Green options for anti-corrosion of high strength concrete incorporating ternary pozzolan materials

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Abstract. This paper applied the densified mixture design algorithm(DMDA) method by incorporating ternary pozzolans (fly ash, slag and silica fume; mix I and mix II) to design high strength concrete (HSC) mixtures with w/cm ratios from 0.24 to 0.30. Concrete without pozzolans was used as a control group (mix III, w/c from 0.24 to 0.30), and silica fume (5%) was added as a substitute for part of the cement and set as mix IV. Experiments performed compressive strength, four-point resistance meter to measure the conductivity, and rapid chloride ion penetrability tests (ASTM C1202) were assessed the anti-corrosion. The life cycle inventory of LEED suggested by the PCA indicated the green options for cementitious materials. Results showed that mix I and II indicated cement used, CO_2 reduction, raw materials and energy consumption all decreased more 50% than mix III, and mix IV was 5% less. The compressive strength and anti-corrosion levels showed that mix I and II were better than mix III and IV, and with ternary pozzolans could enhance the long-term durability (92 days) due to a resistivity greater 20 KΩ-cm and a charge passed lower than 2000 Coulombs. HSC with an appropriate design could reduce the carbon footprint and improve the durability.

1 High strength concrete and corrosion

The definition of high-strength concrete (HSC) is the specified strength greater 41 MPa (6000 psi) [1-3]. HSC mixtures have two key characteristics: a low water-to-cement (cementitious) ratio and a high heat of hydration [1]. These factors lead to the thermal stress between the hydration products of the paste and aggregates, and cause inconsistent deformation of the interface, in turn forming many micro and thermal cracks [4-7]. That is a severe durability problem for HSC, especially when exposed in or adjacent marine environment. Corrosion is the most important and critical issue for concrete structures in Taiwan (because the country was surrounded by the sea). Many factors influenced the heat of hydration of HSC. The most commonly used method for creating HSC was incorporating pozzolans (post-industry products- such as fly ash, blast-furnace slag and silica fume; natural such as calcined clay, calcined shale, and meta-kaolin) in the mixture to decrease its cement content and enhance the fresh, hardened properties and long-term durability [4, 7]. Water, oxygen and chloride ions play important roles in the corrosion of embedded steel and the cracking of concrete. It is obvious that permeability of concrete is the key to control the various processes involved in these phenomena. Concrete mixture properties to ensure low permeability including low water-to-cementitious (w/cm), adequate cement content, control of aggregate size and grading, and use of mineral admixtures [4].

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The ACI 318-11 structural concrete building code is based on the exposure classes presented in Table 4.2.1(P: Requiring low permeability; C: Corrosion protection of reinforcement). It states that concrete mixtures should comply with the most restrictive requirements according to Table 4.3.1 (P1: In contact with water where low permeability is required; C2: Concrete exposed to moisture and an external resource of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these resources). For permeability requirements, the P1 class should have a w/cm less than 0.50 and a specified strength (f'_c) was greater than 4000 psi and the C2 class should have a w/cm below 0.40 and f'_c was above 5000 psi [8]. Proper consolidation(compactness) and curing of concrete are equally essential [4]. One standard method that provides a performance-based indicator of low permeability of concrete is ASTM C1202 for anti-corrosion experiments on permeability and corrosion resistance, which has been found to be reliable in laboratory evaluation than for acceptance in the field. The use of ASTM C1202 to test concrete mixtures proposed for use provides additional information on the performance of these mixtures [9]. For the Confederation Bridge linking Prince Edward Island with New Brunswick in mainland Canada (1997), the anti-corrosion performance of the concrete exterior exposed to a seawater environment showed that it was free crack, and that the higher electrical resistance is much more important than a lower permeability [10, 11].

2 Pozzolans and LEED

The main ingredients of concrete are coarse aggregates, fine aggregates, cementitious materials (cement and pozzolans), and water (included liquid admixture) [4-6]. The carbon footprint for concrete mainly emitted constitute was cement, contributes 5 per cent of annual anthropogenic global CO_2 production [12, 13]. According to a 2015 statistic of the worldwide cement production by major producing countries from 2010 to 2015 [14], China, India, and the United States were among the global top three. The production exceeded more than 40 billion metric tons in 2015. For every 1000 kg of cement manufactured, CO_2 emissions were reduced from 927 kg(before) to 800 kg(now) [12, 15]. The cement industry is a high-intensity manufacturing process. Every 1000 kg of cement produced consumes 1613 kg of raw materials (containing 72% of limestone, 13% of cement rock, 3% of shale, 4% of clay, and 2% of sand). The temperature at the lower end of the kiln is 1870 ^oC. In the hottest part of the kiln, the raw materials reach a temperature of 1480^oC and melt. The molten material from the kiln, known as clinker, is ground into cement. A small amount of gypsum is added to the cement to control its setting time. The weighted average energy consumption, including fuel and electricity, during cement production is 4.8 GJ/metric ton of cement [16-20]. To process slag, it is from a blast-furnace during the production of pig iron, can be used a supplementary cementitious material as a partial replacement for Portland cement in concrete, It quenched with water and ground. One metric ton of slag uses about 14% of energy to produce one metric ton of cement. Additionally, one metric ton of slag produces about 2% of CO_2 emissions to produce one metric ton of cement [16, 21]. The carbon footprint for fly ash and silica fume were regarded as being zero because of recycling and the prevention of air pollution. CO_2 emissions were produced by their main products, electricity and siliceous-steel.

