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Optimization of a geopolymer mixture for a reinforced cantilever concrete bench

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Abstract:
Traditional Ordinary Portland cement (OPC)-based concrete consumes large quantities of natural resources for its production, which is highly energy intensive and has high CO_2 emission. Therefore, development of the geopolymer concrete, based on use of industrial by-products, can provide an environmentally friendly and low-carbon alternative to OPC concrete. Geopolymer concrete characterized with low permeability, mechanical properties and excellent heat resistance, has been receiving increasing attention in building industry nowadays.

However, there are some challenges regarding the structural application, such as adjusting the fast setting time, tailoring the workability, and controlling the shrinkage of blast furnace slag based geopolymer concrete.

The main aim of this study is to design and optimize geopolymer concrete mixture for manufacturing a reinforced cantilever bench. This is accomplished by testing rheological and mechanical properties, and the drying shrinkage of geopolymer concrete.

The geopolymer binder consisted of fly ash (FA), blast furnace slag (BFS) and activator. The activator was made by mixing sodium hydroxide and waterglass solutions. The prolonged setting time of the studied mixture was achieved by using proper type and amount of chemical admixture in order to achieve enough time for casting but not to affect mechanical properties of the hardened concrete. The compressive strength, elastic modulus, flexural strength, drying shrinkage and the effects of curing duration were evaluated.

The application of the optimized geopolymer mixture in the complex structural element such as cantilever bench has shown promising results. Such small scale application and low risk project was suitable to gain the experience and confidence with this innovative type of material for which no international codes or regulations are available. Furthermore, this project has proven to be encouraging for further upscaling of geopolymer concrete for larger scale structural applications, like bridges and/or other structural elements in the building industry.

Keywords: alkali-activated concrete, geopolymer concrete, setting time, workability, elastic modulus, drying shrinkage, structural application

1 Introduction

Alkali activated materials (also called geopolymers) are an environmentally friendly alternative to the OPC-based materials. The production of geopolymer concrete releases less CO_2 and consumes less energy compared to OPC-based concrete [1-3].

Alkali activated binder based on FA and BFS has become very attractive due to the synergistic effects of both waste materials. It can counterbalance the disadvantages that each of the raw materials exhibit when they use separately [2- 4].

The mechanical properties of the geopolymer concrete depend on the factors such as the particle size and chemical composition of raw materials, curing conditions (i.e. temperature, time and relative humidity), liquid/binder (l/b) ratio and type and concentration of the activator. Binders with a blend of FA and BFS show a higher compressive strength compared to the strength of alkali activated FA. [5]

The aim of this study is to optimize the alkali-activated FA and BFS concrete mixture from the previous work for its application in a reinforced cantilever concrete bench [6]. In the previous study, the setting time of concrete was approximately 15 minutes. Due to the large cantilever bench dimensions (3 meter of length and 1.5 meter of height) it was not possible to mix and cast a large concrete volume in the formwork within 15 minutes. The challenge of this study was to provide longer final setting time for the reference mixture and to achieve required workability for casting in the bench formwork. This structural application also required specific mechanical properties of the geopolymer concrete such that it can withstand loading conditions and be stiff enough to limit deformations.

In order to regulate setting time and workability of the reference geopolymer concrete mixture, the study was first performed at the geopolymer paste level, by changing the alkaline activator composition, liquid/binder (l/b) ratio and using different types of retarders and superplasticizers. Consequently, the geopolymer concrete mixture was cast in order to test the setting time and workability of the concrete. In addition, the compressive strength, elastic modulus, flexural strength, drying shrinkage and effects of different curing duration of the optimized geopolymer concrete mixture were evaluated.

