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# Innovative Cement Additives Quality Improvers in Sustainable Cement and Concrete

(Kualiti Inovatif Aditif Simen Penambah Baik Mapan dalam Simen dan Konkrit)

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ABSTRACT

*Cement industries globally produced about 2.282 billion ton/year and 25 billion tons of concrete are produced yearly all over the world, necessary measures are to be taken to reduce energy use along with the prevention of environmental degradation, depletion of the limited resources and contribute 7% to global warming effects due to the release of carbon dioxide to the atmosphere. Cement additives quality improver polymer (CAQIP) was developed from synthesized polymer, waste materials derived from petro-chemical and palm oil waste for production of sustainable cement. Industrial scale trial in a local cement plants by dosing 0.009%-0.690% CAQIP significant improved productivity, 8.3-27.5% efficiency in saving, 24.73-86.36% clinkering energy and 7.7-21.57% grinding energy in the production of Ordinary Portland Cement and sustainable cement. Strength quality improved 7.31-34.8% (2 day) and 3.85-57.58% (28 day). Carbon dioxide and others toxic gases emission was reduced 21.90-90.0% by replacing clinker with waste material such as fly ash (25-35%), out-spec clinker (50-100%) and limestone waste (5-25%). The developed CAQIP significant improved productivity, quality strength, reduced $CO_2$ emission, grinding & clinkering energy and enhanced production of sustainable cement and concrete in Malaysia.*

*Keywords: Cement additives; clinkering and grinding energy; palm oil waste; quality improver polymer; sustainable cement and concrete*

ABSTRAK

*Industri simen global menghasilkan kira-kira 2.282 bilion tan/tahun dan 25 bilion tan konkrit dihasilkan setiap tahun di seluruh dunia, langkah perlu diambil bagi mengurangkan penggunaan tenaga di samping mencegah kemerosotan alam sekitar, penyusutan sumber terhad dan menyumbang 7% kepada kesan pemanasan global disebabkan oleh pelepasan karbon dioksida ke atmosfera. Polimer penambah baik kualiti aditif simen (CAQIP) telah dibangunkan daripada polimer sintesis, sisa bahan daripada petro-kimia dan sisa minyak sawit untuk penghasilan simen yang mapan. Percubaan skala perindustrian di logi simen tempatan menggunakan dos 0.009-0.690% CAQIP telah meningkatkan produktiviti secara bererti, 8.3-27.5% kecekapan dalam penjimatan, 24.73-86.36% tenaga klinker dan 7.7-21.57% tenaga pengisar dalam pengeluaran Simen Portland Biasa dan simen yang mapan. Kualiti kekuatan meningkat kepada 7.31-34.8% (2 hari) dan 3.85-57.58% (28 hari). Pelepasan gas toksid karbon dioksida dan lain-lain berkurangan sebanyak 21.90-90.0% dengan menggantikan klinker dengan sisa bahan seperti abu terbang (25-35%), klinker tidak mengikut spesifikasi (50-100%) dan sisa batu kapur (5-25%). CAQIP yang dibangunkan telah meningkatkan produktiviti, kualiti kekuatan, mengurangkan pelepasan $CO_2$, tenaga pengisar dan klinker serta meningkatkan pengeluaran simen dan konkrit mapan di Malaysia.*

*Kata kunci: Aditif simen; polimer penambah baik berkualiti; simen dan konkrit mapan; sisa sawit; tenaga klinker dan pengisar*

## INTRODUCTION

The use of cement and concrete is essential for the rapid urbanization all around the world. Nowadays, conventional Ordinary Portland Cement (OPC)-based concrete is one of the most versatile and extensively used man-made construction materials worldwide. It is considered as a key element in social, economic and infrastructural development because cement and concrete are vital construction materials in building many mega infrastructures such as buildings, roads, culverts, bridges, flyovers, tunnels, river protection structures and railways.

In the cement production, the main thermal energy is used during the burning process (Specific thermal energy = 1111 kwh/ton to 1387 kWh/Ton) for clinkering process. Thermal energy accounts for about 20–25% of the cement production cost. The typical electrical energy consumption of a modern cement plant is about 110-120 kWh per ton of cement (Alsop 2005). The production of cement and concrete in the world is about 2.282 billion ton and 25 billion tons of concrete per year. Cement production in Malaysia alone is about 20 million ton per year and this segment of industry consumed about 12%

of total energy in Malaysia (Madlool et al. 2011). Cement industry contribute 7% of the global warming/greenhouse effect in the world (Karim et al. 2013; Kibert 2009; Lai 2010). The critical risk of depletion of the natural deposits limited resources materials from the heavily mining industry for clinkering raw materials.

Therefore focus was given on the reduction of energy, reduction depletion of natural deposits raw materials and energy related environmental emissions locally and globally (WBCSD 2012). Thus, necessary measures and research and development are to be taken in the sustainable cement production with cement strength enhancing additives (Lai et al. 2013) to reduce energy use along with the prevention of environmental degradation, depletion of the limited resources and global warming effects due to the release of carbon dioxide to the atmosphere from the production of cement.