The supplementary cementitious materials (fly ash, ground granulated blast-furnace slag, silica fume, and others pozzolans) used for concrete could contribute to green design as follows: (1) As industrial by-products, their use as a partial replacement for Portland cement does not contribute to the energy and CO_2 impacts of cement in concrete; (2)Raw material usage is reduced in the manufacture of concrete; (3) Landfill disposal is reduced and there is an increased use of recovered industrial materials; and (4) SCMs improve concrete service life through greater concrete durability [21-24]. The commonly used materials include fly ash (C and F classes), ground granulated blast-furnace slag, and silica fume, especially fly ash and slag. Worldwide production exceeded over a billion metric tons. These post-industry products were recycled, reused, and reduced to avoid air pollution and to waste a large amount of landfill disposal fields. In many countries, pozzolans have been a recycled resource incorporated in concrete to enhance their properties. Pozzolans were beneficial for improving the durability of anti-corrosion, sulfate resistance, alkali-silica reaction, and regarded as the fifth required material in concrete.

The Leadership in Energy and Environmental Design(LEED) Green Building Rating System was developed by the U.S. Green Building Council (USGBC) in 1998. The LEED rating system is a voluntary, consensus-based, mark driven rating system based on existing proven technology [25-28]. It evaluates environmental performance from a whole building perspective over a building's life cycle, providing a definitive standard for what constitutes a "green building." The rating system is organized into five environmental categories: Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, and Indoor Environmental Quality. An additional category, namely Innovation & Design Process, addresses sustainable building expertise as well as design measures not covered under the five environmental categories [25]. LEED is a performance-based system where credits are earned for satisfying criteria designed to address specific environmental impacts inherent in the design, construction, and operation and maintenance of buildings. For the LEED rating system for New Construction and Major Renovations (LEED-NC2.2) different levels of green building certification are awarded based on the total credits earned rating including Certified, Silver, Gold, and Platinum. The LEED system is designed to be comprehensive in scope yet simple in operation. The use of fly ash and slag can earn about 6 possible points (Sustainable Sites- 1 point, Material & Resources - 4 points, and Innovation in Design - 1 point) [29, 30].

The green options for anti-corrosion of high strength concrete with quaternary cementitious materials (cement, fly ash, slag, and silica fume) applied a densified mixture design algorithm(DMDA) and ACI 211.1R methods to examine the mixture feasibility. The life cycle inventory for the concrete mixture suggested by the Portland Cement Association (PCA) [31-35] and properties comprised of cement used, CO_2 emission, raw materials, energy consumption, compressive strength, surface resistivity, and charge passed.

3 Materials, Mix design and Experiments

3.1 Materials

The component and properties of cementitious materials are respectively matched ASTM C150 (cement), ASTM C618 (fly ash), ASTM C989 (slag) and ASTM C1240(silica fume), as shown in Table 1. Coarse and fine aggregates met ASTM C33 requirements, as shown in Table 2. Water was potable water conformed to ASTM C94. The high range water- reducing agents was produced by Sica Chem. Corp. used as a high flow agent and conformed to ASTM C494 Type G.

Table 1. Properties of cementitious materials.

Item	Cement	Fly ash	Slag	Silica fume
SiO_2	22.0	51.2	34.9	97.7
Al_2O_3	5.6	24.3	13.5	0.7
Fe_2O_3	3.4	6.1	0.3	0.1
CaO	62.8	6.3	41.8	0.4
MgO	2.6	1.6	7.2	0.4
SO_3	2.1	0.6	1.7	0.3
f-CaO	1.1	-	-	-
TiO_2	0.5	-	-	-
Na_2O	0.44	-	-	-
K_2O	0.78	-	-	-
V_2O_5	0.05	-	-	-

Table 2. Properties of aggregates.

Properties	Corse Aggregate*	Fine Aggregate**
$G_s(SSD)$	2.64	2.63
$G_s(OD)$	2.63	2.62
Absorption(%)	1.1	2.2
$D_{max.}(mm)$	12.5	-
F.M.(%)	6.08	2.82
$UW_{dry}(kg/m^3)$	1,536	-

*: Crushed stone
**: River sand

3.2 Mix proportion

The DMDA [36] and ACI 211.1-09 [37] method applied to design the high strength concrete mixtures with water-to-cementitious material(w/c(m)) ratios from 0.24 to 0.30 and different water contents. Ternary pozzolans were incorporated into mix I (5% slag) and mix II (FA: Slag = 7:3) for a higher slag content. ACI 211.1 without pozzolans was set as the control group (mix III), and 5% of cement was substituted using silica fume in mix IV. The results of the mix design were as shown in Tables 3-5.