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2 Materials and Methods

2.1 Materials

The precursors used for preparation of the geopolymer concrete mixture were FA and BFS. The chemical composition of precursors is given in Table 1.The precursors were activated by mixture of two alkaline solutions, i.e., sodium-hydroxide and sodium waterglass. The gravel was crushed granite with a specific gravity of 2650 kg/m^3, while the fine aggregate was natural sand with a specific gravity of 2640 kg/m^3. In order to regulate the setting time, powder admixtures were added to the mixture. The chosen admixtures for the study are the barium chloride dihydrate ($BaCl_2.2H_2O$) and CUGLA admixtures (CUGLA CRETOLENT BT (Retardant, con.25%), CUGLA MMV BT (Retardant, con.36%), CUGLA QQ (Superplasticizer, con. 35%). In order to obtain a better workability for the optimized mixture the liquid to binder ratio was 0.53, whereas for the reference mixture was 0.5. [6]

The reference and optimized mixture design are shown in the Table 2. Besides the concrete casting in the bench, the standard cube specimens and prisms for different mechanical tests and drying shrinkage tests were produced. The mixture was made by mixing first coarse and fine aggregate for 3 minutes. Then, FA, BFS, and retarder were added and mixed for 2 minutes. In the end, the alkaline activator was added and mixed for another 2 minutes. After 24 h from casting, specimens were demolded and placed in a fog room with 20°C and 99 % relative humidity and cured until testing age.

Table 1 Chemical composition of FA and BFS measured by X-ray fluorescence

Oxide (%)	**SiO_2**	**Al_2O_3**	**CaO**	**MgO**	**Fe_2O**	**SO_3**	**Na_2O**	**K_2O**	**TiO_2**	**P_2O**	**L.O.**
BFS	34.3	11.53	39.1	7.81	1.42	1.6	0.23	0.58	-	-	1.15
FA	54.2	23.32	4.23	1.62	8.01	0.6	0.85	1.97	1.23	0.54	3.37

Table 2 Reference and optimized concrete mixture design

		Reference geopolymer concrete mixture [m^3]	**Optimized geopolymer concrete mixture [m^3]**
Components:	**Density [g/cm^3]**	**Mass [kg]**	**Mass [kg]**
Fly ash	2.44	200	200
Blast furnace slag	2.89	200	200
Aggregate [0-4 mm]	2.64	789.14	789.14
Aggregate [4-8 mm]	2.65	439.81	439.81
Aggregate [8-16 mm]	2.65	524.69	524.69
Alkaline activator	1.125	200	212
($BaCl_2.2H_2O$) admixture	3.1	-	2 (0.5 wt.% of the binder)

2.2 Methods

The first focus of the study was on paste level in order to determine the setting time and simultaneously the compressive strength of the paste specimens. The setting time of the pastes is measured under a constant temperature of (20 ± 2) °C according to [NEN-EN 196-3]. The setting time and workability tests of the fresh geopolymer concrete were assessed based on [NEN-EN 12350-2 and EN 12350-5]. Compressive strength tests of geopolymer concrete were done according to the [NEN 5988] on standard cubes with dimension of 150x150x150 mm^3. Three-point flexural bending tests were performed according to [NEN-EN 14651+A1], with the exception that the specimen size was modified to the 100×100×400 mm^3 prisms. A notch of 25 mm was made in the middle of the specimen and the specimen was dried for 2 hours before the three-point bending test was performed. The elastic modulus and the drying shrinkage were measured according to [NEN-EN 12390-13] and [ISO 1920-8], respectively. The specimens for elastic modulus tests and drying shrinkage tests were the prisms with dimension of 100×100×400 mm^3. The specimens were cured for 1, 3, 7, and 28 days, and after each of the curing period, the specimens were moved from the curing room to the laboratory conditions at 20°C and 55% relative humidity when they were exposed to drying shrinkage test. The drying shrinkage tests consist of weight loss and length change measurements.

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3 Results and discussion

3.1 Setting time and compressive strength at the paste level

Table 3 shows the setting time and the compressive strength of the paste mixtures. The setting time of the paste mixtures was measured by changing the alkaline activator composition, l/b- ratio and using different types of retarders and superplasticizers. The compressive strength of the paste samples was measured at 3, 7 and 28 days.

