Australian Journal of Basic and Applied Sciences, 7(4): 253-259, 2013
ISSN 1991-8178

Production Yield, Fineness and Strength of Cement as Influenced by Strength Enhancing Additives

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Abstract: The use of additives enabled producers to achieve cement fineness, production output and other qualities, which otherwise would be hardly possible. A research comprising four projects was conducted to evaluate production output, grindability/fineness, and strength-enhancing effects of incorporating SikaGrinds874MY (SG) on ordinary Portland cement (OPC). In projects I and II, OPC 42.5R was used, and sustainable cement (OPC+10% fly ash) was used in project-III. Project-IV utilized OPC +26% fly ash +12% limestone. Conventional strength enhancer (SE) was applied using the following proportions: 0.0%, 0.05%, 0.19%, and 0.1%. SG was used at 0.015%, 0.04%, 0.05%, and 0.035% by weight of cement in the four projects, respectively. Production increased by 20.8%, 13.5%, 12.5%, and 10.5% by using SG. Blaine fineness considerably improved. Moreover, the compressive strength of mortar was significantly enhanced because of the inclusion of SG. Results show an increase in 14.1%, (5.0%–11.5%), 8.0%, and 14.2% at 2 days; 7.3%, (10.5%–6.9%), 4.1%, and 5.2% at 28 days for the four projects. Thus, compared with SE, SG is a new solution and an opportunity to improve production, grindability/fineness, and strength of cement. SG can also reduce energy demand for OPC toward sustainable cement manufacturing in the future.

Key words: SikaGrinds874MY (SG); strength enhancer (SE); sustainable cement; production output, fineness, compressive strength of cement

INTRODUCTION

In the mid-1930s, cement plants started to use cement additives to increase the production volume of cement. Since then, the use of additives became inherent in cement production. Until the 1960s, the basic materials were amines, amino-acetates, phosphate, lignosulfonate, acetic acid, glycols, and gluconates. Developed countries, such as Japan, United States, Germany, and Russia, conducted intensive research. The application of grinding aids became more diversified. China is the world's largest cement producer, but its development of grinding aids was slow and only started by the end of the1950s. Experiments used pulp waste and detergent waste. Results showed poor performance of these aids. In the beginning of the 1970s, the use of amine glycol and glycol base as grinding aids demonstrated better performance. However, the high cost of materials, limited availability, and uncertain quality limited further development. In the last decades, the main focus was to find new and more efficient amines to enhance grindability and hydration. In 2007, Sika was the first construction chemicals supplier that launched sustainable construction. The company patented the SikaGrind 800 series, a new technology for green products based on polycarboxylic ether polymers. SikaGrind 800 series shows superior performance in grindability, strength enhancement, and flowability compared with the conventional glycol and amine-glycol-based grinding aids.

Note that the total energy consumption for cement production is in the range of 90 kWh/t to 113 kWh/t. Approximately 71% to 85% of the total energy expended in the production of cement is allotted for size reduction of the raw materials and coal grinding. The grinding cement process alone consumes approximately 30 kWh/t to 40 kWh/t (36%). However, only 60% to 70% of the total energy for grinding cement is effectively used for size reduction and grinding of clinker, gypsum, and other supplementary materials. Thus, the energy effectively converted into size reduction work is approximately 21% to 25% of the total energy for cement production. The rest of the 30% to 40% of the total energy for grinding cement is wasted by the following: friction between particles, friction between particles and mill elements, generation of sound, heat and vibration, material turbulence inside the mill, and loss of mechanical efficiency from motor to mill. The highest influence on the energy consumption is provided by the type of grinding system. Energy consumption for normal cement fineness at 3600 cm^2/gm varies according to the system. Generally, 44, 41, 35, and 32 kWh/t are consumed by tube mill open circuit, tube closed circuit, tube mill with pre-grinding unit, and finish grinding system, respectively. Other factors are mill feed (i.e., composition, grindability of components, grain size distribution,

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and moisture content), technical condition (i.e., main machines, general wear parts, mill internals, ball charge, etc.), mill control (i.e., manual and automatic control), and use of grinding aids. Waste energy in the grinding process is an important consideration in terms of the increase in the cost of the final product, especially with today's continuous rise in energy costs and limited sources.