For sustainable development purposes, the development of cement additives chemicals was formulated with the petro chemical waste and palm oil waste. The objective of this study was to investigate the performances of a cement additive quality improver polymer (CAQIP) in the local cement plants for production of Ordinary Portland Cement (OPC) and sustainable cement. The production of sustainable cement in this study was produced by replacing the clinker with waste materials such as the fly ash (30%-60%), out-spec clinker (50-100%) and limestone waste (25%). The CAQIP was formulated from a synthesized polymer, local petro chemical waste and palm oil waste. In this study their performances to improve the production yield, compressive strength, grinding energy, clinkering energy, fineness and carbon dioxide emission with the CAQIP for production of OPC and sustainable cement.

## Experimental Details

### MATERIALS

Acrylic acid (AA) monomer 99.9% purity and Allyl mono polyethyleneglycol (APEG) 95% purity with molecular weight, $M_w$ = 2000g/mol macro-monomer were supplied from Kelong Chemical (Liaoyang) Industrial Co., Ltd, China. Ammonium persulfate (AP) with 98.6% purity was supplied from ABC Chemicals (Shanghai) Co., Ltd China. Petro chemical waste (PCW) was supplied by Optimal Chemical (M) Sdn Bhd and the Palm oil waste (POW) were supplied by Lereno (M) Sdn Bhd. Conventional amine and glycol-based strength enhancer (CSE) supplied by a existing local grinding aids supplier were used. All the raw reagents, monomers, macro-monomer and raw materials were used without further purification.

Sustainable cement was produced in local Cement plants A, B and C by using their existing clinker, out-spec clinker (OSC), limestone waste (LSPW) and fly ash (FA) as in the Table 1.

The CAQIP and CSE was pumped and injected into the ballmill during the clinker grinding process in the production plant trial running according to the dosage specified in Table 1.

### SYNTHESIS POLYMER AND PREPARATION OF CAQIP SOLUTION

The cement additive quality improver polymer (CAQIP) was prepared according to the formulation in Table 2. During the synthesis polymer, the APEG melted at 90°C in a steam jacket lined reactor equipped with propeller (6000 L) then cool down to 50°C and the water and AA was loaded in slowly while mixing at 60 rpm. The reactant

TABLE 1. Cement type and dosage of CAQIP and CSE used in the three cement plants

| Cement Plant | Cement type | Dosage CAQIP (% w/w) | Dosage CSE (% w/w) |
|---|---|---|---|
| Cement Plant A | OPC 42.5N | 0.000 | 0.000 |
| | OPC 42.5N with 50-100% OSC | 0.0126 and 0.030 | 0.000 |
| Cement Plant B | OPC 42.5R | 0.000 | 0.000 |
| | OPC 42.5R | 0.030 and 0.040 | 0.090 |
| | Composite cement 42.5R with 25-38% (LSPW+FA) | 0.035 | 0.000 |
| | Composite fly ash cement 42.5R (25-35% FA) | 0.035, 0.059, 0.133 and 0.32 | 0.000 |
| | Composite pozzolanic (30-60% FA) | 0.500 and 0.690 | 0.000 |
| Cement Plant C | OPC 52.5R | 0.000 | 0.000 |
| | OPC 52.5R | 0.030 and 0.040 | 0.090 |

TABLE 2. Formulation synthesis polymer and production of CAQIP solution

| | Composition (% w/w) | | | | | |
|---|---|---|---|---|---|---|
| Polymer solution | APEG | AA | Water | AP | PCW | POW |
| CAQIP solution | 41.80 | 7.60 | 24.52 | 2.08 | 14.00 | 10.00 |

was mixed for half an hour until it forms a miscible and homogeneous solution. The pre-diluted 25% AP solution were added 2 times in 1 h to the reactor under vigorous stirring. The reactor temperature was elevated to 65°C and maintained at this temperature for 6 h to complete the copolymerization process. After the 6 h, copolymerization sampling the viscous brownish polymer for gel permeation chromatography (GPC) tests to ensure the actual molecular weight. The copolymer molecular weight ($M_w$) was control from 5000 to 7000 g/mol. Finally, the reactant was cool down to 30°C then the PCW and POW was added in slowly while mixing and blending to form a homogeneous light brown CAQIP solution.

### DETERMINATION POLYMER MOLECULAR WEIGHT, FTIR AND $H^1$ NMR

The molecular weight of synthesized copolymer and CAQIP was analyzed and characterized with gel permeation chromatography (GPC), Shimadzu LC-VP. GPC analysis was conducted under the following conditions:

Columns: Shodex Asahipak GS series; Flow rate: 1 mL/min; Temperature: 40°C; Eluent: Acetonitrile and 50 mMNa$NO_3$ in the ratio 3/7 (v/v); Injection volume: 10 μm; and Detector: Refractive index and ultraviolet detector.

Fourier transform infrared (FTIR) analysis by the Spectrofotometer FTIR Perkin Elmer Model 1605 scans from 4000-500$cm^{-1}$. The proton nuclear magnetic resonance ($H^1$ NMR) was analized by the Spectrometer Varian INVOA 400 MHz with DMSO as solvent.

### FINENESS AND PARTICLE SIZE DISTRIBUTION TEST

Blaine number was determined by the Automatic Blaine machine PC-STAR (Zunderwerke Ernst Brun). Sieving was performed through the 45 μm sieve provided by Hosokawa Alpine air jet sieve, residue on 45 μm (R45) sieve and particle size distribution was determined by Laser Granulometer Mastersizer 2000 from Malvern instrument.