Changing the alkaline activator composition, l/b-ratio and addition of CUGLA admixtures did not delay the setting time of the paste mixtures. However, the addition of $BaCl_2.2H_2O$ retarder with 0.5% of total binder weight gave positive test results on the retardation process without compromising the compressive strength. Therefore, $BaCl_2.2H_2O$ was used for testing rheological properties of the geopolymer concrete mixture. Finally, optimized mixture was chosen (mixture labeled bold in Table 3) with the criteria that the setting time was significantly prolonged without affecting the mechanical properties.

Table 3 Mixture compositions of the pastes (with respect to 1 kg FA+BFS), pastes setting time and compressive strength (RT stands for retarder)

	Mix	SiO2	Na2O	RT	l/b	Setting time [min]		Compressive strength		
		(mol)	(mol)	(wt.%)	[-]	initial	final	3 days	7 days	28 days
Alkaline activator composition	1	1.15	0.28	-	0.5	80	124	29.5	-	-
	2	1.15	0.375	-	0.5	22	37	36.1	-	-
	3	1.15	0.56	-	0.5	17	26	42.8	-	-
	4	1.15	0.75	-	0.5	17	30	47	-	-
	5	1.5	0.75	-	0.5	27	35	51.6	-	-
	6	0.75	0.75	-	0.5	36	90	31.2	-	-
l/b	7	1.15	0.75	-	0.45	15	27	57.5	-	-
	8	1.15	0.75	-	0.5	17	30	47	-	-
	9	1.15	0.75	-	0.55	20	34	36.1	-	-
Addition of Barium chloride dehydrate retarder (RT)	10	1.15	0.28	0.25	0.5	200	275	2.2	28.4	36.7
	11	1.15	0.375	0.25	0.5	77	152	1.89	27.3	41.3
	12	1.15	0.375	0.5	0.5	52	112	19.2	35.7	48.5
	13	1.15	0.56	0.25	0.5	34	64	35.5	52.9	69
	14	1.15	0.56	0.5	0.5	48	102	23.3	43.4	52.2
	15	1.15	0.75	0	0.5	17	30	47	-	-
	16	1.15	0.75	0.25	0.5	40	84	43.5	-	-
	17	**1.15**	**0.75**	**0.5**	**0.5**	**53**	**95**	**42.8**	**-**	**-**
	18	1.15	0.75	0.75	0.5	67	102	24.9	-	-

3.2 Setting time and workability at the concrete level

The optimized mixture has showed a satisfactory workability with a slump class S5 (a slump of 25.5 cm) and F4 flow class (average diameter of 55 cm). The initial setting time of the concrete in ambient room conditions was 40 minutes (Fig. 1).

3.3 Compressive strength

Fig.1 Slump test of optimized concrete mixture

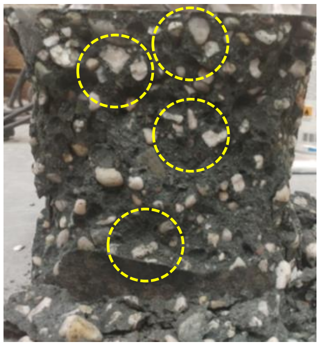

Fig.2 Dotted yellow circles indicate good bonding between matrix and aggregates in the optimized mixture

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The compressive strength of the reference and optimized mixtures from 1 day to 90 days is shown in the Fig. 3. It can be seen that at 1 day the compressive strength for the optimized mixture was lower than for the reference mixture. The lower compressive strength is attributed to the use of the retarder. However, the effect of the retarder on compressive strength is not significant at the later ages. Only a slightly lower value for the compressive strength results are found for optimized mixture. Compared to the reference concrete mixture with liquid to binder ratio of 0.5, the slightly lower compressive strength in optimized mixture might be caused by the higher liquid to binder ratio (0.53) that was used in optimized mixture, in order to obtain a better workability.

An example of the concrete cube after compressive strength test is shown in Fig. 2. It is clear that the good bond between matrix and aggregates was obtained, which contributes to the development of high strength of geopolymer concrete.