Table 3. Mixtures proportion for I groups(kg/m^3).

Materials kg/m^3	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
Cement	284	376	466	217	299	379	197	238	310
Slag	16	21	26	12	17	21	11	13	17
Fly Ash	266	238	220	264	248	231	264	255	240
Silica Fume	15	20	21	12	16	20	10	13	16
Coarse Aggregate	753	700	648	777	728	680	776	750	706
Fine Aggregate	957	890	824	988	926	865	986	954	897
Water (Incl. HRWR)	137	157	177	136	156	176	144	156	175
Rate(%)	**29**	**39**	**48**	**25**	**35**	**44**	**26**	**31**	**40**

*With respect to mix III × 100%.

Table 4. Mixtures proportion for II groups(kg/m^3).

Materials kg/m^3	II-246	II-247	II-28	II-276	II-277	II-278	II-306	II-307	II-308
Cement	242	338	431	212	259	342	155	197	271
Slag	87	87	87	85	85	85	84	84	84
Fly Ash	220	204	189	221	213	199	227	219	206
Silica Fume	22	26	31	20	22	26	18	19	23
Coarse Aggregate	831	772	715	833	804	751	856	828	779
Fine Aggregate	882	820	760	885	853	797	909	879	827
Water (Incl. HRWR)	138	157	177	146	156	176	144	156	175
Rate(%)	**25**	**35**	**45**	**25**	**30**	**40**	**20**	**26**	**35**

*With respect to mix III × 100%.

Table 5. Mixtures proportion for III and IV groups(kg/m^3).

Material kg/m^3	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
Cement	963	856	770	915	813	731
Slag	-	-	-	-	-	-
Fly ash	-	-	-	-	-	-
Silica fume	-	-	-	48	43	39
Coarse Aggregate	633	633	633	633	633	633
Fine Aggregate	471	560	632	413	509	585
Water (Non-HRWRA)	231	231	231	231	231	231
Rate(%)*	**100**	**100**	**100**	**95**	**95**	**95**

*With respect to mix III × 100%.

3.3 Experiments

The life cycle inventory for anti-corrosion characteristics by LEED according to the PCA included cement content, CO_2 emissions, raw materials, energy consumption, compressive strength (ASTM C39 at 7, 28, 56 and 92 days), anti-corrosion properties containing electrical resistivity(four-point resistivity meter made by Swiss Proceed at 7, 28, 56, and 92 days) upon contact with different concrete sections, and a rapid chloride ion penetrability test(ASTM C1202, at 92 day) [9] as shown in Table 6.

Table 6. Criteria of RCPT by ASTM C1202.

Measured Value, Coulombs	Chloride Ion Penetrability
> 4000	High
4000 - 2001	Moderate
2000 - 1001	Low
1000-101	Very Low
< 100	Negligible

4 Results and discussions

4.1 Cement use

With respect to mix III as being 100%, the cement content of mix I, mix II, and mix IV were as shown in the bottom of Tables 3-5. It indicated that mix IV contained 5% less cement. The decreasing rates for mix I and mix II were 25% ~ 48% and 20% ~ 45%, respectively. The amount of cement for mix I and mix II designed by the DMDA method were 50% less than mix III. Pozzolans used in the mixtures could dramatically reduce the cement content. However, it must still be compared with each property. According to suggestions from the PCA, the life cycle inventory for various mixtures of cementitious materials including cement and others pozzolans were compared to CO_2 emissions, raw materials, and energy consumption as shown in Tables 7-15.

4.2 CO_2 emission

Tables 7-9 show that the CO_2 emissions of cementitious material were 927 kg/1000 kg of cement, GGBFS 2% emission of cement, and the carbon dioxide footprint from fly ash and silica fume regarded as 0%. Calculation results showed that CO_2 emissions for mix I and mix II, with respect to mix III as being 100%, were 20% ~ 45% and 20% ~ 40%, respectively. The mixtures significantly decreased 50% more than mix III. The CO_2 reduction rate for mix IV was only 5% similar to the cement reduction. A reduction in the cement content caused a reduction in CO_2 emissions. High strength concrete mixtures with multi-pozzolans (mix I and mix II) may allow more carbon reduction.

Table 7. Life cycle inventory for LEED - CO_2 emission of binders for mix I.