### PREPARATION MORTAR AND CONCRETE FOR COMPRESSIVE STRENGTH TEST

Mortar preparation and casting were conducted according to the BS/EN 196-1:2005. Another strength test according to the ASTM C109/C 109M-05 and ASTM C1437 to evaluate the CAQIP performance in strength enhancing efficiency in the sustainable fly ash cement contained (25% FA, 30% FA and 60% FA) and 25%-38% (LSPW+FA) against their existing OPC. Finally, prisms were used for the compressive strength test of mortar at the ages of 1, 2, 7 and 28 day. The compressive strength of mortar and concrete was determined using the computer-based compression testing machine (Brand Unit test Sdn Bhd) with a capacity of 3000 kN.

### SEM FOR HARDENED MORTAR AND CONCRETE

The hardened concrete was scan with the field emission scanning electron microscopy (FESEM), Zeiss, Germany model SUPRA 55VP and the energy-dispersive X-ray spectroscopy(EDX/EDS), Oxford, U.K model INCA.

## RESULTS AND DISCUSSION

### SYNTHESIZED POLYMER AND CAQIP PROPERTIES

The CAQIP preparations consist of two steps, copolymerization and blending of the synthesized copolymer with PCW and POW as in the Figure 1.

The synthesized copolymer and CAQIP was tested with NMR, FTIR and their results were shown in the Table 3. The synthesized polymer tested with GPC and their molecular weight was outline in Tables 4 and 5. From the GPC test, it was shown that the synthesized copolymer consist of four fraction with 98.33% polymer at average molecular weight at 5739 g/mol and the rest of the fraction is oligomers or unreacted monomers in the minor composition (total = 1.67%). Further confirmation from the NMR test in Table 3, the AA monomer double bond proton ($CH_2$=CH–, 6-8 ppm), APEG double bond proton ($CH_2$=CH–$CH_2$–, 5-6 ppm) peak was disappeared in the synthesized polymer shown that the copolymerization was completed to about 98.33%. The NMR strong peaks in the range 3-4 ppm also confirmed that side chain of polyethyleneglycol (–$CH_2$–$CH_2$–O–) in the synthesized copolymer (Table 3). Finger print FTIR in Table 3 also confirmed the chemical functional group carbonyl (C=O, 1725 $cm^{-1}$), ether (C–O–C, 1108 and 952 $cm^{-1}$), hydroxyl (O–H, 3434 $cm^{-1}$), methylene and carbohydroxyl ($CH_2$, C–O–H, 1458 $cm^{-1}$), exist in the synthesized polymer.

The $\Sigma M_w / \Sigma M_n$ = 1.33 for the synthesized polymer means much narrow molecular weight distribution than the CAQIP ($\Sigma M_w / \Sigma M_n$ = 9.05) since the CAQIP consist of other fragment (total 45%) oligomers average molecular weight at 533, 303 and 43 g/mol. The synthesized polymer showed the ether group FTIR (1108 $cm^{-1}$) in Table 3 and NMR (3.20 and 3.50 ppm) as ethylene oxide (–$CH_2CH_2O$–) side chain in Table 3. The CAQIP polymer mainly consist of three fraction with 55.00% polymer at average molecular weight at 5,600 g/mol and the rest of the fraction is oligomers or unreacted monomers in the minor composition (total = 45%). The NMR strong peaks in the range 3-4 ppm also confirmed that side chain of polyethyleneglycol (–$CH_2$–$CH_2$–O–) remained in this CAQIP (Table 3) after blended with the PCW and POW.

### CEMENT PLANT A: IMPROVED EFFICIENCY ENERGY, PRODUCTIVITY, STRENGTH AND REDUCED $CO_2$

Dosing 0.009, 0.0126 and 0.035% of CAQIP in the actual Cement Plant A trial with 100% out-spec clinker as in Figure 2 has increase the production yield from 120 to 130, 145.1 and 153 ton/h, respectively. The grind ability or grinding energy efficiency (kWh/Ton) improved 7.7% (1.26 kWh/Ton), 17.3% (2.84 kWh/Ton) and 21.57% (3.54kWh/Ton), respectively, (at the same Motor power drive = 1969 kW, saving grinding energy by achieving the

