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Performance of high strength green concrete made utilizing high volumes of supplementary cementing materials

*Ahmed H. Abdel Raheem[1], Ahmed M. Tahwia[2] and Khaled A. Eltawil[3]
[1] *(Prof., Structural Engineering Dept. Faculty of Engineering, Mansoura University, Mansoura)*
[2] *(Associate Prof., Structural Engineering Dept. Faculty of Engineering, Mansoura University, Mansoura)*
[3] *(M. student, Structural Engineering Dept. Faculty of Engineering, Mansoura University, Mansoura)*
Corresponding Author: Ahmed H. Abdel Raheem

Abstract: *This paper presents the results of an experimental study conducted to develop and evaluate the performance of high strength green concrete using different combinations of supplementary cementing materials (SCMs) such as Fly Ash (FA), Slag cement (S), and Silica Fume (SF) which known as quarterly system. To investigate the Green concrete (GC) properties, six concrete mixtures were developed and tested. They were mixed, cast and cured under normal condition. Mixtures were designed to replace 50% of PC by combination of SCMs like FA, S, and SF (quarterly system).The quarterly system has a considerable influence on the workability of GC. It enhanced compressive and splitting tensile strength too. The results analysis showed a high strength that GC can be developed through utilizing quaternary binders with up to 50% of PC replaced by mixing FA, S, and SF. The optimum result achieved when mixed PC, FA, S, and SF by following proportion 50%, 20%, 15%, and 15%, respectively. Its properties enhanced due to the influence of different SCMs complement role between the filler and pozzolanic effect in mixture.*

Keywords: *Green Concrete, Eco-friendly, Supplementary Cementing Materials, quarterly* system

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I. Introduction

The concrete is the most widely used construction material around the world. It is a sustainable construction material because of its durability, ability to resist high temperature, chloride and sulfate attack, andeasiness to manufacture and use. The essential concrete component is Portland cement (PC) which is responsible for seven to eight percent of global carbon dioxide (CO_2) emitted yearly around the world and exhaust our nonrenewable resources in PC manufacturing process [1]. It becomes a burden on the environment by contributing to climate change, greenhouse gas and ozone layer depletion problems [2]. The production of Portland cement is also very energy intensive and consume huge amount of raw materials [3&4]. For this reasons, it becomes necessary to seek innovative alternative PC materials in concrete. This alternative material aims to produce eco-friendly green concrete and reduce the energy and raw materials which were consumed in cement industry. The concrete industry has recently testified an enormous development in all sides of construction. So the green concrete (GC) takes considerable attention in recent age. The GC began in Denmark 1998 [5]. It is used in building, bridge and dams constructions. It represents the future of sustainable construction materials in the world. The GC is a kind of concrete which uses industrial by-product materials as at least one of its components. It is eco-friendly sustainable concrete which its production process does not lead to environmental destruction [6&7].

There are many various strategies to produce the GC [8]. First strategy is utilizing recycling aggregate, Secondly, by minimizing PC content by using supplementary cementing materials (SCMs) such as Fly Ash (FA), Silica Fume (SF), and Slag cement (S). Finally, by fully PC replacement with SCMs such as using in producing geopolymer concrete. The minimizing PC method was considered the most effective environmental problem-solving method. This method worked on reducing CO_2emission , saving energy and resources by reducing PC usage in concrete [9].

The SCMs environmental benefits were kept in our energy and non-renewable resources, reduction the CO_2 emission and increasing the concrete durability. The SCMs like FA, S, and SF are rich in silica and alumina. It has a pozzolanic reaction effect which worked on improving the concrete properties so, they considered suitable partial PC alternative materials. The SCMs needed alkali activator to react as pozzolanic materials. Studies stated that the hydrate PC components involved 70% calcium silicate hydrate (C-S-H), 20% calcium hydroxide (CH), 7% slupho-aluminates and 3% secondary phases [10]. The CH which liberated by PC hydrate represents suitable alkaline which activates the SCMs pozzolanic reaction which produced more C-S-H.

The FA is industrial waste materials whichisrich in silica and alumina product as a secondary product in thermal coal power plants. It is most widespread SCMs around the world. The FA improves the concrete workability. However, reduces the early-age strength [11&12]. Dodson pointed that the replacing FA with an equal volume of PC minimizes the filler effect [13]. Previous work stated that to achieve the same strength of Normal Concrete by replacing of FA instead of PC It is needed to replace 25 % of FA by 20% of PC [14].

