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36th Conference on **OUR WORLD IN CONCRETE & STRUCTURES:** 14 - 16 August 2011, Singapore

Article Online Id: 100036039

The online version of this article can be found at:

http://cipremier.com/100036039

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Keywords: ultra fine slag, durability, chloride penetration, corrosion, rapid chloride migration test

Abstract. *Improving the durability of concrete to sustain a longer life span and producing a greener concrete are becoming important criteria in obtaining quality concrete. Incorporating Ground Granulated Blast-furnace Slag (GGBS) as a mineral admixture improves the workability and pump-ability of fresh concrete. Blended cement concrete have reduced pore connections; thus, reducing the permeability and improving the resistance of the concrete against chloride penetration. With the use of GGBS, the amount of greenhouse gas produced in making the concrete and the energy required to produce the concrete are greatly reduced. Ultra Fine GGBS (UFGGBS) with an average particle size less than 10 µm and a Blaine surface area greater than 600 m^2/kg can greatly improve the properties of the concrete in terms of dispersion and chemical reactivity effects. Compared to GGBS, the UFGGBS increases the rate of hydration and pozzolanic reactions and has a better filling effect. In this work, the early mechanical strength development and durability properties of high strength concrete with UFGGBS is studied. Two mixes with 450 kg/m^3 and 520 kg/m^3 of Ordinary Portland Cement (OPC) and two more mixes of equivalent total cementitious materials with 30% UFGGBS replacement were designed and a total of 168 samples from the four mixes were cast. Compressive strength, flexural strength, modulus of elasticity, and chloride migration test results are presented. Numerical study has been performed to predict the life span of concrete structures in marine environment for these four mixes based on the results of the rapid chloride migration tests. Concrete with UFGGBS has a higher early strength, lower permeability and better durability against chloride penetration compared to OPC concrete.*

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1 INTRODUCTION

Creating quality concrete in the present climate does not depend solely on achieving a high strength property. Improving the durability of the concrete to sustain a longer life span and producing a greener concrete are becoming one of the main criteria in obtaining quality concrete. By using industrial by-products such as Ground Granulated Blast-furnace Slag (GGBS) as mineral admixture partially replacing Ordinary Portland Cement (OPC) in the concrete, the amount of greenhouse gas produced in making the concrete and the energy required to produce the concrete are reduced. GGBS is a by-product formed when molten iron blast furnace slag is rapidly chilled by immersing it in water. When finely ground and mixed with OPC, it will produce binding properties. The production of slag is more environmentally friendly compared to the production of OPC, thus producing a more environmentally friendly concrete than the OPC concrete. It has been well documented that GGBS is a very good mineral admixture to be used in improving the properties of the concrete due to its positive effects on its sustainable development and the environment. High level of quality and durability of concrete are a necessity in reducing the rate of deterioration of concrete. In blending GGBS with OPC, a concrete paste with improved fluidity and reduced bleeding can be achieved[1].

It is well documented that with the addition of GGBS, the early strength of the concrete is affected; however as the concrete curing age increases, the strength of the concrete improves and matches that of the control concrete at 56 days[2,3]. However, with the reduced fineness of the UFGGBS, increasing the Blaine surface area and hence increasing the rate of hydration and pozzolanic reaction, the early strength of the blended concrete will improve significantly. Higher compressive strength for 7 days curing with 50% ultra fine GGBS (UFGGBS) replacement of 600 m^2/kg Blaine surface compared to OPC control samples was reported[4]. The properties of GGBS aid the concrete in resisting chloride induced corrosion[5] and the blended concrete will have a reduced pore connection which helps in preventing chloride penetration. The total pore volume of concrete also decreases as the slag fineness becomes higher[6]. Slag of 786 m^2/kg fineness has a 50% smaller diffusion coefficient than a normal OPC[6]. This coefficient drops more dramatically as the fineness of the slag is improved.