To reduce agglomeration during the grinding of clinker, grinding aids are usually added in the range of 0.02% to 0.1% of the manufactured cement weight. Chemical basis of the grinding aids includes ethanolamines, such as triethanolamine, monoethanolamine, and triisopropanolamine, as well as glycols, such as ethylene glycol and propylene glycol. The high polarity in their chemical functioning groups of -OH, $-NH_2$, -COOR, $-SO^-_3$, etc. causes the tendency to adsorb on electrostatic surfaces from fractured covalent bonds of Ca-O, Al-O, and Si–O, and to resist the rebinding phenomenon, greatly assisting the formation of further cracks in the grinding process (Jeknavorian *et al*. 1998). Eventually, better dry powder dispersion of the ground cement increases mill productivity and cement fineness for the same energy consumption, and produces improvement in flow, leading to faster unloading and improved storage volume of bulk cement storage. Moreover, the filler and the pozzolan contents in blended cement production can be increased to achieve a cost-effective level without deterioration effects. For example, quaternary blended RPTS cement (i.e., cement made with slag, palm oil fuel ash, rice husk ash, and timber ash with a replacement of OPC of up to 66%) can be used for the production of high-strength (100 MPa to 120 MPa), sustainable, and high-performance concrete (Lai, 2009).

The limitations of research on grinding aids remain an obstacle to the development of grinding aids technology. Most of the studies conducted on the hydration processes, interaction mechanisms of the main cement compounds, and the comparison of the effect between higher dosage (0.1% to 1% of the cement weight) and common dosage (0.02% to 0.05%) of grinding aids (Ramachandran, 1976; Heren and Olmez, 1996; Aggoun *et al*. 2008) did not focus on grinding efficiency. In a recent study of Teoreanu and Guslicov (1999), a specific power consumption value of 25 kWh/t to 100 kWh/t was used in cement manufacturing plants for conventional amine-glycol and glycol bases However, no superior performance was observed or no new polymer grinding aids for grindability and strength enhancement in grinding cement were formulated. Majority of the studies in literature (Teoreanu and Guslicov, 1999; Joseph and Salim, 2011) are focused on the laboratory-scale milling control system and may not represent the actual production scale results. Therefore, a comparative study was carried out to evaluate the performance of polycarboxylic ether (PCE)-based new polymer grinding aids (SikaGrind 874MY) and the conventional amine-glycol- and glycol-based grinding aids (conventional/existing strength enhancer (SE)). The parameters used were production output, fineness, and mortar compressive strength.

Methodology:

Materials and Samples:

Industrial clinker used for the production of ASTM C 150 Type I cement, fly ash (FA) that meets the requirements of ASTM C 618 Class N, limestone, and gypsum were used in this study. The chemical compositions of these materials are presented in Table 1. In projects I and II, OPC 42.5R was produced by inter-grinding 95% clinker and 5% gypsum. Sustainable cement was produced with (85% clinker + 10% FA + 5% gypsum) and (62% clinker + 26% FA + 12% limestone) in projects III and IV, respectively. The physical and chemical analyses of clinker, FA, limestone, and gypsum are listed in the Table 1.

Table 1: Physical and chemical analysis of clinker, FA, limestone, and gypsum.

Properties	Clinker	FA	Lime stone	Gypsum
Specific gravity	3.15	2.45	2.67	2.2
SiO_2	21.00	52.50	0.0	0.0
Al_2O_3	5.31	27.52	0.0	0.0
Fe_2O_3	3.44	5.50	0.0	0.0
CaO	65.00	4.50	56.0	36.36
MgO	1.50	0.40	0.0	0.0
SO_3	0.26	0.25	0.0	51.95
Na_2O	0.50	0.40	0.0	0.0
K_2O	0.25	1.40	0.0	0.0
LOI (%)	0.24	2.00	44.0	63.64

