A STUDY ON COMPLEX ALKALI-SLAG ENVIRONMENTAL CONCRETE

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Abstract

In this paper, the environmental and mechanical properties of alkali-slag concrete are discussed. The concrete is prepared by activating the slag as industrial by-product, using the alkali component as activator. Then, the complex slag and complex alkali component are investigated and a new complex alkali-slag environmental concrete has been prepared. Based on the evaluation of environmental effect as well as analysis and comparison of the concrete materials, the authors suggest that this concrete will be a new environmental material, which is in coordination with the environment and can keep a sustainable development.

1. Introduction

Alkali-slag concrete, or JK concrete as it is called in China, is made from slag powder and alkali component as main constituents of cementitious material. The slag powder may be one or a mix of the following: blast furnace slag, phosphorous slag, titanium-containing slag, manganese slag, basic cupola furnace slag, aqueous slag from power plant, nickel slag, silica aluminate. The alkali component as an activator is a compound from the elements of first group in the periodic table, so such material is also called as alkali activated cementitious material or cement. The common activators are NaOH, Na_2SO_4, water glass, Na_2CO_3, K_2CO_3, KOH, K_2SO_4 or a little amount of cement clinker and complex alkali component; therefore, its activity is more than that of compound from the elements of second group as commonly used in traditional cementitious material. The ions with strong ionic force formed during dissociation of alkali metal compound, promote the disintegration of slag powder and hydration of the ions, and then, such ions take part in the structure formation of cement paste, so the cement has properties of rapid hardening and early strength gain [1, 2, 5]. For such type of concrete there is less $Ca(OH)_2$ and high alkali hydrates in hydration products of cement, in case of high Al/Si ratio, there will be some mineral of zeolite type resulting in its high resistance to corrosion [3, 4]. Due to perfect pore structure, small total pore volume, proper distribution of pore diameters, dense structure and good bond of interface between cement and aggregate [3], the special concrete and concrete with the strength of 20-120 MPa can be obtained. The concrete mix has a good workability with slump of 0-22 cm without water reducing agents. The concrete has a high hardening rate with low heat of hydration, consisting of only 1/2 to 1/3 of that for OPC; its impermeability is 1.0-4.0 MPa; the frost resistance reached 300-1000 cycles. There is strong protection of reinforcement with excellent corrosion resistance [1, 2]. It can be used for various building elements and monolithic concrete. Structural tests on concrete elements show that their deformation, bearing capacity and cracking resistance conform to the requirements of the China's standard [2, 4, 6]. For preparing the cementitious material of JK concrete, only the grinding is required with no calcinations. As for the concrete aggregate, the aggregate with large content of mud or fine particles, heavy loam, sea sand, super fine sand, machined sand etc can be used. It is a low cost, energy saving, low resource consumption material, which can promote the recycling of the waste and make an environmental concrete with clean production of cement, environment friendly and in good coordination with the environment.

2. Mechanical Properties of Slag-alkali Environment Concrete

2.1 Mechanical properties of slag-alkali high-strength concrete

Tables 1 and 2 give the examples showing the main components and strength of the representative slag-alkali (JK) concretes.

Table 1:Properties and strength of alkali-slag concrete

No.	Aggre-gate	Slump (cm)	28-day density (g/cm^3)	Compressive strength (MPa) at age of				
				1d	3d	28d	360d	Other
1	A, D	20	2.476	9.6	44.1	77.7	81.9	3.5 years: 95.6
2	A, D	1	2.533	9.6	49.2	90.2	98.4	
3	A, D	16	2.481	18.6	48.5	79.6	88.2	
4	A, D	11	2.521	46.8	70.3	98.0		
5	A, D	7	2.495	38.4		78.5	99.4	
6	A, D	1	2.507	4.6	35.2	80.2	92.2	
7	A, D	8	2.471	3.3	8.8	62.5	91.3	
8	A, D	0	2.447	2.8	2.8	35.1	73.2	
9	A, D	4	2.481	2.4	2.8	37.4	68.2	
10	A, C	3	2.363	27.8	56.4	90.3	100.8	
11	A, D	1	2.522	24.8	41.8	76.7	101.7	
12	A, D	0	2.457	48.5	72.3	90.7	114.7	
13	A, C	3	2.550	56.1	71.3	102.3	112.2	
14	A, C	0	2.524	60.9	80.8	99.0	113.7	
15	A, D	2	2.500	61.5	79.0	99.0	114.4	
16	A, C	1	2.468	68.1	96.2	117.0	132.2	
17	A, D	0	2.436			25.3	75.2	
18	A, C	–	2.458			114.5		R_2 = 106.8
19	A, D	22	2.498	33.6	65.4	86.0		
20	A, D	5	2.548	1.4	9.8	60.4	101.1	Ra = 88.6

Note: A = crushed limestone; B = crushed granite; C = medium sand with FM = 0.24; D = sand powder with FM = 0.56-0.63; Ra = strength of autoclaved specimen.