In this work, the effect of UFGGBS replacement on the durability and mechanical properties of high strength concrete is studied. Four mixes with two different water/cementitious (w/c) ratio and different amount of cementitious materials were studied. The amount of UFGGBS replacement was set at 30%. Compressive strength, flexural strength, and modulus of elasticity tests were performed to study the effect of UFGGBS on the mechanical properties of the concrete. Rapid Chloride Migration Tests (RCMT) were carried out to obtain the chloride migration coefficient to study the durability aspect of the concrete. Numerical study has also been performed to predict the life span of concrete structures in marine environment for these four mixes based on RCMT test results. The UFGGBS replacement resulted in higher early strength, lower permeability, and better durability against chloride penetration compared to OPC concrete.

2 EXPERIMENTAL INVESTIGATION

A total of 168 samples consisting of 100 mm cube specimens, 100mm and 150mm diameter cylinder specimens, and 100 x 100 x 500 mm prism specimens were investigated. Compressive strength, flexural strength, and modulus of elasticity provide the platform to focus on the mechanical aspect. RCMT determines the chloride migration coefficient of the concrete with respect to chloride penetration into the concrete. Therefore the RCMT test results were used to evaluate the durability aspect of the concrete. The characteristic of type 1 OPC and UFGGBS used in this study were examined using particle size analyser and chemical analysis test. The physical properties and oxide compositions obtained were listed in Table 1. The mean particle size of the UFGGBS was 4.09 µm compared to 15.96 µm for OPC. The Fineness-Blaine surface area of the UFGGBS used in this work was 870 m^2/kg compared to 360 m^2/kg for OPC. Figure 1 shows the particle size distribution of cement and UFGGBS. Figure 2 shows the test results from an X-Ray diffraction test. The results in Figure 2 shows a low number of peaks meaning no crystalline phase are detectable in the UFGGBS. Having no crystalline phase and having small particle size indicate that the mineral admixture has a high degree of reactivity. To obtain a minimum slump of 150 mm, a polycarboxylate-based high range water reducing agent (HRWRA) was used.

	Cement (I)	UFGGBS
Physical properties		
Blaine Surface Area (m^2/kg)	360	870
BET Surface Area (m^2/kg)	1466	4968
Particle Mean Diameter (µm)	15.96	4.09
Density(kg/m^3)	3150	2720
Oxide compositions (%)		
SiO_2	21.5	31.2
Al_2O_3	5.5	9
Fe_2O_3	4.5	1
CaO	63	35.1
SO_3	2.5	0.1
MgO	2	11.8

Table 1: Physical and chemical characteristic of OPC and UFGGBS.

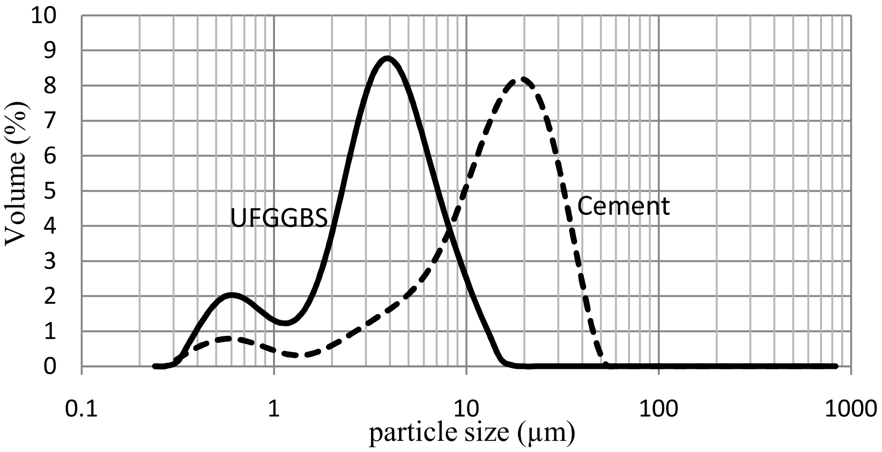

Figure 1: Particle size distribution of UFGGBS and cement.

