DESIGN AND PERFORMANCE OF SUSTAINABLE/GREEN CONCRETE

by

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Abstract

Concrete is the most used construction material in the world. However, the production of one ton of cement, which is the main ingredient of concrete, releases about one ton of carbon dioxide, and consumes natural resources, such as limestone and clay. Furthermore, a concrete structure made of normal concrete can be permeable which expedites the steel reinforcement corrosion process when exposed to severe weather conditions. Therefore, this reduces its durability and service life. Implementing sustainable/green technologies in concrete design and production can solve these problems and extend the structure lifespan. In this thesis, the possibilities of making sustainable/green concrete from locally available materials were investigated. Supplementary cementitious materials, such as ground granulated blast furnace slag (GGBS) and silica fume (SF), were used in order to reduce the cement content and to improve the size distribution and the grading of the particles. Their quantities were determined based on a new mix modeling platform called EMMA program. 130 concrete specimens of 10 different concrete mixes were tested and evaluated to measure the improvement levels in the new concrete. Low air content test results between 1% and 1.4% and higher concrete strength were obtained. These results reflected the improved particles packing of the concrete produced by EMMA program. Mechanical tests showed that the compressive strength of concrete incorporating SF and GGBS improved by 16%. Rapid Chloride Permeability Test (RCPT) showed results as low as 392 coulombs for mixes with supplementary cementitious materials. Microstructural analysis using a Scanning Electron Microscope (SEM) supported the RCPT findings and the mechanicals tests which showed that concrete with supplementary materials has less voids, has a more homogenous integration of ingredients and has an abundance of C-S-H product. EMMA program modeling has been useful to improve particles packing in the concrete. Last, a cost analysis showed that sustainable/green concrete in the UAE can be produced at the same price of the regular concrete.

Search Terms: *Sustainable/green concrete, Supplementary cementitious materials, EMMA modeling program, SEM analysis, Mechanical test, RCPT, Cost.*

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Chapter 1: Introduction to Green Concrete

1.1 Background

The construction industry in the UAE has recently witnessed a massive advancement in all aspects of construction. A lot of money has been invested in constructing houses, buildings and towers in the UAE. This construction relied mainly on concrete as the primary construction material due to its durability and ability to resist the harsh environment of the gulf region in terms of temperature, chloride and sulfate exposure. However, manufacturing the main ingredient of concrete, which is cement, has some negative effects on the environment, and it contributes to about 7% to 8% of carbon dioxide (CO_2) emissions yearly around the world and consumes natural resources. Several studies have been conducted to look into innovative methods that aim at making concrete more environment friendly through enhancing its properties, elongating its life span, using less natural resources in the manufacturing process and reducing CO_2 emissions. Supplementary materials are among the most effective methods to produce green/sustainable concrete that produces less CO_2, uses fewer natural resources and enhances concrete properties.

Fly ash, rice husk ash, ground granulated blast furnace slag (GGBS) and silica fume are the most common concrete supplementary materials. These materials, which are by products of other industries, are used in concrete for partial replacement of cement in addition to direct improvements to physical and mechanical properties [1]. Implementing green design for concrete is subjected to two main conditions: The level of awareness of how important and beneficial the green concrete is, and the feasibility of using sustainable/green concrete in construction.

Fly ash is a byproduct of thermal power plants that generate electricity by burning coal. The fly ash is collected from the exhaust system in the plant and the remaining slag of the burned coal. Quality of fly ash and its particle size depends on many factors, such as the quality of the burning and collecting system, the composition of burned coal, level of pulverization, and the way of storing and handling fly ash before use [2]. Fly ash particle size is between 1 to 150 µm [3]. The spherical shape of its particles (as shown in Figure 1) improves the concrete's pumping ability and workability [4].

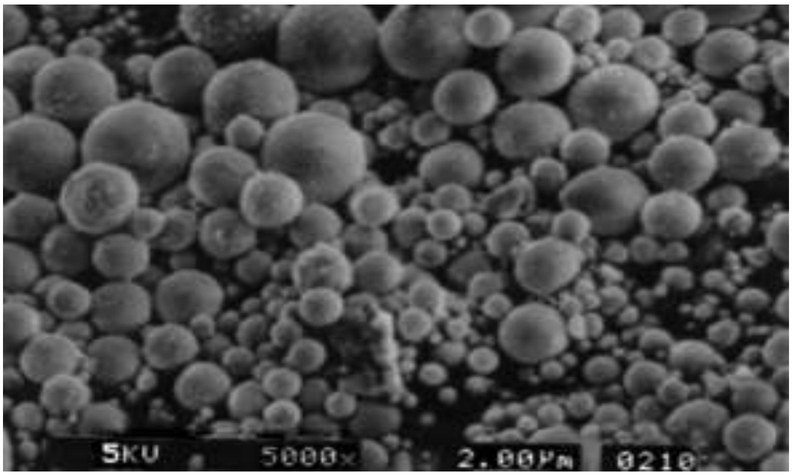


Figure 1: Fly Ash Particles Under SEM at 5kx Magnification [4]