Life cycle inventory- CO_2 emission of binders for concrete mix(kg/m^3)									
Material kg/m^3	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
Cement	263	349	432	201	277	351	183	221	287
Slag	0	0	0	0	0	0	0	0	0
Fly ash	0	0	0	0	0	0	0	0	0
Silica fume	0	0	0	0	0	0	0	0	0
Total	263	349	432	201	277	351	183	221	287
Rate(%)*	**29**	**39**	**48**	**25**	**35**	**44**	**26**	**31**	**40**

Cement CO_2 Emission: 927 kg/1000kg Cement;
Slag CO_2 Emission: 2% of 927 kg/1000kg Cement;
Fly Ash and Silica Fume CO_2 Emission: None.
*With respect to mix III × 100%.

Table 8. Life cycle inventory for LEED - CO_2 emission of binders for mix II.

Life cycle inventory- CO_2 emission of binders for concrete mix(kg/m^3)									
Material kg/m^3	II-246	II -247	II I-248	II -276	II -277	II -278	II -306	II -307	II -308
Cement	224	313	400	197	240	317	144	183	251
Slag	2	2	2	2	2	2	2	2	2
Fly ash	0	0	0	0	0	0	0	0	0
Silica fume	0	0	0	0	0	0	0	0	0
Total	226	315	402	199	242	319	146	185	253
Rate(%)*	**25**	**35**	**45**	**25**	**30**	**40**	**20**	**26**	**35**

Cement CO_2 Emission: 927 kg/1000kg Cement;
Slag CO_2 Emission: 2% of 927 kg/1000kg Cement;
Fly Ash and Silica Fume CO_2 Emission: None.
*With respect to mix III × 100%.

Table 9. Life cycle inventory for LEED -CO_2 emission of binders for mix III&IV.

Life cycle inventory- CO_2 emission of binders for concrete mix(kg/m^3)						
Material, kg/m^3	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
Cement	893	794	714	848	754	678
Slag	0	0	0	0	0	0
Fly ash	0	0	0	0	0	0
Silica fume	0	0	0	0	0	0
Total	893	794	714	848	754	678
Rate(%)*	**100**	**100**	**100**	**95**	**95**	**95**

Cement CO_2 Emission: 927 kg/1000kg Cement;
Slag CO_2 Emission: 2% of 927 kg/1000kg Cement;
Fly Ash and Silica Fume CO_2 Emission: None.
*With respect to mix III × 100%.

4.3 Raw materials

The pozzolans used in the concrete were post-industry waste recycled resource materials. Raw materials mainly including limestone and clay (3:1) for the manufacturing process of cement consumed a large amount natural resources. According to the PCA, raw materials required to produce 1000 kg of cement had to consume more than 1613 kg of natural resources. The intrusive destruction of nature due to the territorial integrity were destroyed and air pollution were serious problems. The consumption of raw materials for cementitious materials in kg/m^3 were as shown in Tables 10-12. With respect to mix III as being 100%, the amount of raw materials consumed by mix I, mix II, and mix IV were 25% ~ 48%, 20% ~ 45% and 95%, respectively. Mixtures designed with the DMDA method showed that the raw materials of cementitious materials consumed significantly decreased more than 50%; meanwhile, the reduction of mix IV was very limited.

Table 10. Life cycle inventory for LEED – Raw materials of mix I for binders.

Life cycle inventory- Raw materials consumption of binders for concrete mix I									
Material kg/m^3	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
Cement	458	606	752	350	482	611	318	384	500
Slag	-	-	-	-	-	-	-	-	-
Fly ash	-	-	-	-	-	-	-	-	-
Silica fume	-	-	-	-	-	-	-	-	-
Total	458	606	752	350	482	611	318	384	500
Rate(%)*	**29**	**39**	**48**	**25**	**35**	**44**	**26**	**31**	**40**

Raw Materials: 1613kg/1000kg Cement.
*With respect to mix III × 100%.

Table 11. Life cycle inventory for LEED – Raw materials of mix I for binders.

Life cycle inventory- Raw materials of binders for concrete mix II									
Material, kg/m^3	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II -308
Cement	390	545	695	342	418	552	250	318	437
Slag	-	-	-	-	-	-	-	-	-
Fly ash	-	-	-	-	-	-	-	-	-
Silica fume	-	-	-	-	-	-	-	-	-
Total	390	545	695	342	418	552	250	318	437
Rate(%)*	**25**	**35**	**45**	**25**	**30**	**40**	**20**	**26**	**35**

Raw Material : 1613 kg/1000 kg Cement.
*With respect to mix III × 100%.

Table 12. Life cycle inventory for LEED – Raw materials of mix I for binders.

Life cycle inventory- Raw materials of binders for concrete mix III & IV						
Material kg/m^3	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
Cement	1553	1381	1242	1476	1311	1179
Slag	-	-	-	-	-	-
Fly ash	-	-	-	-	-	-
Silica fume	-	-	-	-	-	-
Total	1553	1381	1242	1476	1311	1179
Rate(%)*	**100**	**100**	**100**	**95**	**95**	**95**

Raw Material : 1613kg/1000kg Cement.
*With respect to mix III × 100%.