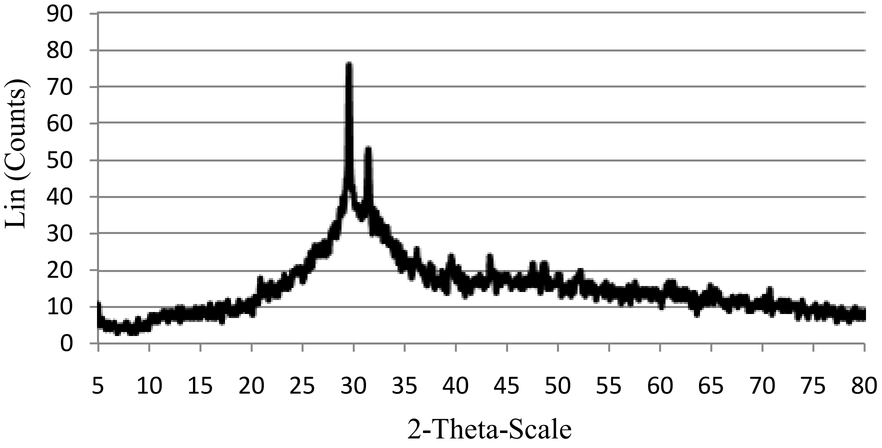

Figure 2: X-Ray Diffraction test results

In this work, a total of four mixes were studied. Two different grades of concrete were studied, the first one has a w/c ratio of 0.35 and 450 kg of cementitious materials, and the second one has a w/c of 0.28 and 520 kg of cementitious materials (Table 2). The amount of UFGGBS replacement was set at 30%. Mix A was set as the standard concrete mix. Mix B maintains the similar proportion to Mix

A with the 30% UFGGBS replacement. Mix C represents a higher concrete grade compared to Mix A and it has a lower w/c ratio and higher cementitious content. Mix D maintains similar proportion to Mix C with the 30% UFGGBS replacement. The details of the mix proportions are presented in Table 2. The samples were water cured in lab temperature of close to 25 °C for 3, 7, 28, 56 and 90 days.

Mix	A	B	C	D
Water / cementitious	0.35		0.28	
Aggregate / cementitious	4		3.35	
Slag replacement (%)	0	30	0	30
Total Cementitious	448	445	523	518
Coarse / fine aggregate	1			
Superplastizer / cementitious (%)	0.6	0.6	1	1
Aggregate by weight ratio	0.747	0.747	0.722	0.722

Table 2: Mix Proportion Details

Four sets of specimens were cast in four batches according to each mix design.The concrete was cast and cured until testing time as shown in the different test dates as listed in Table 3.

Mix Design	Curing Regime	Type of specimens	Number of specimens	Testing Days	Test Conducted	Total
A,B,C,D	Water	Cube	3 each	3, 7, 28, 56 and 90	Compression	60
A,B,C,D	Water	Prism	3 each	3, 7, 28 and 56	Flexural	48
A,B,C,D	Water	150 Ø Cylinder	3 each	28	Modulus of Elasticity	12
A,B,C,D	Water	100 Ø Cylinder	3 each	3, 28, 56 and 90	RCMT	48
					Sub Total	168

Table 3: Specimens details

The specimens subjected to water curing due for testing were removed from the water prior to the test according to BS EN 12390-2[7]. All the specimens were tested between 3 and 90 days after casting. The compressive cube strength test and three-point flexural test were completed using a 2000 kN compression machine according to BS EN 12390-3[8] and BS EN 12390-5[9] respectively. The 50 mm specimens for the rapid chloride migration test were cut from the 100 mm diameter cylinder specimens according to Nordtest method NT BUILD 492[10]. The migration of chloride ions into the concrete specimen is induced by applying an external electrical potential across the specimen to force the chloride ions outside the specimen to migrate into the specimen. After certain test duration depending on the quality of the concrete, the specimen is axially split. The chloride penetration depth can be measured via a visible silver chloride precipitation formed when silver nitrate is sprayed onto one section of the split specimen.