Table 2: Mechanical properties of high and super high strength JK concrete

No.	1	2	3	4	5	6
f_{cu} 28d (MPa)	52.9	61.2	76.5	81.6	91.2	120.5
f_c (MPa)	4.04	4.04	4.22	4.58	4.71	
f_f (MPa)	6.71	7.87	7.59	7.43		
f^t_c (MPa)	46.6	49.6		64.6	78.6	
f_c / f_{cu}	0.076	0.068	0.055	0.056	0.052	0.046
f_{cu} / f_c	13.094	14.606	18.128	17.817	19.369	21.595
f_f / f_{cu}	0.127	0.129	0.099	0.091		
f'_c / f_{cu}	0.881	0.810		0.791	0.861	0.826
f'_c / f_{cu}	11.84	11.84		14.01	14.93	15.98
Bond (MPa)	6.00	5.48	6.05	6.21		
$E \times 10^4$ (MPa)	3.77	3.89	4.01	3.82	3.82	2.95

Notes: For Nos. 1-5 the aggregate is limestone and fine sand (FM = 0.63). For No. 6 the aggregate is granite and medium sized sand. f_{cu} = compressive strength; f_c = splitting strength; f_f = flexural strength; f^t_c = axial compressive strength.

2.2 Development of strength and impermeability of alkali-slag concrete

The strength of alkali-slag concrete at later age developed quite well, especially for the ordinary concrete. For the concretes of 15-30 MPa, the strength increased to 40-83 MPa after 6-12 years; the increment is as high as 198%-107%. For the concretes of 70-96 MPa, strength increased to 101-122 MPa, or 11%-57% of the increment. The impermeability increased from 0.5-1.0 MPa to over 1.8-2.0 MPa with an increment of 100%-200%. An investigation on JK concrete elements and structures after 22 years of service shows that no marks of external damage or trace of reinforcement corrosion found [7, 8, 9]. Due to enhancement of durability and prolongation of the service life, the cost of life cycle was lowered and the expense for maintaining reduced greatly.

3. Characteristics of Environmental Materials Based on Alkali-Slag Concrete

3.1 Environmental characteristics for preparing the cementitious materials and concrete

For preparing the JK cementitious material, only the drying of wet slag and one grinding are needed, without high temperature calcination and two grindings: for raw materials, then for clinker and additives as in the traditional cement manufacture. Therefore, the equipment expenses, energy consumption for its preparation will be reduced greatly. The alkali component can be added as admixture or in case of solid alkali in mixed grinding with the slag. The dosage of alkali component takes only about 3%-6% of the activated material. The natural alkali component or industrial alkali containing waste can be used. In manufacture there is no CO_2 emission; the utilization rate of the slag is as high as 80%-100% and reduction of coal consumption by 66%-86% and electricity consumption by 50% [5, 10]. The concrete production and construction can be realized with existed mixers and equipments for construction work. There will be clean production for the cement and concrete by energy saving and low consumption with lowering the noise and dust during its production. Even in case of a little amount of cement clinker used as activator, the CO_2 emission will be reduced by 90%.

3.2 Turning the slag into a resource

For preparing the alkali activated cement concrete, except for granulated blast furnace slag, other industrial slag can be used as well, for example, there could be alkali fly-ash slag concrete [11], alkali titaniferous slag concrete, alkali alumo-silicate concrete and alkali phosphorous slag concrete etc prepared. It may be a combination of several kinds of slag. So such application is significant for making the slag into a resource.

3.3 Full use of low grade aggregate

For alkali slag concrete the low grade aggregate can be used, such as heavy loam, sea sand, aggregate with powder content up to 20%, aggregate with clay content over 5%, slowly cooled slag, color metal slag, recycled aggregate, powdered sand with fineness of modulus of 0.56-0.62. A concrete with 28-day compressive strength of 20-99 MPa can be produced with these aggregates, thus to expand the scope of the resource. This type of concrete has more increment of strength at later age and good durability.

3.4 Contribution of high durability to the energy and resource use, operating function and maintenance

In former Soviet Union, there was an irrigation canal built from JK concrete with strength of 15 MPa, using heavy loam. Twelve years later, its strength reached 40 MPa and the freeze thaw cycle was up to 900. For concrete road cover with sea sand as aggregate, the strength increased from 16 to 47.6 MPa. For assembled pile and breakwater, the strength was increased from initial 30 MPa to final 71.8 and 62.0 MPa, and frost resistance up to 600 and 570 cycles, respectively. The impermeability increased by 100%-200% [8, 9]. The engineering practice in Ukraine shows that the reinforcing steel bar embedded in drainage elements from alkali-slag concrete with protective cover only 3mm hasn't been corroded after 20 years of service. Using the powder sand with fineness of modulus 0.62 from Yangtze River in Chongqing and crushed limestone, a JK concrete with 28-day compressive strength of 99 MPa and after one year 114.4 MPa has been prepared, its impermeability reached over 3.5-4.0 MPa [1, 5]. Such JK concrete has excellent resistance to sulfate corrosion, after its immersion in 2% solution of $MgSO_4$ for 2 years, the strength increased by 22.1%-39.2% and in 0.234 N HCl for 2 years, the strength increased by 33.1%-48.3%, only damaged in concentrated hydrochloric acid [5, 6]. Due to that the JK concrete kept a high increment of strength during its service, making itself a high or even super high strength one, its resistance to deterioration increased with the age. Consequently, the service life of construction prolonged and the function could be guaranteed with great saving in resource consumption and maintenance expense and lowering the life cycle cost. It would have an active effect on the environmental load.