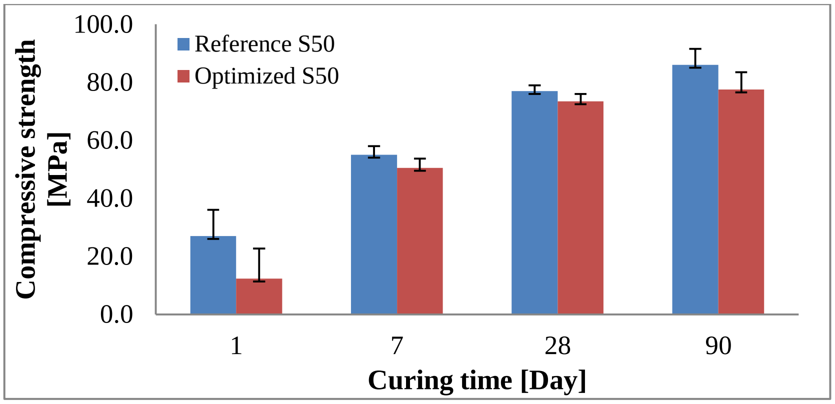

Fig.3 Compressive strength test results for reference and optimized mixture

3.4 Flexural strength

The flexural strength test setup is shown in Fig.4. The flexural strength of the mixture is 4.58 MPa at 28 days, with a standard deviation of 0.311 MPa (Fig. 5).

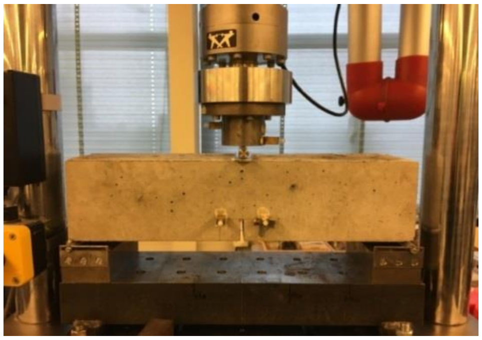

Fig.4 Flexural strength test setup

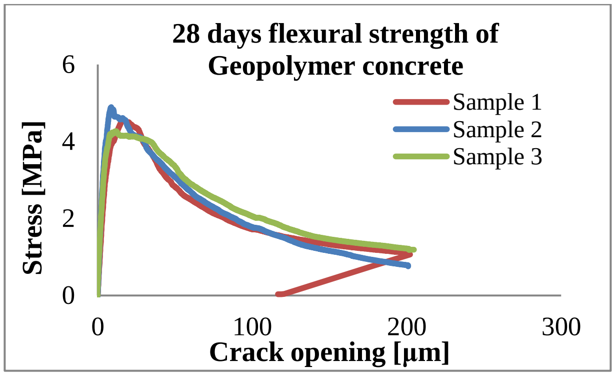

Fig. 5 Flexural strength at 28 days

3.5 Elastic modulus and Poisson's ratio

The elastic modulus test set up is given in the Fig.6. The tests were done at curing age of 3, 7 and 28 days. Fig.7 shows that the elastic modulus increases over time. The elastic modulus of the optimized mixture at 28 days is 31.26 GPa. Comparing the research work of Criado et al. [2], the modulus of elasticity is between 30.51 and 23.56 GPa. Their research also show that an increase in FA decreases of the modulus of elasticity, exhibit a low ductility and toughness compared to 100% of slag binder.