3 TEST RESULTS AND ANALYSIS

3.1 Compressive strength

Compressive strengths of the cube specimens tested are compiled and listed in Table 4. To study the effect of UFGGBS on the compressive strength of the concrete, Mix A was compared with Mix B and Mix C was compared with Mix D. As presented in Table 4, regardless of curing duration, the specimens containing 30% of UFGGBS achieved higher compressive strength compared to its companion concrete Mix without UFGGBS as early as 3 days curing. Comparing Mix B with Mix A shows an average increase of 7%, and comparing Mix D with Mix C shows an average increase of 23% in compressive strength for the various curing duration. The UFGGBS leads to a higher rate of hydration and pozzolanic reaction compared to the conventional GGBS. In addition, the UFGGBS is able to fill up the pores in the Interfacial Transition Zone (ITZ) better compared to GGBS. This explains the higher early strength obtained by the concrete from Mix B and Mix D.

Day	Mix A	Mix B	Mix C	Mix D
3	55.67 (**1.90**)	62.52 (**2.70**)	76.83 (**0.66**)	94.47 (**2.53**)
7	67.57 (**0.53**)	75.03 (**1.01**)	82.70 (**1.84**)	106.38 (**3.44**)
28	76.24 (**3.11**)	82.48 (**1.56**)	91.63 (**3.69**)	109.80 (**2.98**)
56	82.00 (**0.41**)	86.42 (**3.49**)	93.10 (**3.60**)	112.37 (**3.69**)
90	88.53 (**0.54**)	89.79 (**0.97**)	97.03 (**6.72**)	115.73 (**1.50**)

*standard deviation is presented in bracket

Table 4: Compressive strength results (MPa)

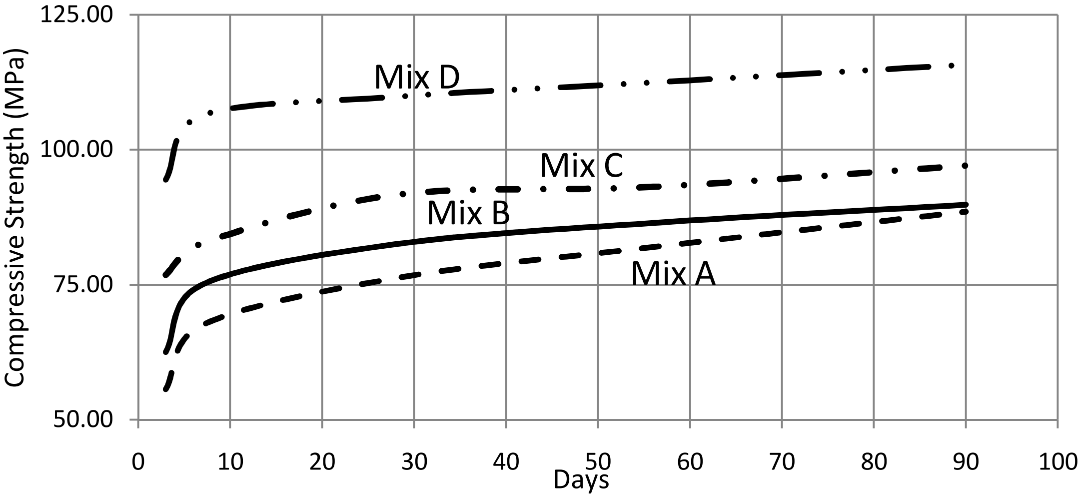

Figure 3: Compressive Strength Development

3.2 Flexural strength

Table 5 and Figure 4 shows the results of the flexural strength tests(modulus of rupture tests) obtained from this study. The standard deviation of the strength values is relatively small, representing a consistent mix. From the results, it can be seen that the mixes with UFGGBS achieved higher flexural strength compared to the control OPC concrete. The difference in flexural strength varies from 5% to 23% for the lower grade concrete and between 40% to as much as 60% for the higher grade concrete. With the addition of UFGGBS, Mix D obtained a flexural strength of 10.8 MPa after 3 day compared to 6.94 MPa for the control OPC concrete.

