive strength of 30 MPa for geopolymer mortar containing 8 wt.% of metakaolin that was activated by 5 M NaOH solution [16].

The main objective of the present research is to explore the feasibility of reusing waste-glass powder as a suitable precursor in geopolymer binder production if its deficiency in reactive-Al is supplied. For this reason, three main types of CACs that are rich in reactive alumina were chosen as additives. The geopolymer mortars prepared at different Na_2O concentrations and CAC replacement levels were characterized using workability, setting time, compressive strength, free-alkali content, tendency for efflorescence formation, FTIR and SEM.

2. Experimental program

2.1. Materials

Materials used in this study were waste-glass powder (WGP), CACs of different alumina contents, reagent grade 98% NaOH and aqueous sodium silicate. The WGP was obtained by grinding the