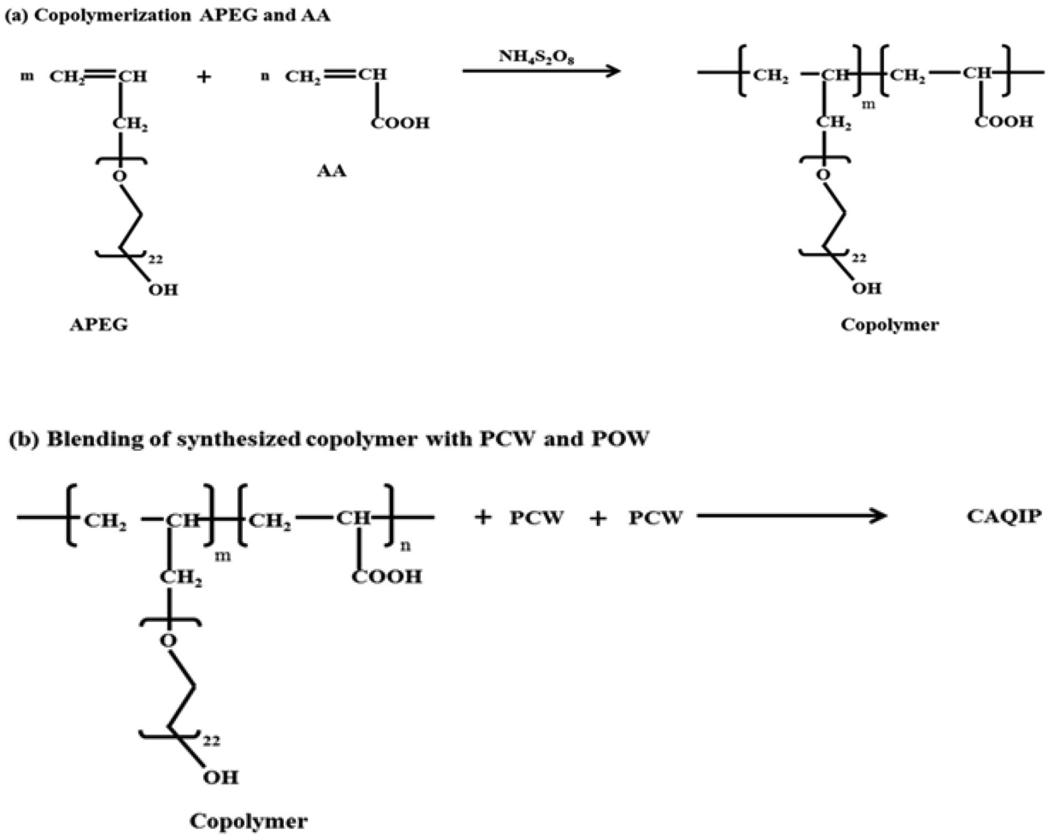


FIGURE 1. Schematic process of the (a) mechanism of copolymerization reaction, and (b) blending of synthesized copolymer with PCW and POW

TABLE 3. NMR Chemical shift and FTIR Chemical functional group

| Compound | Chemical Functional group | NMR Chemical shift | FTIR Wave length |
|---|---|---|---|
| AA | $CH_2$=C- | 6-8 ppm | - |
| APEG | $CH_2$=CH-$CH_2$- | 5-6 ppm | - |
| APEG | -$CH_2$-$CH_2$-O- | 3-4 ppm | - |
| Synthesized Polymer & CAQIP | C=O | - | 1725cm$^{-1}$ |
| Synthesized Polymer CAQIP | C-O-C | - | 1108cm$^{-1}$, 952cm$^{-1}$ |
| Synthesized Polymer CAQIP | -OH | - | 3434cm$^{-1}$ |
| Synthesized Polymer CAQIP | -$CH_2$- and C-O-H | - | 1458cm$^{-1}$ |
| Synthesized Polymer CAQIP | -$CH_2$-$CH_2$-O- | 3.2ppm, 3.5ppm | - |

TABLE 4. GPC fraction of synthesized copolymer

| Synthesized copolymer properties | Peak of chromatogram | | | |
|---|---|---|---|---|
| | 1st | 2nd | 3rd | 4th |
| Retention time (min) | 21.3 | 28.7 | 29.6 | 33.0 |
| Average molecule, $M_w$ (g/mol) | 5,739 | 700 | 617 | 442 |
| Average molecule, $M_n$ (g/mol) | 4,724 | 700 | 617 | 441 |
| ($M_w$/$M_n$) | 1.21 | 1.00 | 1.00 | 1.00 |
| Percentage fraction (%) | 98.33 | 0.38 | 1.03 | 0.26 |
| $\Sigma M_w$ (g/mol) | 5,654 | | | |
| $\Sigma M_n$ (g/mol) | 4,249 | | | |
| $\Sigma M_w / \Sigma M_n$ | 1.33 | | | |

TABLE 5. GPC fraction of CAQIP

| CAQIP properties | Peak of chromatogram 1st | 2nd | 3rd | 4th |
|---|---|---|---|---|
| Retention time (min) | 21.5 | 29.4 | 31.8 | 46.0 |
| Average molecule, $M_w$ (g/mol) | 5,600 | 533 | 303 | 43 |
| Average molecule, $M_n$ (g/mol) | 4,600 | 530 | 286 | 42 |
| ($M_w/M_n$) | 1.21 | 1.01 | 1.06 | 1.02 |
| Percentage fraction (%) | 55.00 | 3.16 | 33.38 | 8.46 |
| $\Sigma M_w$ (g/mol) | | 2,704 | | |
| $\Sigma M_n$ (g/mol) | | 299 | | |
| $\Sigma M_w / \Sigma M_n$ | | 9.05 | | |

targeted fineness in shorter time against the cement 0.000% CAQIP production yield = 120 Ton/h).

The productivity (Ton per labour man hour) increased to 8.3, 20.8 and 27.5%, respectively (base on existing equipment and 4 labour man hours). This indicated that the CAQIP significant improved production yield, grinding energy efficiency and productivity in cement production. The reduction in grinding energy efficiency was due to the CAQIP polymers providing the stronger hindrance steric repulsive force as in the literature (Lai et al. 2013) to de-agglomerate the raw mill particles, thus, much better grinding and separation out as finished good during the milling process against the milling process without CAQIP.