Day	Mix A	Mix B	Mix C	Mix D
3	4.93 **(0.43)**	5.19 **(0.40)**	6.94 **(2.29)**	10.77 **(2.02)**
7	5.45 **(1.64)**	6.73 **(0.32)**	7.21 **(0.13)**	11.63 **(0.62)**
28	6.71 **(0.37)**	7.23 **(1.59)**	8.47 **(0.14)**	11.82 **(1.08)**
56	7.24 **(0.41)**	7.38 **(1.13)**	8.70 **(0.09)**	11.90 **(1.64)**

*standard deviation is presented in bracket

Table 5: Flexural strengths of different mixes (MPa)

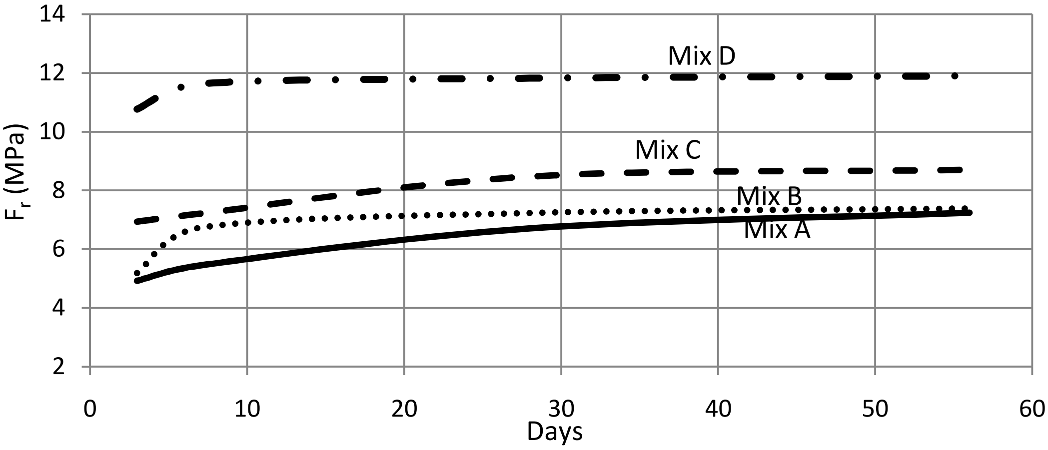

Figure 4: Flexural Strengths versus time

3.3 Modulus of elasticity

The moduli of elasticity of the different mixes are plotted in Figure 5. It can be seen that Mix B and Mix D generally achieved higher results compared to the control Mixes of A and C.

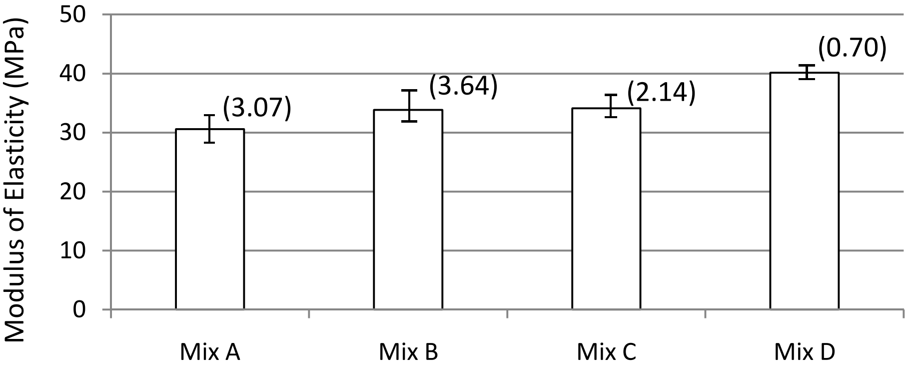

Figure 5: Modulus of Elasticity Results

3.4 Chloride migration coefficient

The chloride migration coefficient can be calculated via the following equation according to Nordtest NT BUILD 492[10].