Silica fume is obtained from the ferrosilicon alloy and from the silicon metal manufacturing process. Silica fume is collected by advanced filtering system installed on the stacks of the silicon manufactures. Silica fume was tested in concrete for the first time in the early 1950s. Higher performance of concrete was obtained using silica fume in terms of sulfate resistance and mechanical strength. The average particle size of silica fume is less than 1 µm and is usually between 0.2 to 0.3µm.The fume of the silicon is harmful to human and animals life in which it cause breathing difficulties and problems. Reusing it in concrete has double benefits of enhancing concrete properties and protecting the environment from wastes and harmful materials [4] [5]. Silica fume affects the color of concrete and make it darker. Thus, SF is supplied in different range of gray color to give the ability for controlling concrete color where necessary as shown in Figure 2.

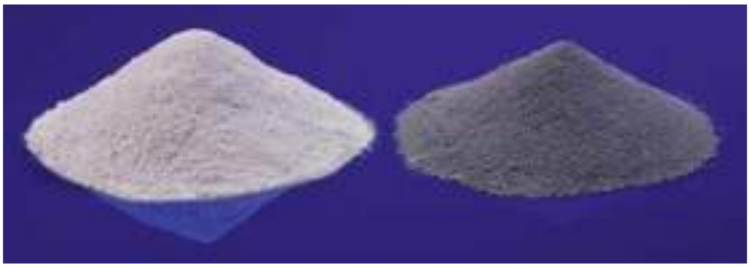


Figure 2: Silica Fume Powder [5]

The slag of the manufacturing process of iron in iron blast furnace is called ground granulated blast furnace slag (GGBS). It is a non-metallic byproduct that mainly contains calcium silicates and aluminosilicates. Slag particle size is about 10–

45 µm. Chemical composition varies depending on the source of iron raw materials [4].

Fly ash was eliminated from this study due to several reasons related to local suppliers. The main problem with fly ash in the UAE was found to be the storage of the material. High humidity in the region can significantly affect the performance of the fly ash and increase storing and handling costs. Thus, the main focus in this research will be on GGBS and silica fume. Both, GGBS and silica fume, are insolvable by water, and they react only with the product of cement hydration $Ca(OH)_2$ or the shortcut CH.

Byproducts can help reduce cement content in concrete and therefore achieve the required mechanical and physical properties with smaller sections and less concrete.

The UAE government is investing a lot of efforts to educate and instruct engineers to construct green buildings. Estidama in Abu Dhabi, developed by Abu Dhabi Urban Planning Council, published a green building code with a rating system called Pearl Building Rating System (PBRS). The new system consists of five levels. New buildings must get at least level one to get construction approval [6].

Dubai, being the economic city of the UAE and the largest city in terms of new construction volume, has applied new laws in 2015 that force the construction companies to use recycled materials and supplementary byproducts in the concrete used for construction. They also specify the minimum requirements that need to be applied in concrete mix to be qualified for construction approval.

1.2 Objectives of the Study

The main aim of this research is to design and produce high quality green/sustainable concrete in UAE at affordable cost. The objectives of this research are:

- design green/sustainable concrete mixture
- model particles packing using EMMA computer software
- evaluate the rheology of the new sustainable concrete
- evaluate the mechanical strength of the new sustainable concrete

- evaluate concrete durability using RCPT test
- investigate the microstructure of the green/sustainable concrete using SEM
- carry out a cost study of using green concrete in local construction

1.3 Literature Review

The benefits of using supplementary cementitious materials in concrete mix design have been proven in many researches. The enhancements almost cover every aspect of concrete; whether it is physical or mechanical property. The use of these materials is considered green enhancement to concrete due to their ability to reduce the use of natural materials in concrete.

Babu and Kumar [7] conducted experiments in 2000 to examine the effect of replacing cement in concrete mix by ground granulated blast furnace slag (GGBS) at different proportions of replacement. Slag was used to replace cement in different proportions starting from 10%, with an increment of 10% up to 80%. Figure 3 shows the variation in the compressive strength of concrete mixes at different water/binder ratios and different slag replacement levels.