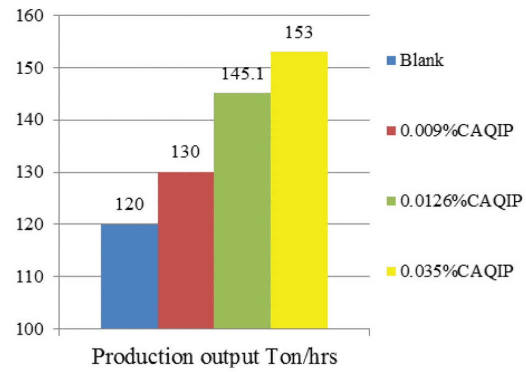


FIGURE 2. Production yield performance for CAQIP

Quality compressive strength in Figure 3, CAQIP improved 1.45, 6.28 and 11.11%, respectively, early strength at 1 day. Quality compressive strength improved 11.64, 14.10 and 11.70%, respectively, early strength at 2 day. However, the ultimate 28 day compressive strength increased to 3.85, 8.89 and 9.53%, respectively, against the OPC 42.5 N production without the CAQIP. This enable Cement Plant A produce higher grade 42.5R OPC instead of 42.5N without major investment plant and scarifying the loss in low productivity.

In short term, saving clinkering energy of 43.18 to 86.36% was possible using the 50 to 100% of out-spec clinker (Appendix 1). At the same time, $CO_2$ emission reduced 45.0 to 90.0% against their control/blank OPC

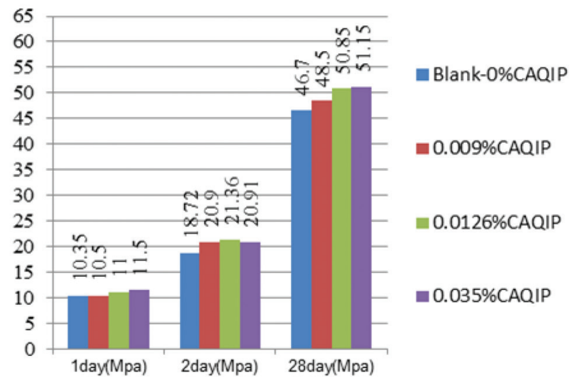


FIGURE 3. Compressive strength with CAQIP against the blank

cement. Due to this efficiency reducing energy & $CO_2$ emission, productivity and quality strength improved by the CAQIP, the Cement Plant A can produce the buffer stock of good quality cement in-time delivering without delaying for the general faster construction project especially for sustainable Mega Dam Construction Project in Malaysia.

## CEMENT PLANT B: IMPROVED EFFICIENCY ENERGY, STRENGTH AND REDUCED $CO_2$

Dosing 0.035% CAQIP has been tried in Cement Plant B for interground blended pozzolanic/composite total 25-38% (fly ash + Limestone waste) cement (42.5R Composite cement) and 25–35% fly ash low heat fly ash cement. In this trial, the production yield was maintained at existing production line, thus it could not gained the production yield increasing benefits but saving clinkering energy 32.98% and higher efficiency 29.3% reduction in $CO_2$ emission against their control OPC cement as shown in Appendix 1.

The low heat fly ash cement production was used in billion ringgit Malaysia Mega MRT (Mass Rapid Transit) precast tunnel linner segment projects in Malaysia. The fly ash cement has been produced successfully at their existing production yield but finer (Table 6) due to better grinding ability/efficiency and better early strength fly ash cement (Table 6) to cater the bottle neck demoulding time and transfer strength at 10hrs (>12 Mpa) for faster and efficient Mega MRT construction project. The successful plant trial precast concrete tunnel linner segment results shown that concrete grade 60 can be achieved >12 Mpa at 10 h although with this low heat fly ash cement (25-35% fly ash replacement the clinker) in the actual precast factory casting yard (Table 6). The concrete strength grade 60 base on this low heat fly ash cement has significant much better early strength (26.98%) especially at 10 h age against the normal low heat fly ash cement (35% fly ash cement) without CAQIP.

The durability of this interground fly ash cement is equivalent or better to the silica fume cement whereby its rapid chloride penetration test is about 360 Coulomb (specification is <1000 coulomb) suitable for designing the long service life concrete structure >100 years. The tunnel linner segment concrete ultimate strength with this 35% fly ash cement at 28 day can reach up from 70 to 80 MPa (Table 6).

In terms of micro-cracking against the silica fume cement concrete, it is well known that silica fume cement is sensitive in the early age of shrinkage-micro-cracks against the fly ash cement because the end product of hydration silica fume cement is majority of high shrinkage calcium-silicate base gel but the fly ash cement majority is much lower than shrinkage calcium-aluminosilicate base binding matrix. Another merit of the interground fly ash cement concrete can be self-healing effects by reacting itself the enscapsulated microspherical in Figure 4, fly ash with the