Commercially available SikaGrind 874MY (PCE-based polymer) supplied by Sika and SE with conventional amine and glycol-based SE supplied by the local grinding aids supplier were used. SikaGrind 874MY (SG) was used during the clinker grinding process in the production plant trial run. Its performance in production output, Blaine, residue on 45 µm sieve, and particle size distribution were benchmarked to the conventional SE. The molecular weight of PCE polymer, a comb-type polymer, was analyzed and characterized with gel permeation chromatography (GPC). GPC analysis was conducted under the following conditions:
Columns: Shodex Asahipak GS series
Flow rate: 1 ml/min

Temperature: 40 0C
Eluent: Acetonitrile and 50mMNaNO3 in the ratio 3/7 (v/v)
Injection volume: 10 µm
Detector: Refractive index and ultraviolet detector
The PCE polymers and their molecular weights are presented in Table 2.

Table 2: Physical and chemical analyses of the SE and SG.

Properties	SE used in project			SG
	II	III	IV	
Average relative molecular weight (g/mol)	143	143	101	6500
Solid content (%)	90.0	95.0	90.0	90.0
Color	Dark brown liquid	Dark brown liquid	Dark brown liquid	Brownish liquid
Density (kg/l)	1.18	1.19	1.18	1.15

A total of 10 test series (Table 3) for the four projects were conducted to determine the effect of production yield or output on the variations of SG dosage against existing productions that operate with or without SE and use production control for the normal routine of quality cement performance. In each testing, a sampling of the 5 kg sample for testing the Blaine number, residue at 45 µm, particles size distribution, and mortar strength was processed after the first 6 h. At this time, the production line had already reached stable condition. During the production trial run, the SEs were dosed into the raw mill conveyor belt by an automated dispensing pump to maintain a digitally displayed flow rate, which is equivalent and consistent to the targeted dosage. The production output or yield, milling temperature control at 102 ^{0}C to 108 ^{0}C, and power consumption could be directly read from the online center control. In project II, the production sample without SE was employed for the net chemical activation test program. The strength test was conducted according to the EN196-1. The sample with SG or SE was treated during the mixing process of fresh mortar without interground basis. To ensure that the trial run results would be reproducible under real production scenarios, the local clinker, limestone, and the gypsum from the same delivery lot, as supplied by the existing local integrated cement plant, were utilized.

Table 3: Cement type and doses of SE and SG used in the four projects.

Test No.	Project	Type cement and grade	Dosage of SE and SG (%)
1	Project I	OPC42.5R	0.00% SE
2		OPC42.5R	0.015% SG
3	Project II	OPC42.5R	0.00% SE
4		OPC42.5R	0.05% SE
5		OPC42.5R	0.04% SG (Blaine 3880 cm^2/gm)
6		OPC42.5R	0.04% SG (Blaine 3608 cm^2/gm)
7	Project III	Sustainable cement 42.5R (10%FA)	0.19% SE
8		Sustainable cement 42.5R (10%FA)	0.05% SG
9	Project IV	Sustainable cement 42.5R (26%FA+12%Lime stone)	0.1% SE
10		Sustainable cement 42.5R (26%FA+12%Lime stone)	0.035% SG

Instruments and Equipment:

In projects I and II, the production used the 580 kW Polycom pre-grinder with a maximum capacity 145 ton/h. The 2200 kW ball mill maximum capacity of 550 tons/h was derived using the third generation separator. The milling process used a closed circuit system, as shown in Fig. 1. Projects III and IV used the same closed circuit system but utilized the ball mill maximum capacity of 80 ton/h and second-generation separator without the pre-grinder milling system. GPC was conducted using the Shimadzu LC-VP. Fineness of cement was determined using the Automatic Blaine machine PC-STAR (Zunderwerke Ernst Brun), and sieving was performed through the 45 µm sieve provided by Hosokawa Alpine air jet sieve. The compressive strength of mortar was determined using the computer-based compression testing machine (Brand Unit test Sdn Bhd) with a capacity of 3000 kN.