The Slag cement is produced from the blast furnace. It is Eco-friendly materials which provides needed energy less than PC industry by fifth and output emittedCO_2less than PC by the tenth [15]. It had an adverse influence on early age properties due to its slower reaction rate like FA. The SF is one of the rich SCMs in SiO_2. It is called condensed SF. It is a by-product material from metallic silicon industry. Its output is near (1:1.5) ton per year [16]. It had significantly enhanced influence on concrete properties in early age because of its filler and pozzolanic reaction. The optimum percent of SF in the mixture was 15 % [12]. It enhanced the concrete workability.

The concept of developing a high strength green concrete mixture with a high volume of cement replacement is not new, and several researchers have incorporated up to 60% of FA in their studies. The aim of this study is to explore the feasibility of developing a high strength sustainable concrete by replacing 50% of PC through blending three kind of SCMs (Quarterly system). This paper presents the results of an investigation into mixing three kinds of SCMs with PC as binder on GC microstructure improvement. The main aim of mixing the three pozzolanic materials used in the quarterly system is to take the benefits and advantages of these materials and use all its features together to improve the concrete properties.

II. Materials

- Portland cement (PC): Local ordinary Portland cement (CEM I 52.5 N) produced by El Arish Portland cement (Alaskary) which was used through this research and conformed to the requirements of Egyptian Specifications (ES 4756-1 /2013). The chemical composition of used cement is shown in Table 1, and its physical and mechanical properties are shown in Table 2.
- Fly Ash (FA): The FA type S according to BS EN 450 was used. It was supplied by Dirk India Private Limited Company in India, and it is known commercially as Pozzocrete 63. Its chemical composition is shown in Table 1, and physical properties are shown in Table 3.
- Silica Fume (SF): It is a local secondary industrial waste from silicon and silicon alloys industry. It is obtained from Egyptian Ferro Alloys Corporation (EFACO). Its chemical composition analysis is shown in Table 1. The SF used satisfy ASTM C 1240. The used SF physical properties are shown in Table 4.
- Slag cement (S): The slag grade 80 supplied from Helwan Iron and Steel Company and ground by using a drum mill machine in EGY sand company. Its average particle size is 150 µ with brown color. The chemical composition is shown in Table 1. It is also known as ground granulated blast furnace slag (GGBFS).
- Crushed Dolomite: Local crushed dolomite was used. It is supplied from Suez. It contents the combination of white and dark black dolomite stone with nominal maximum size 9.5 mm. The Physical properties are shown in Table 5.
- Sand: The fine and clean sand is used with fineness modulus of 2.95. The specific gravity of sand is 2.55.The Physical properties are shown in Table 6.
- Chemical admixture: The superplasticizer (SP) with density of 1.08 (kg/l) was used to achieve good fresh and hardened properties. The used SP belongs to the third generation which is used to make concrete more identical mixture. It is an aqueous solution of modified polycarboxylate and had the turbid liquid appearance. It is supplied from SIKA EGYPT Company. It conforms to ASTM C-494 types G and F.
- Water: The clean water is used in mixing and curing.

Table 1 Chemical composition of cementitious materials

Constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	L.O.I
PC	22.12	5.56	3.69	62.87	0.26	0.11	2.36	0.91	1.22
FA	92.47			2.38	0.48	-	2.92	0.96	1.10
SF	95.9	0.52	0.05	0.2	-	0.4	0.18	0.1	2.9
S	37.80	13.14	0.23	38.70	1.03	0.20	7.11	1.19	0.00

Note: C = Cement & FA = Fly Ash & S = Slag cement & SF = Silica Fume

Table 2 Physical and Mechanical properties of cement CEM I 52.5 N

Properties	Cement Fineness (m^2/kg)	Setting Time (min.)		Compressive strength (MPa)	
		Initial	Final	2 days	28 days
Test result	365	75	205	22	55.8
ES 4756-1/2013 limits	Not less than 2750	Not less than 45	-	Not less than 20 MPa	Not less than 52.5 MPa

Table 3 Physical properties of used FA and SF

Materials	Fineness	Bulk weight (t/m^3)	Bulk density (t/m^3)	Specific gravity (t/m^3)	Color	Particle shape
FA	< 10% retained on a 45-μ sieve	0.9	-	2.3	Light grey	Spherical
SF	23420 (m^2/kg)	-	8.0	2.2	Grey	Spherical

Table 4 Physical properties of used crushed dolomite aggregate

	Physical properties of used crushed dolomite aggregate					
	Specific weight	Bulk density (t/m^3)	Clay and fine dust content %	Coefficient of Impact %	Crushing value %	Absorption %
Crushed dolomite	2.60	1.65	0.8	12.2	22.5	1.6
ES 1109/2008	-	-	Less than 3.0	Less than 30	Less than 30	Less than 2.5