4.4 Energy consumption

By PCA reports, the energy consumption for cement manufacturing was 4.8 GJ/1000 kg of cement and ground granulated blast-furnace slag was 14% per 4.8 GJ/1000 kg of cement for slag grinding. Since the energy consumption was owing to their front of the main products, electricity and siliceous-steel, fly ash and silica fume were regarded as having zero energy consumption. According to Tables 13-15, the energy consumption of cementitious materials in the mixtures with respect to mix III being=100%, were 26% ~ 49% (mix I), 22% ~ 41% (mix II), and 95% (mix IV), respectively. Mix I and mix II used the DMDA method and in comparison to the cementitious materials with mix III, they consumed 50% less energy.

Table 13. Life cycle inventory for LEED - Energy consumption of binders for mix I.

Life cycle inventory- Energy consumption of binders for concrete I									
Material kg/m^3	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
Cement	1.36	1.80	2.24	1.04	1.44	1.82	0.95	1.14	1.49
Slag	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Fly ash	-	-	-	-	-	-	-	-	-
Silica fume	-	-	-	-	-	-	-	-	-
Total	1.37	1.81	2.26	1.05	1.45	1.83	0.96	1.15	1.50
Rate(%)*	**30**	**39**	**49**	**26**	**35**	**45**	**26**	**31**	**41**

Cement Energy Consumption: 4.8GJ/1000kg Cement;
Slag Energy Consumption: 14% of 4.8GJ/1000kg Cement.
*With respect to mix III × 100.

Table 14. Life cycle inventory for LEED - Energy consumption of binders for mix II.

Life cycle inventory- Energy consumption of binders for concrete II									
Material kg/m^3	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II-308
Cement	1.16	1.62	2.07	1.02	1.24	1.64	0.74	0.95	1.30
Slag	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Fly ash	-	-	-	-	-	-	-	-	-
Silica fume	-	-	-	-	-	-	-	-	-
Total	1.22	1.68	2.13	1.08	1.30	1.70	0.80	1.01	1.36
Rate(%)*	**26**	**36**	**46**	**26**	**32**	**41**	**22**	**27**	**37**

Cement Energy Consumption: 4.8GJ/1000kg Cement;
Slag Energy Consumption: 14% of 4.8GJ/1000kg Cement.
*With respect to mix III × 100%.

Table 15. Life cycle inventory for LEED - Energy consumption of binders for mix III & IV.

Life cycle inventory- Energy consumption of binders for concrete III&IV						
Material kg/m^3	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
Cement	4.62	4.11	3.70	4.39	3.90	3.51
Slag	-	-	-	-	-	-
Fly ash	-	-	-	-	-	-
Silica fume	-	-	-	-	-	-
Total	4.62	4.11	3.70	4.39	3.90	3.51
Rate(%)*	**100**	**100**	**100**	**95**	**95**	**95**

Cement Energy Consumption: 4.8GJ/1000kg Cement;
Slag Energy Consumption: 14% of 4.8GJ/1000kg Cement.
*With respect to mix III × 100%.

4.5 Compressive strength effect

The front four-items for life cycle inventory were used to assess the effect of design and production for cementitious materials in the mixtures. Next, tests were executed the performance of hardened properties and durability. This paper performed compressive strength development, surface resistivity, and rapid chloride ion penetrability tests to evaluate anti-corrosion.

The compressive strength development (7, 28, 56, and 92 days) were shown in Tables 16-18. Mix I and mix II with the DMDA method at 28 days showed that the strength ranged from 47 MPa to 73.6 MPa and 52.4 MPa to 72.9 MPa, respectively. Mix III and mix IV with the ACI 211.1 method indicated strengths from 50.7 MPa to 54.9 MPa and 53.9 MPa to 54.1 MPa, respectively. The cement content of mix III and IV were as twice as that of mix I and II, and the compressive strength increased slowly. At 92 days, mix I, II, III, and IV had strengths of 75.9 MPa ~ 98.4 MPa, 65.9 MPa ~ 99.5 MPa, 62 MPa ~ 65.7 MPa, and 65 MPa ~ 69.7 MPa, respectively. The cement amount for mix III was too high to rarely enhance the compressive strength. Mix IV had the same result. Pozzolans in high strength concrete had a very important effect in lowering the heat of hydration and refining the microstructure to be denser to improve the long-term properties. For the compressive strength ratio as shown in Table 19-21, with respect to mix III as being 100%, the strength ratios were 122% ~ 150%(mix I), 106% ~ 151%(mix II), and 105%~106%(mix IV) at 92 days. Mix I and mix II with quaternary cementitious materials increased the compressive strength. Meanwhile, that of mix IV only increased a little.

Table 16. Compressive strength development for mix I(MPa).