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Fig.6 E-modulus test setup

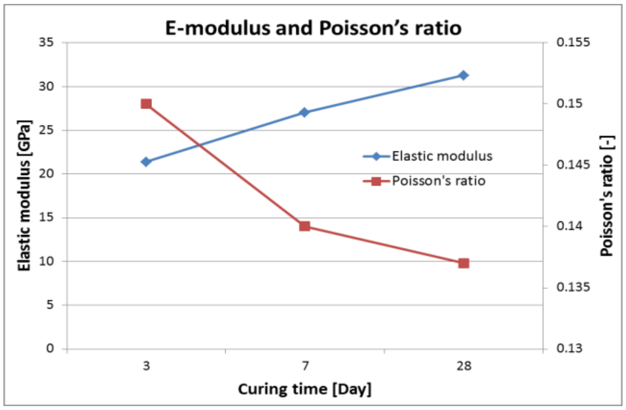

Fig.7 E-modulus and Poisson's ratio

3.6 Drying shrinkage test

After demolding three prisms were kept unsealed in order to investigate moisture exchange with the surrounding environment, i.e. to measure drying shrinkage and weight loss. The prisms are placed in a climatized room, where the temperature (20ºC ± 2ºC) and relative humidity (50% ± 2%) are kept constant. The drying shrinkage test setup is shown in the Fig.8. The rest of the samples were placed in the fog room with 20°C and 99 % relative humidity and kept there until the age of 3, 7 and 28 days. Subsequently, they were exposed to the shrinkage test. The results of drying shrinkage and weight loss of optimized mixture are shown in Fig. 9- Fig. 12. It is clear that the drying shrinkage of the samples exposed to dry after 1 day and 3 days curing is larger compared to 7 and 28 days cured samples. The weight loss is caused by the evaporation of free water. Comparing the drying shrinkage results shown in Fig. 12 for geopolymer concrete with the results of CEM III/B concrete measured by Mors [7] the 69 days shrinkage strain of CEM III/B specimens cured for 28 days showed a factor of around 1.5 higher than that of geopolymer concrete.

This observation is also consistent with the finding reported by Deb [8]. Their findings show that a higher slag and content and a low sodium hydroxide ratio in the mixture decreases the drying shrinkage. Thus, drying shrinkage depends on the binder ratio but also on the composition and ratio of the activator.

The effect of drying shrinkage on the development of the surface cracking is shown in the Fig.13. Only samples cured for 28 days prior to shrinkage testing did not exhibit cracking on the surface.

Fig.8 Drying shrinkage test setup

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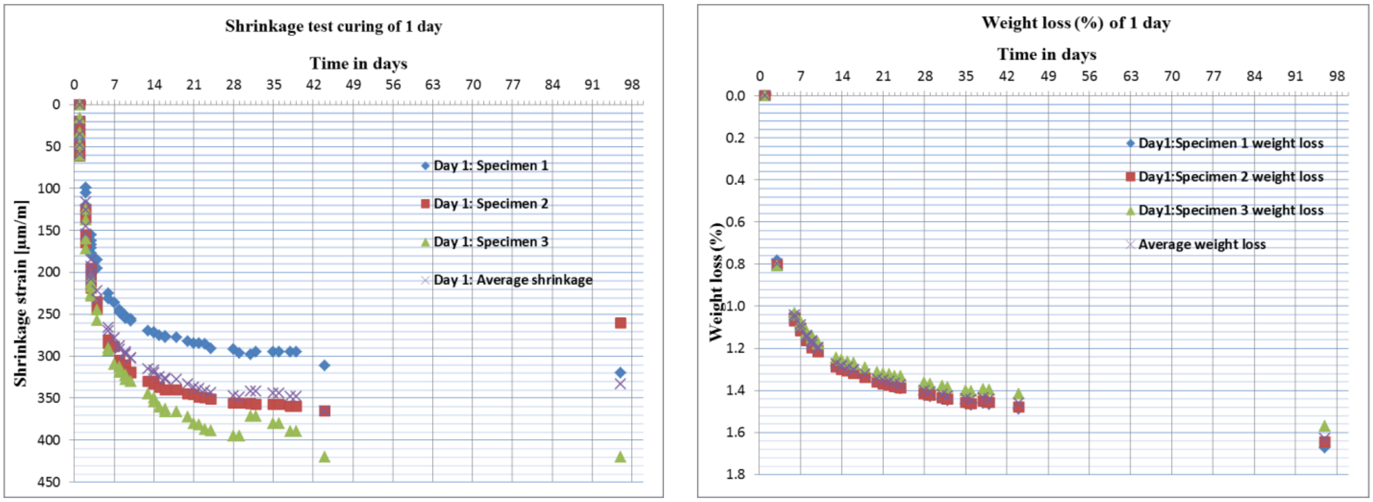