III. Experimental program

To achieve the investigation objectives,six concrete mixes were designed to study the effect of replacing 50% of PC by blending three kinds of SCMs (Quarterly system)on the fresh and mechanical properties of concrete as shown in Table 5. So, a high-range water reducer with a suitable dosage in range (1.5:1.7) % was used to reduce the water to binder ratio without reducing the workability of fresh concrete. The SCMs were used as cementitious materials by percentages 50% of binder contents. All other mixtures were prepared by changing the contents and proportions of SCMs with the total amount of PC and SCMs remained constant at 450 kg/m^3 to achieve target compressive strength (80 ± 5) MPa. In addition, the water to binder (W/B) was kept constant at 0.3. The superplasticizer (HRWRA) dosages was adjusted as needed so that all mixtures achieve a plastic slump flow value between 100 and 120 mm. A typical PC mixture (M1) was prepared as a control mixture.

Table 5 Mix proportions of concrete (kg/m^3).

Mixture	Mixture Code	PC	FA	S	SF	Sand	Dolomite	Water	SP.
M1	C	450	…..	…..	…..	711	1067	135	13.5
M2	25F25S	225	112.5	112.5	…..	730	1095	135	6.75
M3	30F5S15SF		135	22.5	67.5	716	1074	135	7.65
M4	5F30S15SF		22.5	135	67.5	728	1092	135	7.20
M5	20F15S15SF		90	67.5	67.5	727	1090	135	6.75
M6	15F20S15SF		67.5	90	67.5	724	1085	135	7.42

Note: C = Portland Cement & F = Fly Ash & S = Slag cement & SF = Silica Fume

1.1 Mixing Procedure and Specimens

All concrete mixtures were mixed using laboratory drum rotary mixer with capacity 60 liters. The mixing process sequence consisted of mixing fine and coarse aggregates for one minute. The PC and SCMs were subsequently added with half of the total amount of the mixing water, and finally, the HRWR which was mixed with remaining part of the mixing water was added, and mixing was continued for three minutes.

From each concrete mixture, a total of fifteen 100 x 100 x 100 mm concrete cubes and fifteen 100 x 200 mm concrete cylinder were casted. The cubes and cylinders were used to estimate the compressive strength and splitting tensile strength, respectively at 2, 7, 28, 56, and 90 days. All samples compacted by using a vibrating table to achieve maximum compaction. The specimens were demolded after 24 hours and cured in water bath at 20 ± 2° C until they are required for testing.

1.2 Test procedures

To measure the workability of concrete, Slump Test was conducted according to BS EN 12350-2: 2000. The compressive strength of concrete cube specimen 100 x 100 x 100 mm as per BS EN 12390-4: 2000 standard was conducted by compression machine with capacity 2000 KN for 2, 7, 28, 56, and 90 days. If the test results of the cube samples vary by more than 10%, the results are ignored, and the test is repeated. The split tensile strength was measured by cylinder specimen 100 x 200 mm according to BS EN 12390-6: 2009 for 2, 7, 28, 56, and 90 days.

IV. Test results and Discussion

1.3 Influence of high quaternary blend volume of SCMs on workability of green concrete

The results of the slump test are shown in Fig. 1. The results showed the effect of SCMs on the sustainable concrete workability. The high quaternary blend volume of SCMs enhanced the workability more than the control mixture M1. The mixtures M2 and M4 workability showed improvement in the results although their used smaller high water reducer dosage than control mixture M1. The SCMs improved the workability of concrete. The workability improved by the different influence of SCMs and superplasticizer. The SF had an extreme fineness and having spherical shape could provide additional water reduction through its potential ball-bearing effect [17]. The FA particle are spherical like SF. Inaddition, it had a slower reaction like S. The superplasticizer improved the workability by dispersing the cement and SCMs particles through its adsorption and electrostatic repulsion mechanisms. In other words, results showed improvements in the workability due to using quaternary with less amount of water than that used in the control mixture M1.