$$D_{nssm} = \frac{0.0239\,(273+T)L}{(U-2)\,t}\left(x_d - 0.0238\sqrt{\frac{(273+T)L\,x_d}{U-2}}\right) \qquad (1)$$

where:
D_{nssm}: non-steady-state migration coefficient, x 10^{-12} m^2/s;
U : absolute value of the applied voltage, V;
T : average value of the initial and final temperatures in the anolyte solution, °C;
L : thickness of the specimen, mm;
x_d : average value of the penetration depths, mm;
t : test duration, hour.

The computed coefficients are presented in Table 6. It is clear that concrete samples from Mix B and Mix D have lower permeability, leading to smaller chloride migration coefficient. For Mix B, a 35-50% reduction is observed compared to Mix A. For Mix D, an 80% reduction in the chloride migration coefficient compared to Mix C was obtained. As the concrete curing age increases, due to more complete hydration, the permeability of the concrete decreases and hence the chloride migration coefficient becomes smaller. Figure 6 shows the test setup of rapid chloride migration test used in this study.

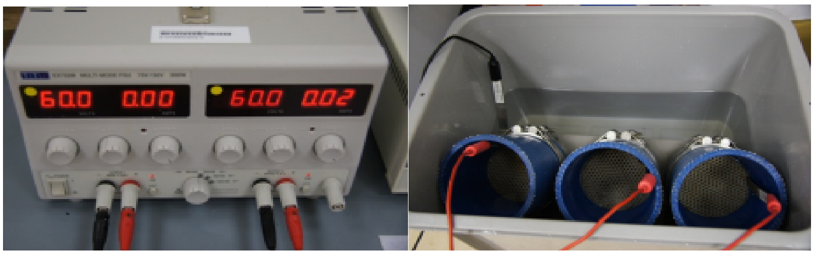

Figure 6: Test setup of rapid chloride migration test

Day	Mix A	Mix B	Mix C	Mix D
3	15.64 **(0.24)**	8.35 **(0.95)**	10.18 **(1.63)**	2.63 **(0.14)**
28	10.61 **(0.35)**	7.92 **(1.22)**	7.91 **(0.21)**	0.95 **(0.07)**
56	9.88 **(1.27)**	6.39 **(0.50)**	6.01 **(0.74)**	0.71 **(0.15)**
90	9.47 **(0.54)**	4.33 **(0.68)**	3.80 **(1.17)**	0.50 **(0.08)**

Table 6: Chloride migration coefficient

From the RCMT results, it is possible to classify the resistance of the concrete against chloride penetration according to Table 7[11]. With reference to Table 7, the resistance of the concrete samples at different concrete age is listed in Table 8. The resistance of the concrete against chloride penetration increases with the curing age. Generally, all the concrete mixes achieved high level of resistance against chloride penetration at curing age of 56 days. However, in real practice, the curing period in some cases can be limited to only a few days. From the results, it can be seen that for a higher grade concrete, the inclusion of the UFGGBS makes a significant impact on the resistance of the concrete even at an early age of the hardened concrete.