TABLE 6. Plant B: Production yield, particles size distribution, fineness, chemical activation and compressive strength

| Sample trial | Grinding aids dosage (%) | Production output/ yield (Ton/h) | Particles size distribution | | | Residue at 45 µm (%) | Blaine number ($cm^2/g$) | Compressive strength ($N/mm^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | d(0.1) (µm) | d(0.5) (µm) | d(0.9) (µm) | | | 10h | 1d | 2d | 7d | 28d |
| Blank[a] | - | 100 | 2.435 | 12.322 | 47.320 | 5.5 | 4500 | - | - | 15.80 | 24.47 | 39.89 |
| CAQIP[a] | 0.035 | 100 | 1.392 | 10.689 | 42.435 | 3.5 | 4600 | - | - | 21.29 | 30.00 | 44.80 |
| Blank[b] | - | 100 | 2.435 | 12.322 | 47.320 | 5.5 | 4400 | 18.90 | 34.40 | 44.22 | 61.33 | 80.00 |
| CAQIP[b] | 0.035 | 100 | 1.392 | 10.689 | 42.435 | 3.5 | 4600 | 24.00 | 37.29 | 46.42 | 66.60 | 81.00 |
| Blank[c] | - | - | - | - | - | 8.0 | 3500 | - | 100 | 100 | 100 | 100 |
| CAQIP[d] | 0.035 | - | - | - | - | 7.5 | 4500 | - | 103.60 | 137.24 | 143.81 | 110.27 |
| CAQIP[d] | 0.059 | - | - | - | - | 7.5 | 4500 | - | 96.43 | 156.71 | 162.52 | 123.24 |
| CAQIP[e] | 0.1333 | - | - | - | - | 7.0 | 4450 | - | 101.06 | 114.71 | 132.86 | 125.46 |
| CAQIP[e] | 0.320 | - | - | - | - | 10.0 | 4450 | - | 148.43 | 158.8 | 164.29 | 147.18 |
| CAQIP[f] | 0.500 | - | - | - | - | 7.5 | 4480 | - | 118.57 | - | 170.48 | 140.03 |
| CAQIP[f] | 0.690 | - | - | - | - | 7.5 | 4480 | - | 195.86 | - | 197.14 | 157.58 |
| CAQIP[g] | 0.500 | - | - | - | - | 5.0 | 4580 | - | 90.91 | - | 121.90 | 121.52 |
| CAQIP[g] | 0.690 | - | - | - | - | 5.0 | 4580 | - | 169.30 | - | 154.81 | 145.45 |

a. Mortar test 42.5R (composite cement) and 35% fly ash, b. Concrete test 42.5R (composite cement) and 35% fly ash, c. Mortar ASTM C109/C 109M-05 and ASTM C1437 test 42.5R OPC, d. Mortar ASTM C109/C 109M-05 and ASTM C1437 test composite cement (25FA+5%LSP), e. Mortar ASTM C109/C 109M-05 and ASTM C1437 test fly ash low heat (LH) 35%FA, f. Mortar ASTM C109/C 109M-05 and ASTM C1437 test fly ash 30%FA and g. Mortar ASTM C109/C 109M-05 and ASTM C1437 test fly ash 60%FA

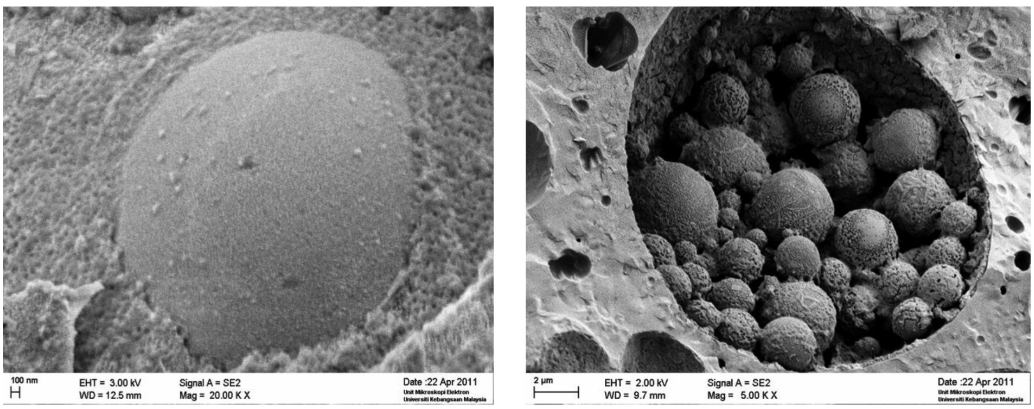


FIGURE 4. SEM hardened fly ash cement auto-healing effects

free lime from OPC hydration product within the cracks to form the secondary binding/sealed the cracks.

Surprisingly, we found the super-strength enhancing effect in Table 6 by optimised dosing 0.035-0.059% CAQIP whereby strength improved -3.57% to 3.6% (1 day), 37.24 to 56.71% (3 day), 43.81 to 62.52% (7 day) and 10.27 to 23.24% (28 day) in the sustainable composite cement with (25% FA + 5% LSPW) according to the ASTM C109/C 109M-05 and ASTM C1437. Further trial at higher dosage 0.1333 to 0.320% CAQIP in sustainable fly ash cement (35% FA) showed significant strength enhanced from 1.06 to 48.43% (1 day), 14.71 to 58.80% (3 day), 32.86 to 64.29% (7 day) and 25.46 to 47.18% (28 day).

Another series of test showed in Table 6, dosing 0.50-0.69% CAQIP in the sustainable fly ash cement (30%) significant enhanced strength 18.57 to 95.86% (1 day), 70.48 to 97.14% (7 day) and 40.03 to 57.58% (28 day). Further increased of the fly ash content to 60% FA cement, the early strength 1 day was enhanced -9.29 to 69.36% (1 day), 21.90 to 54.81% (7 day) and ultimate strength 21.52 to 45.45% (28 day). Thus, by optimizing the dosage of the CAQIP from 0.035 to 0.69%, the early and ultimate strength significant enhanced without any deterioration strength even though the fly ash content increased from 30 to 60% FA.