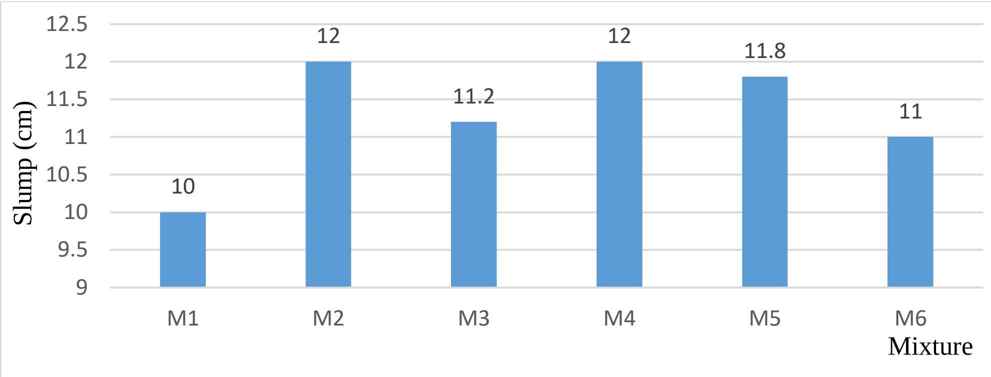

Fig. 1 Slump results of various concrete mixture

1.4 Influence of high quaternary blend volume of SCMs on compression strength of green concrete

The results showed that using high volume of SCMs had good influences on the green concrete compressivestrength, as given in Table 6 and shown in Fig. 2.In general, utilizing high quaternary blend volume of SCMs showed the lowest compression strength at an early age like ternary concrete that confirmed with Jeong, Y., et al.,[9]. However, at a later age achieved highest compression strength. The mixture M4 showed highest early strength at two days. It recorded a relative high early strength 74% M1. The M5 achieved highest compression strength at 90 days. It recorded a relative strength of 107.9% M1.

Table 6 The GC mechanical and durability properties result

Mix No.	Compressive Strength (MPa)					Splitting Tensile Strength (MPa)				
	Test time (days)					Test time (days)				
	2	7	28	56	90	2	7	28	56	90
M1	54	73	85.3	85.5	88	2.87	5.12	5.42	5.73	6.69
M2	27.8	53	70	72	75	2.5	3.80	4.40	4.77	6.08
M3	35.3	55	75	81	93	3.5	5.07	5.25	5.72	6.07
M4	40	45	62.7	80	83	3.11	3.76	4.68	4.77	4.79
M5	36	62	77	91	95	3.30	4.37	6.02	6.25	6.94
M6	37.5	58.4	71.4	81	92	3.28	5.03	5.47	5.82	6.91

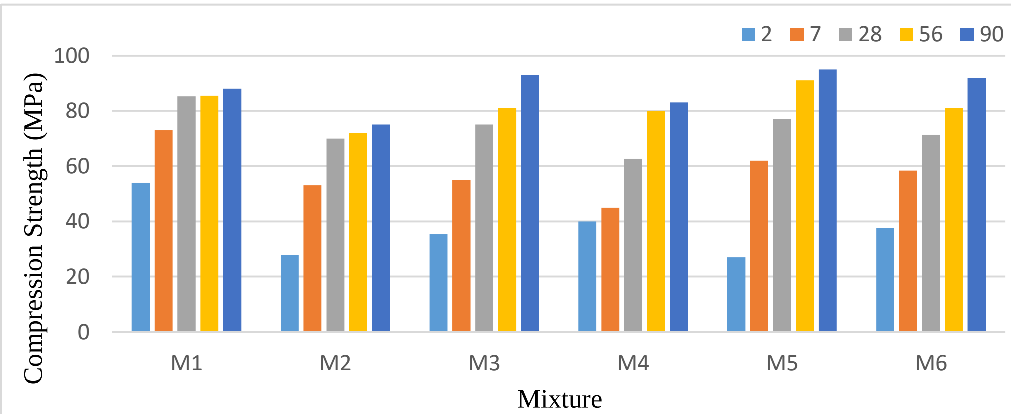

Fig. 2 Compression strength of various concrete mixture at different ages

1.5 Influence of high quaternary blend volume of SCMs on splitting tensile strength of sustainable concrete

The effect of a high content of SCMs on splitting tensile strength is shown in Fig. 3. The mixture M5 and M6 showed highest splitting tensile strength at 90 days. They recorded a relative strength of 104% and 103% of M1 in 90 days. From the results,the splitting tensile strength had a direct relation with compression strength. Its increased with the compression strength increased showed in mixture M5 and M6 results.

1.6 Discussion

The mixture M2 result showed lowest compression strength. It could be attributed to S type used. Grade 80 is not activated enough. The microstructure can be enhanced by mixing three SCMs type (quarterly systems). The quarterly system improved the complement role between pozzolanic, and filler effect of used material played a great role in improving the concrete microstructure. All SCMs needs alkalis to activate their pozzolanic reaction. The cement hydrate produced calcium silicate hydrate (C-S-H), calcium hydroxide (CH) and ettringite. The CH which liberated from cement hydrate represented the suitable alkalis to onset the pozzolanic reaction of SCMs. The SCMs worked on reducing the CH by converting it to secondary C-S-H gel. The C-S-H was important in improving the concrete microstructure. It made microstructure more dense and durable.