Fig.9 Drying shrinkage and weight loss for the samples exposed to drying after 1 day of curing

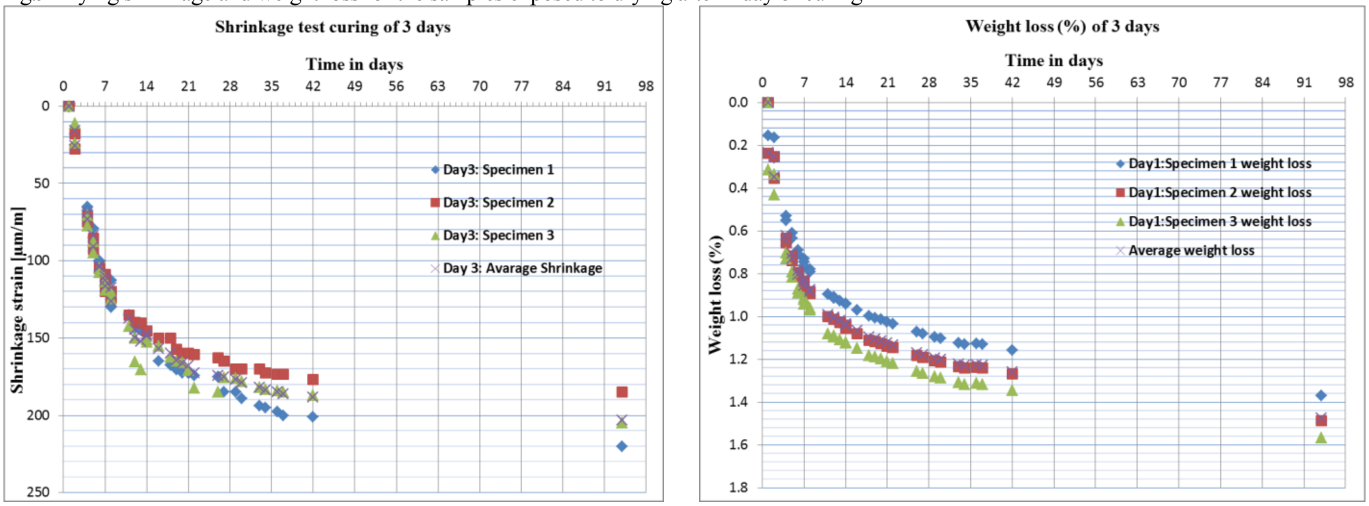

Fig.10 Drying shrinkage and weight loss for the samples exposed to drying after 3 days of curing