Chloride diffusivity, $D_{28} \times 10^{-12}$ m^2/s	Resistance to chloride penetration
> 15	Low
10 - 15	Moderate
5 - 10	High
2.5 - 5	Very high
< 2.5	Extremely high

Table 7: Resistance to chloride penetration of various types of concrete based on the 28-day chloride diffusivity[11]

Mix	Curing Regime	Day	Chloride Migration Coefficient	Resistance to chloride penetration
Mix A	Water	Day 3	15.64	Low
	Water	Day 28	10.61	Moderate
	Water	Day 56	9.88	High
	Water	Day 90	9.47	High
Mix B	Water	Day 3	8.35	High
	Water	Day 28	7.92	High
	Water	Day 56	6.39	High
	Water	Day 90	4.33	Very High
Mix C	Water	Day 3	10.18	Moderate
	Water	Day 28	7.91	High
	Water	Day 56	6.01	High
	Water	Day 90	3.80	Very High
Mix D	Water	Day 3	2.63	Very High
	Water	Day 28	0.95	Extremely High
	Water	Day 56	0.71	Extremely High
	Water	Day 90	0.50	Extremely High

Table 8: Classification of the concrete for resistance to chloride penetration

3.5 Probability of failure

It is possible to estimate the rate of chloride penetration by simplifying the complex transport mechanisms for penetration of chlorides into concrete. Combining the Law of Diffusion[12,13] with a time-dependent chloride diffusion coefficient[14,15], equations (2) and (3) can be derived:

$$C(x,t) = C_s\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D(t).t}}\right)\right] \tag{2}$$

where in equation (2), C*(x,t)* is the depth of chloride concentration *x* after time *t*, C_s is the chloride concentration at the concrete surface, *D* is the concrete chloride diffusion coefficient and *erf* is the mathematical function.

$$D(t) = \frac{D_0}{1-\propto}\left[\left(1+\frac{t'}{t}\right)^{1-\propto} - \left(\frac{t'}{t}\right)^{1-\propto}\right]\left(\frac{t_0}{t}\right)^{\propto} . k_e \tag{3}$$

where in equation (3), D_0 is the diffusion coefficient after the reference time t_0, and *t'* is the age of the concrete at the time of chloride exposure. The parameter *α* represents the time dependence of the diffusion coefficient, while k_e is a parameter which takes the effect of temperature into account[16]:

$$k_e = \exp\left[b_e\left(\frac{1}{293} - \frac{1}{T-273}\right)\right] \tag{4}$$

where *exp* is the exponential function, b_e, is a regression parameter, and *T* is the temperature. Equation (4) ensures the temperature at which the concrete is under the effect of chloride penetration is considered in estimating the rate of chloride penetration.

Empirical α-values of 0.4 (0.08) is recommended for OPC concrete(standard deviation indicated in bracket), and 0.5 (0.1) for slag-blended cement concrete[17]. Due to the inclusion of slag as part of the binder, the ageing factor recommended for a slag-blended concrete is higher than that of a normal OPC. DURACON is a program which integrates equations (2)-(4) with a Monte Carlo Simulation to provide the calculation of the probability of failure[18]. In addition to the empirical α-values, the diffusivity coefficients for 28 day water cured samples presented in Table 6 were the input parameters in the analysis. Details of the input parameters are presented in Table 9. Analysis using Duracon Software was carried out with the input parameters in Table 9 and the results are presented in Figure 7.

Mix design	A	B	C	D
Design life	100 years			
Cover depth	75 (2) mm			
Temperature	28ºC			
Dcoef	10.61 (0.35)	7.92 (1.22)	7.91 (0.21)	0.95 (0.07)
t0 (age when tested)	28 days			
te (age when exposed)	28 days			
n (age factor)	0.4 (0.08)	0.5 (0.1)	0.4 (0.08)	0.5 (0.1)
Ccr (critical chloride content)	0.4 (0.08)			
Cs (surface chloride content)	3.8 (0.9)			

*standard deviation is presented in bracket

Table 9: Input parameters in calculation for probability of failure

In locations with harsh weather conditions like Norway, it is specified that the probability of failure should be limited to 10 percent in the serviceability limit state as specified in Standard Norway[19]. From the results presented in Figure 7 with the use of recommended α-values, Mix D obtained 0.28% probability of failure for a service period of 100 years. With the exception of Mix D, the rest of the mixes generally fall outside the serviceability limit required. For the lower grade concrete of Mix B, the probability of failure was 67%.