4. Titaniferous slag and concrete with mixed alkali activated slag powder

4.1 Characteristics of titaniferous slag as a raw material

Among various slag, the acidic one and titaniferous one are considered as non-active ones and are difficult to be used. Their chemical composition is given in Table 3 [4, 12]. Activated by alkali or physico-chemical treatment, a mixed slag environmental concrete can be prepared from titaniferous slag.

Table 3: Comparison of titaniferous slag and granulated blast furnace slag

No	Slag	Chemical composition									K
		CaO	MgO	MnO	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SO_3	Loss	
1	BF slag	42.7	5.4	1.6	31.72	10.3	1.8	1.59	1.07	0.42	1.67
2	Ti slag	25.1	8.1	2.9	27.1	15.6	5.3	14.8	0.39	0.42	1.09
3	Ti slag	32.11	7.57	0.11	26.09	15.64	0.78	17.90	0.30	0.66	1.25
4	Ti slag	29.03	8.43	-	23.4	16.43	0.44	22.30	0.27	0.64	1.17
5	Ti slag	26.46	8.11	0.24	23.08	15.64	3.06	23.80	0.29	0.98	1.06

Note: The quality factor K= CaO + MgO + Al_2O_3/ SiO_2 + MgO + TiO_2.

With the increase of TiO_2 in titaniferous slag, its difference from other slag is enlarged. When the TiO_2 content is more than 15%-25%, the activity of the slag is quite poor, especially for the melted one, as for water soaked one obtained by long distance transport and discharge into water, its activity would be poor, this is due to that there would be perofskite crystal formed with no hydraulic activity and improper water quench with a little amount of glass phase formed. Such slag has been piled up as much as a mountain, making the river blocked. Usually, it was used as filling material for the road [1, 2]. In order to fully utilize such slag, the alkali and physical activation was applied and a good result is obtained. If the fluorite would be added during iron smelting to improve the quality of water quench, even the industrial waste with high titanium containing slag could be used as a resource.

4.2 Mechanical properties of alkali activated concrete with titaniferous slag and mixed powder

Water soaked titaniferous slag with 20%-25% of TiO_2 is a non-active additives, if it is used as additives for portland cement the dosage should be less than 15%. If it is used for preparing the alkali activated concrete, the addition could reach 50%-100%. Based on chemical activation, in addition of heat activation, the strength could reach about 90 MPa. In this study, the JK concrete was prepared with water soaked titaniferous slag, which will promote the utilization of industrial slag as a resource. In Table 4, the mechanical properties of alkali-activated concrete with titaniferous slag and mixed slag are given. Its special application and specific properties are under investigation.

Table 4: Mechanical properties of alkali activated concrete with titaniferous slag and mixed powder

No.	Type of aggregate	Content of slag (%)			Type of alkali	Compressive/flexural strength (MPa)				
		Ti	BF slag	Other slag		Normal curing 3d	Normal curing 7d	Normal curing 28d	Steam curing	Auto-claved
1	A, D	100			I, III	7.1		24.2	80.8	92.4
2	A, D	100			I, II	7.5				97.3
3	C	100			I, III	15.9/ 4.3	30.5/ 5.9	54/ 10.1	–	–
4	C	50	50		I, I	23.6/ 4.8	46.2/ 57.6	75/ 10.6	–	–
5	C	95		5	I, II, III		27.2/ 5.2	52/ 8.2	–	–
6	C	50	50		I, II, III	3.0/ 2.3			83/ 7.5	

Notes: Nos. 1 and 2, water quenched titaniferous slag with TiO_2 content of 24%-25%; Nos. 3, 4, 5 and 6, water soaked slag with TiO_2 content of 24%-25%. A = crushed limestone; C = medium sand, FM = 2.4; D = powder sand, FM = 0.56-0.63.

5. Conclusion

The JK concrete prepared from pozzolanic slag activated by alkali has excellent mechanical properties and durability, turning the slag into a resource. During cement production, it can lower the environmental load and increase the utilization rate of the slag due to low energy consumption without emission of CO_2 and using the mixed slag. During concrete production, the aggregate with high content of silt and powders can be used as well as sea sand and powder sand, so the environmental characteristics is quite good and can become a new environmental material coordinated with the environment and capable of sustainable development.

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