Ages	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
7 days	55.6	60.2	62.7	39.1	43.9	51.0	29.6	36.5	43.0
28 days	67.8	80.2	73.6	57.5	60.4	65.0	47.0	49.6	59.1
56 days	86.3	95.1	92.2	71.9	72.4	84.0	61.5	66.9	70.4
92 days	96.5	98.4	96.9	83.6	83.6	89.1	75.9	76.3	83.1

Table 17. Compressive strength development for mix II(MPa).

Ages	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II-308
7 days	40.3	50.2	63.6	35.0	43.9	48.1	30.0	39.4	35.9
28 days	79.9	70.3	72.8	63.3	61.0	64.4	58.7	60.7	52.4
56 days	93.3	92.0	84.8	82.5	82.2	77.6	65.9	67.5	65.7
92 days	99.1	99.5	98.5	93.0	85.2	83.8	65.9	79.8	76.6

Table 18. Compressive strength development for mix III&IV(MPa).

Ages	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
7 days	55.9	52.3	48.8	53.0	52.7	51.9
28 days	59.5	54.9	50.7	53.9	54.0	54.1
56 days	62.7	61.2	60.7	67.7	66.0	62.0
92 days	65.7	64.4	62.0	69.7	68.5	65.0

Table 19. Relative percent of compressive strength for mix I(as mix III=100 %).

Ages	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
7 days	99	108	112	75	84	98	61	75	88
28 days	114	135	124	105	110	118	93	92	117
56 days	138	152	147	117	118	137	101	110	116
92 days	147	150	150	130	130	138	122	123	134

Table 20. Relative percent of compressive strength for mix II(as mix III=100 %).

Ages	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II-308
7 days	72	90	114	67	90	92	62	81	74
28 days	134	118	122	115	111	117	116	120	103
56 days	149	147	135	135	134	127	109	111	108
92 days	151	151	150	144	132	130	106	129	124

Table 21. Relative percent of compressive strength for mix III & IV(as mix III=100 %).

Ages	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
7 days	100	100	100	95	101	106
28 days	100	100	100	91	98	107
56 days	100	100	100	108	108	102
92 days	100	100	100	106	106	105

4.6 Electrical resistivity

If the concrete structure compactness is high, there are fewer pores; thus, the connection is more difficult. As a result, the conducting channels are decreased or lengthened, and electrical resistivity is enhanced. The conductivity of concrete is mainly influenced by the moisture content. Concrete specimens were cured in saturated lime water, extracted from water, and then dried (interior saturation condition) to measure the surface resistivity at different points of various mixtures. Tables 22-24 show the resistivity development of different mixes. During the early ages (7 days), surface resistivity had a slow development. Only II-248 and IV-2711 groups had more than 20 KΩ-cm low corrosion occurrence threshold values. After 28 days, the resistivity for mix I, II, and IV groups incorporating various pozzolans significantly increased more than 20 KΩ-cm. Adding pozzolans could make the concrete interior microstructure denser to decrease the connection channels. At 92 days, the resistivity of a low w/cm ratio of 0.24 for mix I and mix II displayed poorer conductivity properties (all greater than 100 KΩ-cm). Mix II groups with a higher pozzolans-binder ratio and adjusted fly ash-slag ratio might increase the compressive strength and resistivity as shown in Tables 17 and Tables 23. According to ACI 318-11, the design criteria for anti-corrosion of concrete should have a lower the water-to-cementitious ratio and proper content of pozzolans added. In this study, mixtures with multi-pozzolans and lower w/cm ratios were identified the design results and performance similar to ACI 318-11.

All mixes, with respect to 20 KΩ-cm, indicated that the resistivity ratio in comparison to 20 KΩ-cm as shown in Table 25-27. At 92 days, the ratios expressed that mix I, mix II, mix III, and mix IV groups were respectively 400% ~ 705%, 350% ~ 705%, 85% ~ 105% and 230% ~ 290%. Mixtures without pozzolans might have difficulty in avoiding corrosion.

Table 22. Surface resistivity of mix I (KΩ-cm).

Ages	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
7 days	5	17	17	7	11	10	6	7	8
28 days	52	74	80	38	51	53	25	36	42
56 days	94	95	97	69	74	81	44	52	65
92 days	141	137	126	91	94	91	80	82	82

Table 23. Surface resistivity of mix II (KΩ-cm).

Ages	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II-308
7 days	14	15	21	11	8	13	6	9	12
28 days	73	75	82	64	61	75	43	42	56
56 days	98	94	100	97	90	89	72	75	72
92 days	141	134	129	138	124	113	99	94	70

Table 24. Surface resistivity of mix III & IV (KΩ-cm)

Ages	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
7 days	11	10	8	17	20	14
28 days	16	15	13	41	40	30
56 days	20	18	16	50	47	39
92 days	21	19	17	58	56	46

Table 25. Rate of surface resistivity for mix I (as 20 KΩ-cm = 100%).