Mortar Prism Preparation and Testing:

Mortar preparation and casting were conducted according to the BS/EN 196-1:2005 using the standard mortar prism with 40 mm × 40 mm × 160 mm size. Water-to-binder ratio was fixed at 0.5 for all of the specimens. Prepared mortar prisms were taken from the mold after one day and placed into the water tank for curing at room temperature of 20± 2 ^{0}C until the desired age of testing was achieved. Finally, prisms were used for the compressive strength test of mortar at the ages of 1, 7, 28, 56, and 90 days.

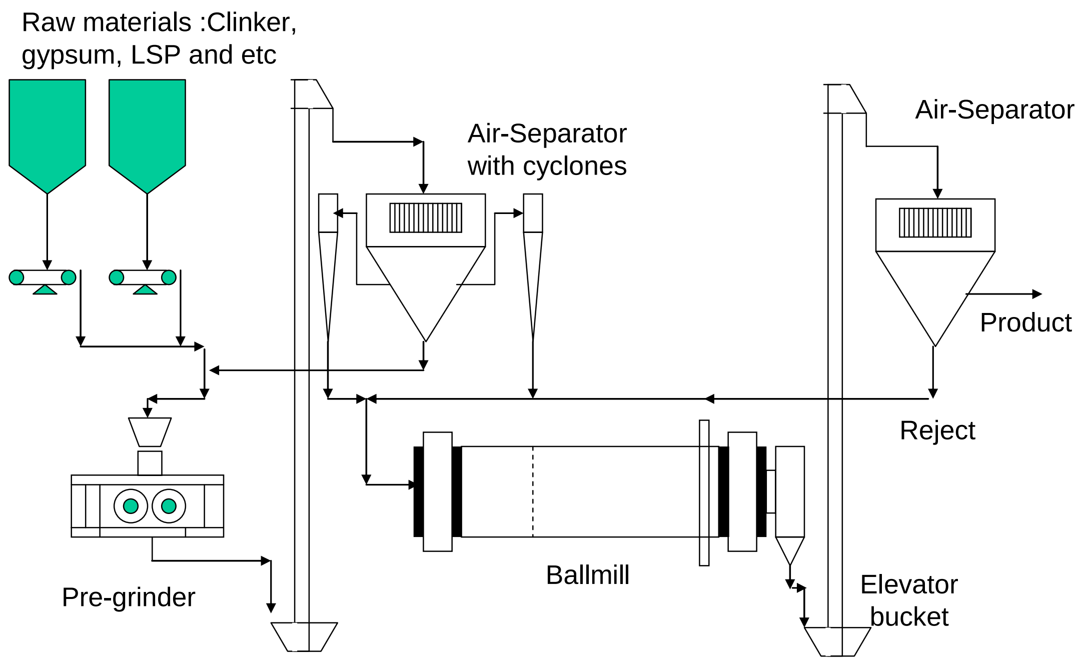

Fig. 1: Simplified configuration process for a closed circuit system of the studied cement plant.

RESULTS AND DISCUSSION

Production Yield or Output:

The production output of the cement industry is important for economic purposes. Therefore, the effects of SE and SG on the production yield or output were evaluated. Results are presented in Table 4. The production capacities of the different projects are significantly enhanced by the application of SG. In project I, production increased by more than 20%, and an increase of 23.5% was achieved in project II compared with treatments without SE (0% SE). Production yield also increased because of SG inclusion compared with conventional SE doses (Table 4). Increments of production output were 13.5%, 12.5%, and 10.5% for projects II, III, and IV, respectively. However, with lower doses of SG application, production yield was greater than that of the existing/conventional SE.