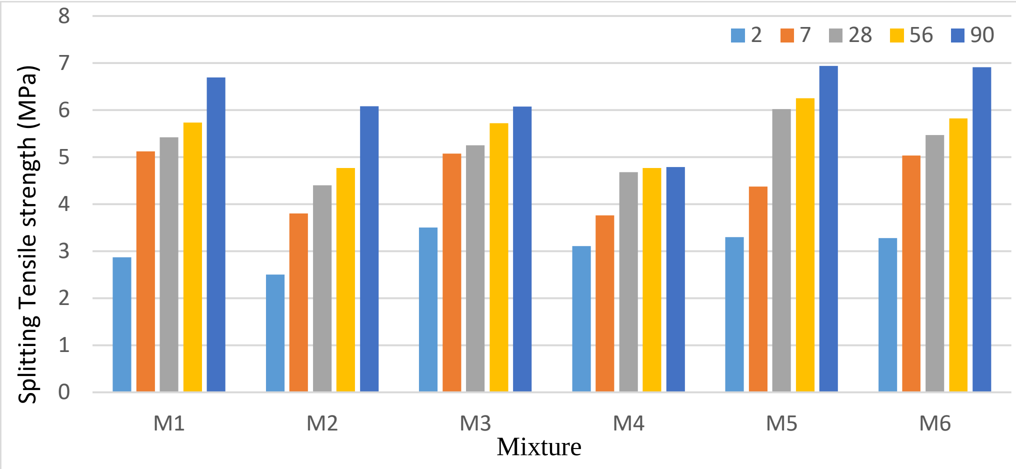

Fig. 3 Splitting tensile strength of various mixture at different ages

At an early age, the results showed more decrease in compression strength than M1. It was attributed to the slow reaction of SCMs. Although, the concrete properties enhanced at the later age. The FA improved the later age concrete properties. The FA reaction was accelerated when mixed with SF or S [11]. The SCMs reacted with CH which liberated by cement hydration process and converted it to C-S-H gel which is responsible for improving the concrete properties.

The mixture results M4 and M6 showed that S reacts faster than FA especially, at an early age. However, it had a slow pozzolanic reaction, so the early concrete properties were improved by using S with FA. The SF reacted with CH faster than FA and S, so its influence appearedat the early age. Its reaction started during three or four days [12]. The SF improved the microstructure not only by its pozzolanic effect o but also by its micro filler effect. It had fine particles which fill the pores, capillary pores, and micropores in the microstructure of concrete.

In the combination of FA, SF, and S. The SF and S started reactions with CH which liberated from cement hydrations process and converted it to secondary C-S-H gel. It is precipitated with CH and ettringited around FA particles. It has increased the FA pozzolanic reaction rate by breaking down its glass and performing C-S-H gel. In the same time, the SF reacted with CH and converted it to secondary C-S-H gel which increased the early strength and played micro filler role as its particle fineness by filling pores in microstructure and C-S-H. In the same time, SF filled all micropores in the microstructure, so the microstructure became denser and stronger. The combination of SCMs complemented the pozzolanic and filler effect role to improve the concrete microstructure and enhance its properties.

V. Conclusion

From the whole investigation and research, the following conclusions can be drawn:

- Pozzolanic materials have significant influence on workability and mechanical properties of green concrete.
- Using high volume of SCMs (quarterly system)up to 50% enhanced the mixture of workability with lower dosage of superplasticizers.

- All quarterly system mixtures showed good workability than M1.
- Using high volume of SCMs (quarterly system) up to 50% improved the sustainable concrete compressive strength. The mixture M4 resulted in increasing S proportion to 30% in blended mixture that had an inverse effect on compressive strength. The mixture M3 resulted in observed compression strength that increased with increasing FA in blended mixture. Mixing SCMs within the range of (15 to 20) % with each other in blended mixture improved compressive strength. The mixtures M5 and M6 results proved it. The optimum mixing quarterly system was 50PC20FA15S15SF.
- Using high volume of SCMs (quarterly system) up to 50% improved the green concrete splitting tensile strength. The mixtures M5 and M6 results proved it. Utilizing FA or S in percent excess more than 20% had an inverse effect on splitting tensile strength. The optimum mixing quarterly system was 50PC20FA15S15SF.

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