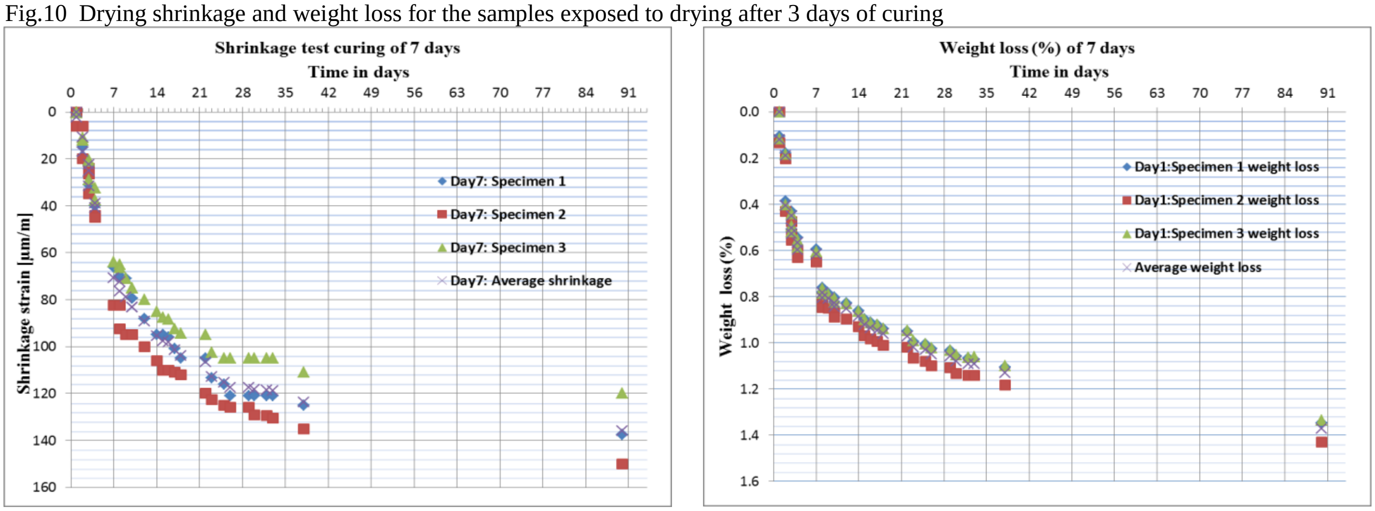

Fig.11 Drying shrinkage and weight loss for the samples exposed to drying after 7 days of curing

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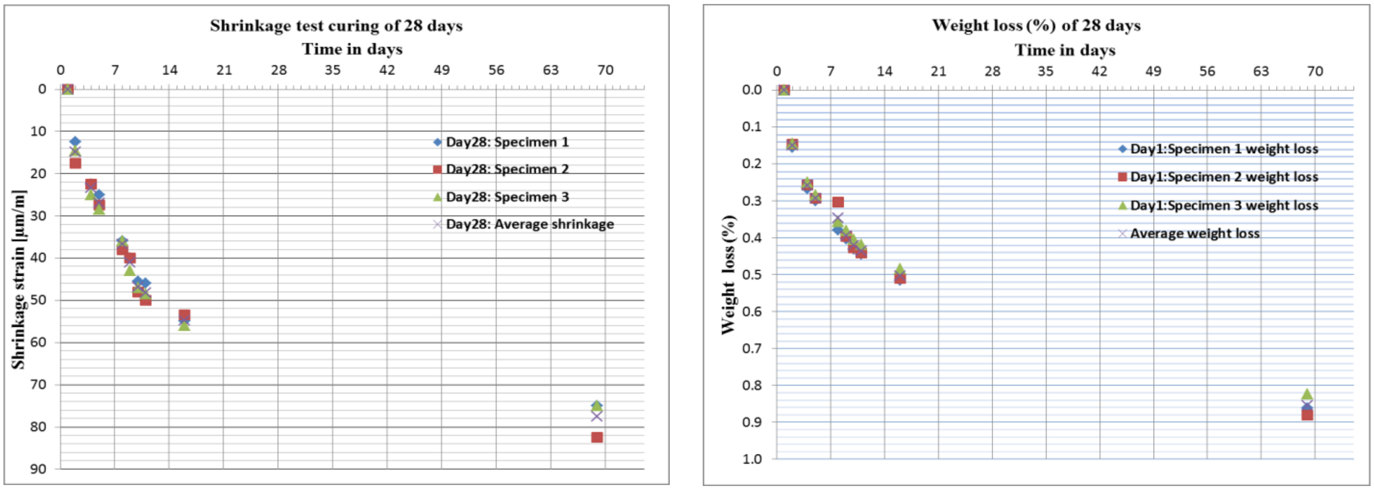

Fig.12 Drying shrinkage and weight loss for the samples exposed to drying after 28 days of curing