The improved production output and fineness might have occurred because of the existence of a stronger hindrance repulsive force for the particles' better dispersion caused by the PCE polymer, unlike in the conventional amine-glycol base grinding aids (Uchikawa *et al*., 1997; Lai, 2010), as shown in Fig. 2. Thus, the fine particles were more effective in dispersing to form a finer grinding stage, free from agglomeration/rebinding effects, and faster or easier to separate to form the finished cement when going through the air separator. Rejection was lower for the SG than for the SE in the separator, and output was higher and particles were finer than those for SE. Better dispersion force can avoid the fine particle-coating formation in the ball media and the ball mill liner, which normally occurs in the milling process without using the grinding aids, causing poor grinding efficiency. At the end of the production trial, the ball mill was opened. Coating formed on the ball media and liner in the case study without SE but not in the case studies that used SE and SG. Thus, the production output decreased according to the sequence SG > SE > without SE.

Effect of SG on Fineness of Cement:

Fineness of cement is one of the important properties of cement. Therefore, fineness of cement was determined by the Blaine number and sieving through 45 µm sieve. The results are presented in Table 2. Fineness of the final product (cement) of the four projects remarkably increased because of the incorporation of SG compared with those with existing SE doses and without SE milling system. Although the doses of SG were lower than those of SE, fineness of cement significantly increased. In project II, the introduction of the same SG doses increased production output by 23.5% compared with that in the case without SE. However, production only improved by 3.2% compared with the case with conventional SE (0.05% SE) if the Blaine fineness of cement was controlled at 3880 cm^2/g. Although the lower dosage of 0.04% SG was used to control the lower Blaine fineness at 3608 cm^2/gm and 45 um residue (3.0%), the production output increased to 13.5% compared with the case with SE (3543 cm^2/g, 3.8%). The reasons for these improved results are the same as those mentioned in Section 3.1 and Fig. 2. (i) The PCE polymer is more effective in dispersing the fineness because of the thicker gel layer, which provides higher hindrance steric repulsive force than the conventional SE. Consequently, the particles are prevented from agglomerating, and coating ball media/liner effects are eliminated during milling in the ball mill. Thus, better grindability, better output, and finer particles are attained, unlike in SE. (ii) Separating the fine particles can be more effective because of the more effective powder dispersion from agglomeration in the air separator. Thus, the reduction in rejection leads to the increase in feeding raw mills. In other words, better output than that with SE is achieved. However, a slightly higher Blaine value and a lower residue were obtained as well. For example (production and fineness values of project II, as shown in Table 4), if control targeted the same Blaine values of 3543 cm^2/g and 3380 cm^2/g as those of the 0.05% SE and 0% SE, the output of SG predicted in Fig. 3 would be approximately 215 tons/h or 16% higher (corresponding to 0.05% SE) and 225 tons/h or 32.35% higher (corresponding to 0%SE). Therefore, SG can be used effectively to increase the grindability and fineness of cement compared with SE and without the SE milling system. SG contributes to the reduction of the energy required to maintain the same fineness of cement.

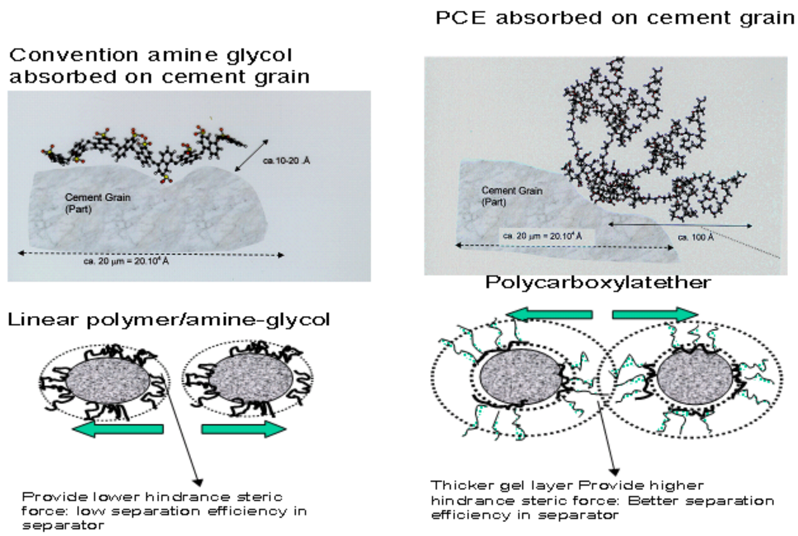

Fig. 2: Hindrance steric force dispersion for PCE when absorbed on cement grain.