As discussed, different ageing factor is recommended for different type of cement. Therefore for a conservative analysis, a smaller ageing factor similar to normal OPC was used to study the probability of failure of Mix D at 100 years. With a smaller aging factor of 0.4 (0.08) instead of 0.5 (0.1), the probability of failure for Mix D increased to 1.14% over 100 years, still far below the 10% limit. When projected for a 150 years design life using the conservative ageing factor of 0.4 (0.08), the probability of failure for Mix D was 4.52%. This probability is still less than the 10% specified by the standard, showing the ability of this concrete mix to last 150 years with normal black steel.

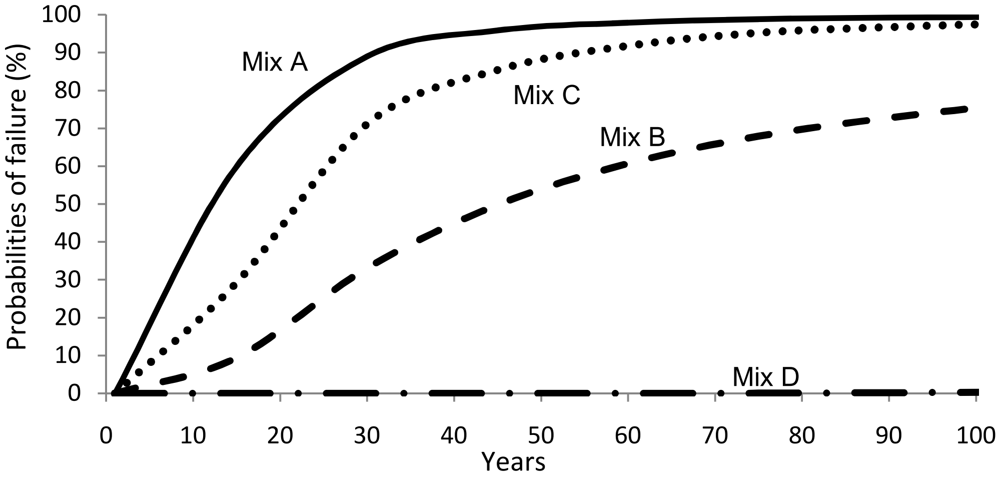

Figure 7: Probability of failure with recommended ageing factor for 100 years

4 CONCLUSIONS

1. UFGGBS has a larger total surface area, and thus, more of it is available for hydration and pozzolanic reaction, campared to normal GGBS. In addition, better workability andhigher consistency were achieved by utilizing UFGGBS. This will lead to an early strength development in terms of compressive and flexural strength, as studied. A higher compressive and flexural strengths compared to the control concrete was achieved at age of 3 days. This early development of strength is contrary to well established knowledge of ordinary GGBS.
2. With the inclusion of UFGGBS into the concrete, it is possible to obtain a consistent mix, as the high surface area of UFGGBS improves the rheology of fresh concrete.
3. With the inclusion of UFGGBS, there is a significant improvement in the mechanical properties of the concrete. The improvement is more obvious for higher concrete grade.
4. With the inclusion of UFGGBS, the permeability of concrete is reduced significantly. Due to the reduced permeability, chloride penetration into the concrete is reduced. This marked a significant improvement in the durability aspect of the concrete, especially for Mix D.

ACKNOWLEDGEMENT

The authors are very grateful for the research funding provided by National Research Foundation of Singapore (NRF) through the Competitive Research Programme entitled "Underwater Infrastructure and Underwater City of Future". The UFGGBS was provided free of charge by EnGro Corporation Limited and the superplasticizer was provided free of charge by BASF South East Asia Pte Ltd.

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