Ages	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
7 days	55	85	85	35	55	50	30	35	40
28 days	260	370	400	190	255	265	125	180	210
56 days	470	475	485	345	370	405	220	260	325
92 days	705	685	630	455	470	455	400	410	410

Table 26. Rate of surface resistivity for mix II (as 20 KΩ-cm = 100%).

Ages	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II-308
7 days	70	75	105	55	40	65	30	45	60
28 days	365	375	410	320	305	375	215	210	280
56 days	490	470	500	485	450	445	360	375	360
92 days	705	670	645	690	620	565	495	470	350

Table 27. Rate of surface resistivity for mix II (as 20 KΩ-cm = 100%).

Ages	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011
7 days	55	50	40	85	100	70
28 days	80	75	65	205	200	150
56 days	100	90	80	250	235	195
92 days	105	95	85	290	280	230

4.7 Charge passed

The final options of the life cycle inventory for high strength concrete in this study performed a rapid chloride penetrability test (RCPT) according to ASTM C1202 to evaluate the durability of anti-corrosion after 92 days. The test results of the RCPT were as shown in Table 28. Mix I and Mix II were 292 C ~ 828 C and 251 C ~ 555 C, respectively. From the anti-corrosion on chloride ion penetrability in Table 5, these mixtures showed the rating of chloride ion migration as being at a very low level. Mix III and mix IV were 1003 C ~ 2091 C and were attributed to a rating of Moderate to Low. Mixtures incorporating pozzolans and applying the DMDA method could enhance the compactness and refine the pore structure of the conducting channels causing a decrease or lengthening [11].

Table 28. Test results of rapid chloride ion penetrability(Coulombs).

Mix I	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
92 days	292	324	515	414	448	540	517	653	828
Mix II	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II-308
92 days	251	311	352	308	362	402	423	504	555
Mix III & IV	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011	-	-	-
92 days	1977	2003	2045	1090	1596	1841	-	-	-

Test results of the mixtures used 2000 C (Low level permeability) as the denominator to calculate the corresponding percentage in Table 29. Mix I, mix II, mix III, and mix IV were 15% ~ 41%, 13% ~ 27%, 99% ~ 102%, and 55% ~ 92%, respectively. The effects of anti-corrosion with pozzolan mixtures were much better than when no pozzolans were used. Mix II (with a higher amount of slag) was superior to mix I. Further, mix IV with ACI 211-11 and adding silica fume were beneficial in anti-corrosion, but the traditional mix method for mix III without any pozzolans was not suitable for the exposed marine environment. Green options for anti-corrosion mixtures of high strength concrete included the following seven items containing cement used, CO_2 emissions, raw materials, energy consumption, compressive strength, the surface resistivity, and charge passed. The first four items were used to evaluate the carbon reduction of cementitious material mixtures, and the last three items were applied to assess the sustainable development of high strength concrete for anti-corrosion. The carbon emissions and resource consumption for mix I and mix II decreased by more than 50%, and mix IV had a reduction only 5%, all with respect to mix III. Sustainable development of anti-corrosion properties in this study was regarded as the resistivity and charge passed. The former is a non-destructive test method adopted in the laboratory and field having a simple, light, and fast technique to obtain a lot of useful data; meanwhile, the latter is a widely used destructive test performed in the lab to evaluate the conductivity of concrete.

Table 29. Percent of rapid chloride ion penetrability for mixes (as 2000 C = 100%).

Mix I	I-246	I-247	I-248	I-276	I-277	I-278	I-306	I-307	I-308
92 days	15	16	26	21	22	27	26	33	41
Mix II	II-246	II-247	II-248	II-276	II-277	II-278	II-306	II-307	II-308
92 days	13	16	18	15	18	20	21	25	28
Mix III & IV	III-2411	III-2711	III-3011	IV-2411	IV-2711	IV-3011	-	-	-
92 days	99	100	102	55	80	92	-	-	-

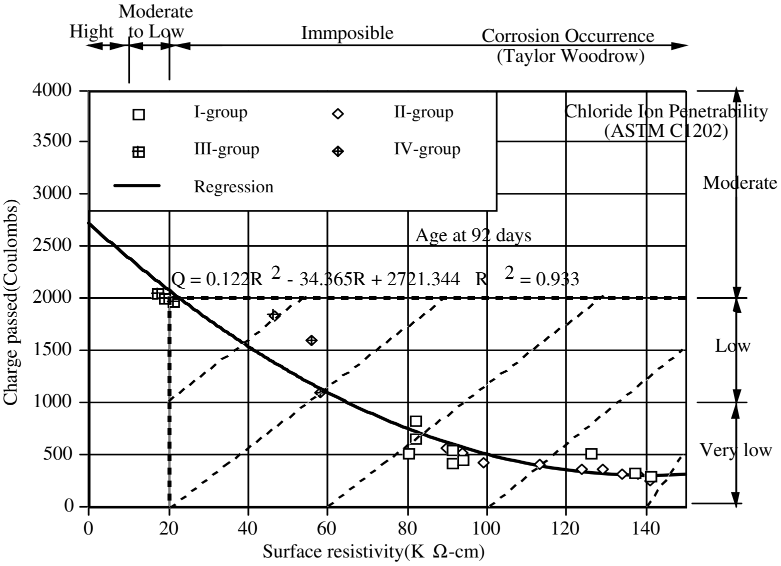

Figure 1. Probability of sustainable potential of green options for various mixtures according to Taylor Woodrow (resistivity, R) and ASTM C1202 (RCPT, Q).