Table 4: Effect of SE and SG on fineness and production yield in the four projects.

Projects	Dosage of SE and SG (%)	Production (ton/h)	Production increase (%) against		Fineness	
			0% SE	Control SE	Blaine (cm^2/g)	Residue on 45 µm
Project I	0.00% SE	120	-	-	2850	14.8
	0.015% SG	145	20.8	-	3420	9.4
Project II	0.00% SE	170	-	-	3380	6.0
	0.05% SE (Control)	185	8.8	-	3543	3.8
	0.04% SG[a]	191	12.3	3.2	3880	2.8
	0.04% SG[b]	210	23.5	13.5	3608	3.0
Project III	0.19% SE (Control)	40	-	-	4050	2.5
	0.05% SG	45	-	12.5	4270	1.7
Project IV	0.1% SE (Control)	95	-	-	4200	4.8
	0.035% SG	105	-	10.5	4400	3.5

[a]Blaine fineness 3880 cm^2/gm; [b]Blaine fineness 3608 cm^2/gm

Compressive Strength of Mortar:

Compressive strength of cement is the most essential property in relation to its practical application in construction works. Thus, compressive strength of cement mortar was determined according to the BS/EN 196-1 testing standard. Results are given in Tables 5 and 6. Table 5 shows that compressive strength of the produced cement significantly increased at the early age and later ages compared with that of cement with conventional SE doses. With lower doses of SG, strength of the produced cement remarkably increased in the four projects compared with that of conventional SE application. The increased strength of cement mortar was caused by the following reasons: (i) greater fineness and more reactive capacity especially at the early age of cement hydration, and (ii) ability of the chemical functioning groups of the SG to form a stable complexometric with the metal ions, accelerating the dissolution of the mineral phase of C_3S, C_4AF, and C_3A, which in turn contributes to better crystallization and nano-densification effects during hydration of the cement [9] in the early to later age (Fig. 4). The reasons for the greater strength development of SG mixed samples were evaluated by the net chemical activation test by adding SG and SE to OPC. The results are presented in Table 6. Table 6 shows that even without the contribution strength caused by the required more grinding of fine particles, the early strength at 2 days and the ultimate strength at 28 days were significantly enhanced by 11.4% and 9.0%, respectively, by the net chemical activation. Conventional SE only enhanced strength by 6.8% and 2.4% at the same ages. As regards the net chemical activation test on strength, SG is better than conventional SE.

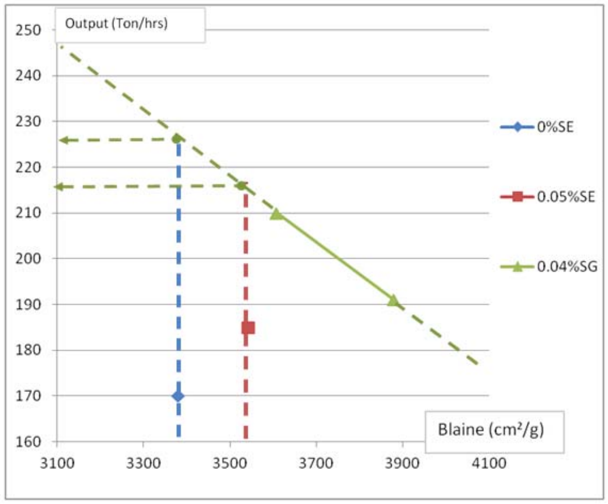

Fig. 3: Production output vs. Blaine value.