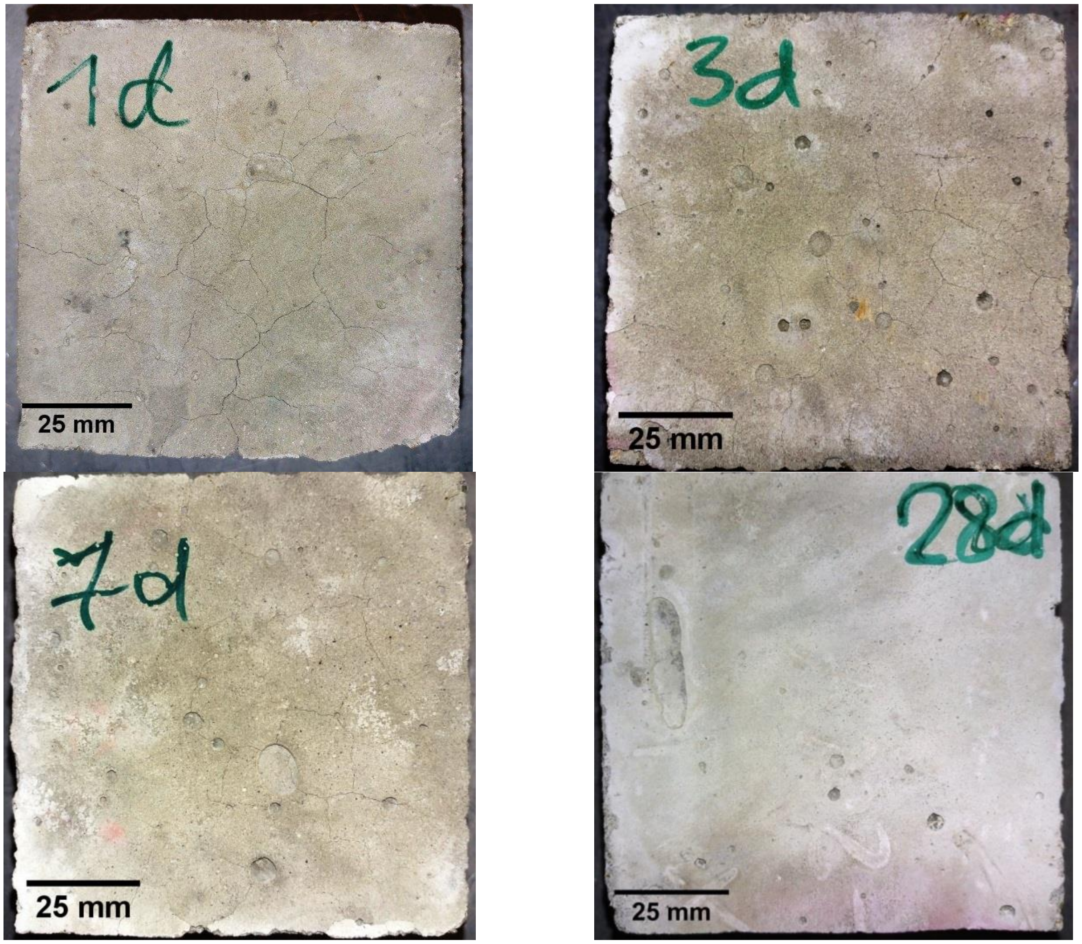

Fig. 13. Development of the drying shrinkage cracks on the specimens surface cured in the fog room for 1, 3, 7, 28 days and subsequently exposed in the room with 20ºC ± 2ºC and relative humidity 50% ± 2%. The photos are made 90 days after first measurements.

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4 Conclusions

In this paper, a geopolymer concrete mixture used for reinforced concrete structures is studied. The setting time of geopolymer concrete was regulated by using proper amount of barium chloride dihydrate retarder. The study shows that the use of retarder has not affected the compressive strength at 7, 28 and 90 days.

The 28 days flexural strength reached 4.58 MPa with a standard deviation of 0.311 MPa. Modulus of elasticity on 28 days curing reached above the 30 GPa and has a comparable Poisson's ratio as the OPC.

The drying shrinkage results indicate that when shrinkage tests start from 28 days of curing, no cracks were observed on the surface of the prisms, while at other ages the cracks were visible. It seems that geopolymer concrete is more sensitive to curing and drying conditions compared to the traditional concrete. From drying shrinkage measurements, the proper curing period of 28 days is recommended for the alkali-activated FA and BFS concrete for the structural applications. The application of the optimized geopolymer mixture in the cantilever bench has shown promising results and provided significant experience and confidence for further upscaling of geopolymer concrete and its structural application in larger scale projects.

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