The fly ash cement treated with CAQIP contained the synthesized copolymer which can disperse the fresh mixed mortar/concrete cement particles contribute from their steric hindrance repulsive force, thus the reduced water and its workability maintained and eventually hardened mechanical strength increased rapidly cause the nano-micro voids decreased and binding matrix became denser and stronger as in the literature (Lai et al. 2013).

Thus, the cement additive quality improver polymer (CAQIP) in general improve the cement production efficiency, productivity, high performance quality, reduced clinkering energy, $CO_2$ emission and durability cement suitable for the contemporary trend of construction in Malaysia which required high efficiency, productive, high quality and high durability construction technology (Appendix 1).

### CEMENT PLANT C: IMPROVED EFFICIENCY ENERGY, PRODUCTIVITY, STRENGTH AND REDUCED $CO_2$

Dosing 0.03 and 0.04% CAQIP in the actual Cement Plant C trial shown in Table 7 improved the grind ability or grinding efficiency (kWh/ton), 17.50% (3.32 kWh/ton) and 21.4% (4.07 kWh/ton), respectively. In this study, at the same Motor power drive = 3130 kW, the CAQIP enable saving grinding energy by achieving the targeted fineness in shorter time against the cement without CAQIP with existing production yield of 165 ton/h.

The production yield increased from 165 to 200 ton/h (21.20%) and 210 ton/h (27.27%), respectively. The productivity ton per labour man hour increased to 21.2 and 27.3%, respectively (base on the same quality and existing equipment and 6 labour man hour). The grinding efficiency energy with dosage 0.03 and 0.04% CAQIP was reduced to 1.01 and 5.76% against the CSE-GA, respectively. The production yield improved 1.01 and 6.06% and productivity increased 1.00 and 6.06%, respectively, against the CSE-GA.

However, quality compressive strength improved 17.11 and 22.63%, respectively, early strength at 2 day as shown in Table 7 against the Blank OPC. For ultimate strength at 28 day increased 14.33 and 17.10%, respectively, against the Blank OPC cement without CAQIP. The strength enhancing effects, 0.04% CAQIP improved +1.87 MPa (2 day), +1.25 MPa (7 day) and significant +4.5 MPa (28 day) higher than the CSE-GA. Thus, Cement Plant C can locally apply 0.03 to 0.04% CAQIP to enable them to produce the higher grade 52.5R quality OPC by upgrading their existing lower grade quality 42.5R OPC successfully and cost effectiveness (Appendix 1).

Separately, five series test programme showed in Table 7 was conducted for the chemical activation strength

TABLE 7. Plant C: Production yield, particles size distribution, fineness, chemical activation and compressive strength

| Sample trial | Grinding aids dosage (%) | Production output/ yield (Ton/h) | Particles size distribution | | | Residue at 45 µm (%) | Blaine number ($cm^2$/g) | Compressive strength ($N/mm^2$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | d(0.1) (µm) | d(0.5) (µm) | d(0.9) (µm) | | | 2d | 7d | 28d |
| Blank | - | 165 | 2.022 | 17.251 | 52.092 | 8.3 | 3730 | 25.19 | 39.90 | 49.53 |
| CSE-GA | 0.09 | 198 | 2.806 | 15.639 | 49.161 | 3.8 | 3543 | 27.63 | 42.94 | 53.50 |
| CAQIP | 0.03 | 200 | 2.629 | 14.066 | 44.098 | 3.2 | 3572 | 30.89 | 44.97 | 56.63 |
| CAQIP | 0.04 | 210 | 2.667 | 14.095 | 42.715 | 2.8 | 3440 | 29.50 | 44.19 | 58.00 |
| Blank[a] | - | - | - | - | - | 8.5 | 3600 | 22.71 | 38.52 | 50.80 |
| CAQIP[a] | 0.05 | - | - | - | - | 8.5 | 3600 | 26.24 | 45.82 | 63.71 |
| CAQIP[a] | 0.04 | - | - | - | - | 8.5 | 3600 | 24.37 | 42.00 | 58.89 |
| CAQIP[a] | 0.03 | - | - | - | - | 8.5 | 3600 | 25.20 | 42.94 | 57.20 |
| CSE-GA[a] | 0.09 | - | - | - | - | 8.5 | 3600 | 24.3 | 41.9 | 53.40 |

a. Chemical activation mortar test

performance as in Lai et al. (2013) by dosing at 0.05% CAQIP significant improved strength 15.54% (2 day), 18.95% (7 day) and 25.39% (28 day) against the normal OPC 42.5R in Cement plant C. When dosing at 0.04% CAQIP also showed significant improved strength of 7.31% (2 day), 9.03% (7 day) and 15.93% (28 day). Further reduced dosage to 0.03%, CAQIP still show significant improved strength of 10.96% (2 day), 11.47% (7 day) and 12.60% (28 day).

The conventional strength enhancer can only improve 2 day early strength (1.59 MPa) and 28 day ultimate strength (2.60 MPa). However, CAQIP significant improved 2 day early strength (1.66-3.53 MPa) and especially 28 day ultimate strength (6.40-12.91 MPa) whereby it can offer much better solution in strength quality improvement against the conventional strength enhancer.