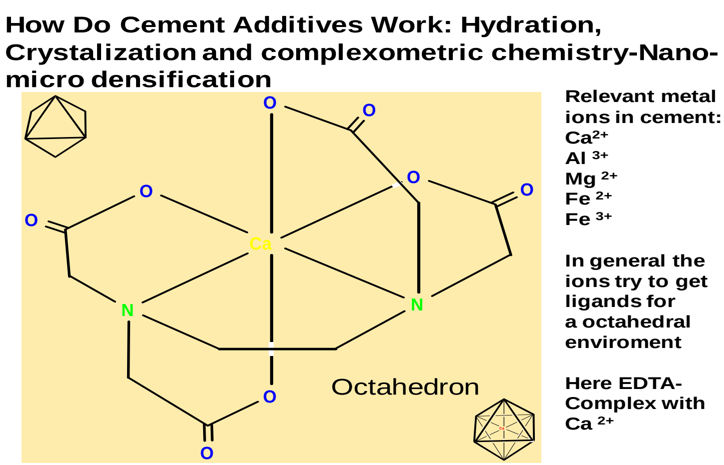

Fig. 4: Complexometric of polymer SG with metals.

Table 5: Compressive strength of the produced cement as influenced by SE and SG.

Project	Dosage of strength enhancer SE and SG (%)	Compressive strength in MPa at ages				Compressive strength enhanced in % compared to Control SE and (0% SE) at ages			
		1 day	2 days	7 days	28 days	1 day	2 days	7 days	28 days
Project I	0.00% SE	10.4	18.7	-	47.4	-	-	-	-
	0.015% SG	11.0	21.4	-	50.9	- (*5.7*)	- (*14.4*)	-	7.3 (-)
Project II	0.00% SE	-	22.0	41.0	51.0	-	-	-	-
	0.05% SE (Control)	-	27.7	42.9	53.0	-	- (*25.9*)	- (*4.6*)	- (*3.9*)
	0.04% SG[a]	-	30.9	47.3	62.0	-	11.5 (*40.4*)	10.2 (*15.3*)	16.9 (*21.6*)
	0.04% SG[b]	-	29.1	44.2	58.6	-	5.0 (*32.2*)	3.0 (*7.8*)	10.5 (*14.9*)
Project III	0.19% SE (Control)	13.0	21.1	32.7	50.5	-	-	-	-
	0.05% SG	13.8	22.8	35.4	52.6	6.1 (-)	8.0 (-)	8.2 (-)	4.1 (-)
Project IV	0.1% SE (Control)	-	21.0	34.0	47.5	-	-	-	-
	0.035% SG	-	24.0	42.5	50.0	-	14.2 (-)	25.0 (-)	5.2 (-)
[a]Blaine fineness 3880 cm^2/gm; [b]Blaine fineness 3608 cm^2/gm									

Table 6: Net chemical activation test of OPC samples treated with SG and SE.

Project	Dosage of strength enhancer SE and SG (%)	Compressive strength in MPa at ages			Strength enhanced in % compared with Control SE and (*0% SE*) at ages		
		2 days	7 days	28 days	2 days	7 days	28 days
Project II	0.00% SE	22.0	41.0	51.0	-	-	-
	0.05% SE (Control)	23.5	42.0	52.2	- (6.8)	- (2.4)	- (2.3)
	0.04% SG	24.5	43.2	55.6	4.2 (*11.3*)	2.9 (*5.3*)	6.5 (*9.0*)

Conclusions:

Based on the experimental test results of the four different projects, the following conclusions are drawn:

(i) Unlike the conventional SE with lower doses of PCE base polymer, the SG can increase production output and fineness. Therefore, SG is a promising grinding aid to improve production capacity/output, grindability, strength, and fineness of cement.

(ii) Based on net chemical activation test results, the chemical reactivity of SG is better than that of conventional SE. Thus, SG contributes to the strength enhancement of cement.

(iii) SG can be applied to the production of economically sustainable cement by using FA from 10% to 26% or the combination of 26% FA + 12% limestone, which can reduce clinker consumption. SG has positive effects on the reduction of carbon dioxide gas emission during cement manufacturing. Thus, SG can contribute to formulating a sustainable concrete construction process and to building a sustainable world in the future.

ACKNOWLEDGMENT

The authors are grateful to Universiti Kebangsaan Malaysia (UKM) for providing us support and encouragement while conducting this research. We also acknowledge the Sustainable Construction Materials and Building System research group of UKM and the staff that assisted us in one way or another.

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