According to the occurrence of corrosion suggested by Woodrow Tayler [38] and the criteria for chloride ion penetrability with ASTM C1202, green options for anti-corrosion performance of high strength concrete are listed in Table 24-26 and Table28. For all mixtures in the paper, the relationship between the resistivity and charge passed were as shown in Figure 1 and Formula 1. The correlation r^2 was equal to 0.933, which belonged to a highly relevant level.

$$Q = 0.122R^2 - 34.365R + 2721.344 \quad r^2 = 0.933 \tag{1}$$

Sustainable criteria for anti-corrosion at 92 days were that the resistivity should be greater than 20 KΩ-cm and the charge passed should be less than 2000 C. Mixtures for mix I, mix II, mix IV, and III-2411 matched the requirements; however, III-2711 and III-3011 mixtures did not. High strength concrete with a lower water-to-cement ratio (III-2411) could meet the criteria for anti-corrosion, but the cement content was too high to maintain the performance demands. The water content of mix I and mix II (See Table 3-4 and Table 29), w/cm was fixed, the higher the water amount, the lower the charge passed could be displayed the trend. That's water used in mixtures dominated the durability issue. CO_2 emissions and resource consumption for the cementitious materials in the mix displayed neither carbon reduction nor sustainability. Multi-pozzolans incorporated in the mixtures (mix I and mix II groups) designed with the DMDA method could enhance the long-term performance and sustainable development during the service life. In order to obtain a carbon dioxide reduction and sustainability for concrete mixture, a proper mix design and an addition of the correct amount of pozzolans will present an optimal option.

5 Conclusions

Mixture proportions adopted the densified mixture design algorithm (DMDA) method and water-to-cementitious material (w/cm) ratios from 0.24~0.30 with various amounts of pozzolans (mix I & II). ACI design method acted as control groups (mix III) and added silica fume (mix IV groups). Green options for anti-corrosion of the life cycle inventory of the Leadership in Energy and Environmental Design (LEED) suggested by the Portland Cement Association (PCA) included cement used, CO_2 emissions, raw materials, and energy consumption, the compressive strength and surface resistivity development and a rapid chloride ion penetrability test (RCPT), respectively. Test results are summarized as follows:

1. The DMDA applied packing between aggregates by fly ash and slag to enhance the density of aggregate structures for mix I and II. The cement content used was 25% ~ 48% and 20% ~ 45% than that of mix III. Meanwhile, mix IV was 95%.
2. CO_2 emissions for mix I and mix II groups, with respect to mix III, were 25% ~ 48% and 20% ~ 45%. Meanwhile, mix IV was 95%. CO_2 emissions were similar to the ratio of cement content used.
3. With respect to mix III, raw materials of cement production for mix I, II, and IV were 25% ~ 48%, 20% ~ 45%, and 95%, respectively.
4. With respect to mix III, the energy consumption of cement manufacturing for mix I, II, and IV was 26% ~ 49%, 22% ~ 46%, and 95%, respectively.
5. At 28 days, the compressive strength of mix I and mix II were all greater than 100% with respect to mix III. However, that of mix IV was 91% ~ 107%. After 56 days, all the mixtures were above 100%. For II-24 groups (w/cm=0.24~0.30), the compressive strength ratio exceeded 150% at 92 days. This clearly indicated the effect of incorporating pozzolans.
6. At 28 days, the surface resistivity for mix I, II and IV groups, were all greater than 20 KΩ-cm. This was a high potential of anti-corrosion. For mix III after 56 days, only III-2411 was larger than 20 KΩ-cm, others had a high corrosion risk in the field of application.
7. RCPT results showed that all mixtures, except III-2711 and III-3011, were below 2000 C, had a lower chloride ion penetrability, and higher anti-corrosion levels. Mix I and II indicated that the charge passed were all less than 1000 C to highlight the benefits of pozzolans.
8. This paper attempted to indicate the options of sustainable potential for anti-corrosion of high strength concrete mixtures. Let $Q_s \leqq 2000$ C and $R_s \geqq 20$ KΩ-cm at 92 days. All the mixtures, except III-2711 and III-3011, could match the above requirements. In order to achieve carbon dioxide reduction and sustainability for a concrete mixture, a proper mix design and addition of the correct amount of pozzolans will present an optimal option.

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