## Conclusion

Based on the experimental test results in the actual three cement plants, the following conclusions are drawn for the innovative cement additives quality improvers CAQIP.

Unlike the conventional strength enhancer grinding aids (CSE-GA) with much lower dosage of CAQIP significantly increased the production yield, productivity, fineness, quality strength, reduced clinkering energy, reduced depletion of limited resources and $CO_2$ emission. Good quality cement in time delivering without delaying for the general faster construction project especially the Mega MRT projects and Mega Dam construction project in Malaysia.

Based on net chemical activation test results, the chemical reactivity of CAQIP strength enhancing property is better than that of conventional strength enhancer. Super-strength enhancing effect was found by optimization dosing whereby strength improved significantly in the production of sustainable cement even though it contains 30-60% fly ash. The application of the sustainable cement in the mega concrete construction projects in Malaysia can be completed in the targeted schedule time with good quality, significantly enhanced sustainability social-economy in the cement and concrete industries.

## References

Alsop, P.A. 2005. The concise guide to cement manufacture. *The Cement Plant Operations Handbook*. 4th ed. International Cement Review pp. 140-145, 206 & 226.

Karim, M.R., Zain, M.F.M., Jamil, M. & Lai, F.C. 2013. Fabrication of a non-cement binder using slag, palm oil fuel ash and rice husk ash with sodium hydroxide. *Construction and Building Materials* 49: 894-902.

Kibert, C.J. 2009. *Sustainable Construction: Green Building Design and Delivery*. New Jersey: John Wiley & Sons, Inc. pp. 5-14.

Lai, F.C. 2010. SikaGrind for cement quality improver and strength enhancer Asia Pacific experiences. Paper presented to all Malaysian cement manufacturers and invited by Cement & Concrete Association Malaysia, Kuala Lumpur, 21st October, Malaysia. pp: 29-33.

Lai, F.C., Karim, M.R. & Zain, M.F.M. 2013. Production yield, fineness and strength of cement as influenced by strength enhancing additives. *Australian Journal of Basic and Applied Sciences* 7(4): 253-259.

Madlool, N.A., Saidur, R., Hossain, M.S. & Rahim, N.A. 2011. A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy Reviews* 15(4): 2042-2060.

World Business Council for Sustainable Development's (WBCSD) Cement Sustainability Initiative (CSI) Progress Report 2012. 10 years of progress - moving on to the next decade (www.wbcsdcement.org).

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APPENDIX 1. Summary CAQIP performance, potential economy and enhanced sustainability in construction

| | Cement Plant A | Cement Plant B | Cement Plant C |
|---|---|---|---|
| Cement type production | OPC 42.5N with 50-100% out-spec clinker | Composite (25% Limestone waste) and Composite LH (25-35% fly ash) and Compo-pozzolanic (30 and 60% FA) | OPC 52.5R |
| CAQIP dosage | 0.009, 0.0126 and 0.035% | 0.035, 0.059, 0.133, 0.320, 0.500 and 0.690% | 0.050, 0.040 and 0.03% |
| Improved efficiency (reduction in clinkering energy) | 43.18 to 86.36% | 24.73 to 60.91% | NA |
| Improved grinding efficiency | 7.7 to 21.57% | NA | 17.5 to 21.45% |
| Improved efficiency (reduction $CO_2$ emission and others toxic gases) | 45 to 90% | 21.90 to 53.90% | NA |
| Improved efficiency (depletion limited natural resources for cement) | 50 to 100% sand, clay and limestone | 25 to 35% sand, clay and limestone | NA |
| Improved productivity (ton per man hour) | 8.3 to 27.5% | NA | 21.20 to 27.27% |
| Improved quality mortar strength | 1.45-11.11%(1 day)<br>11.64-14.10%(2 day)<br>3.85-9.55%(28 day) | 34.8% (2 day)<br>22.6% (7 day)<br>12.3% (28 day) | 17.11-22.6% (2 day)<br>10.75-12.71% (7 day)<br>14.33-17.10% (28 day) |
| Improved quality mortar strength mechano-chemical activation test | NA | Optimized dosage 1.06 to 95.86% (1 day)<br>21.90 to 97.14% (7 day)<br>10.27 to 57.58% (28 day) | 7.31-15.54% (2 day)<br>9.03-18.95% (7 day)<br>12.60-25.39% (28 day) |
| Improved quality concrete strength and durability >100 years | NA | 26.98% (2 day)<br>8.6% (7 day)<br>1% (28 day), durability>100 years | NA |
| Total economy benefits per year (Individual cement plant) | RM68.05 to RM145.52 million | RM44.62 to RM51.40 million, (RM58.49 million if included saving concrete cost) | RM3.98 to 7.75 million |
| Total economy benefits from 1st Jan 2012 to 30th June 2013 | RM102.07 to RM218.27 million | RM66.94 to RM77.11 million, (RM87.74 million if included saving concrete cost) | RM5.97 to 11.62 million |
| Potential total economy benefits per year for Malaysia | RM0.681 to 1.455 billion | RM446.2 to RM514.0 million, (RM584.9 million if included saving concrete cost) | RM39.8 to 77.5 million |
| Applied in Construction Project | Mega Murum Dam and ready mix concrete | Mega MRT Project and repairing concrete | Precast and ready mix concrete |