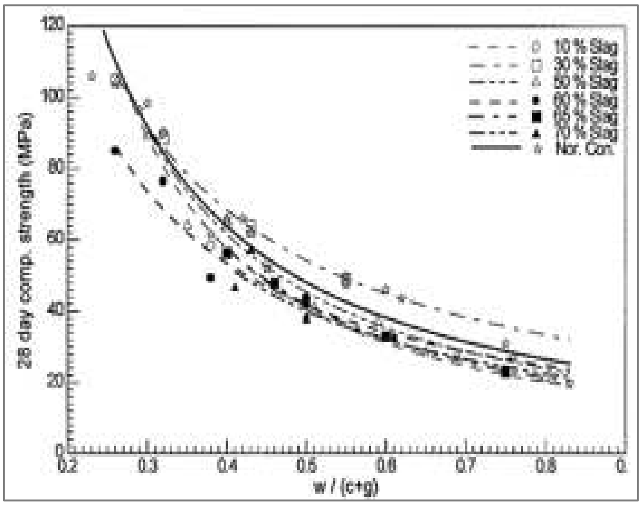


Figure 3: Compressive Strength at 28 Days of Different Concrete Specimens [7].

Figure 3 shows that the addition of GGBS as a partial replacement for Portland cement did not significantly change in the compressive strength compared to the normal concrete. However, it was found that the maximum compressive strength was obtained at replacement level between 25 to 50% among other replacement proportions.

Elchalakani et al. [8] conducted a study in 2014 to evaluate the ability of using environment friendly concrete in the United Arab Emirates. The aim of the study was to produce sustainable concrete with the locally available materials and to use byproducts as a partial replacement to cement with the focus on keeping the price within an acceptable price range. 13 types of concrete mixes were prepared to evaluate different aspects of durability in the new concrete. Cement was replaced by 50%, 60%, 70% and 80% of GGBS to reduce the carbon dioxide footprint.

Compressive strength test and RCPT were conducted to evaluate the strength and permeability of the mixes ash shown in Figure 4 and Figure 5. A mix design with 80% GGBS was concluded as best price to properties mix. It has been noted that the compressive strength of concrete with 50% GGBS is in line with the study of Elchalakani et al. [8].

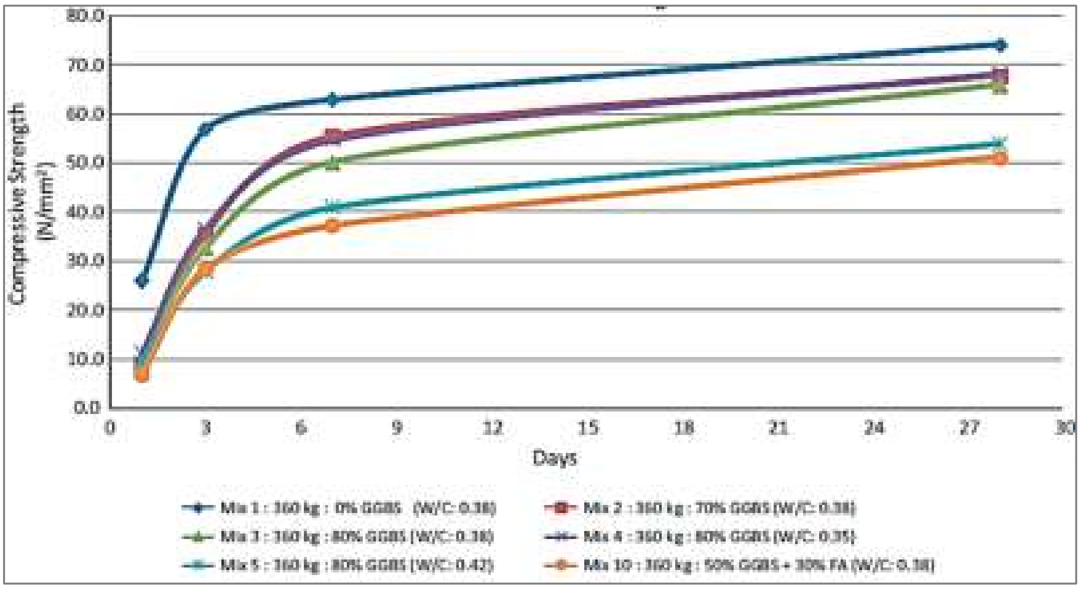


Figure 4: Compressive Strength of Different GGBS Mixes at 1, 3, 7 and 28 Days [8].

Results showed an excellent RCPT test result which means a very good permeability resistance from concrete that has GGBS. The worst RCPT test results were from concrete with ordinary Portland cement (OPC) only. Moreover, the compressive strength of concrete containing GGBS was close to the OPC concrete. Also, it has been concluded that the setting time of concrete containing GGBS generally was increased by 10% to 29% than normal OPC concrete [8]. The cost of sustainable concrete mixes was very close to the original mix (OPC only).

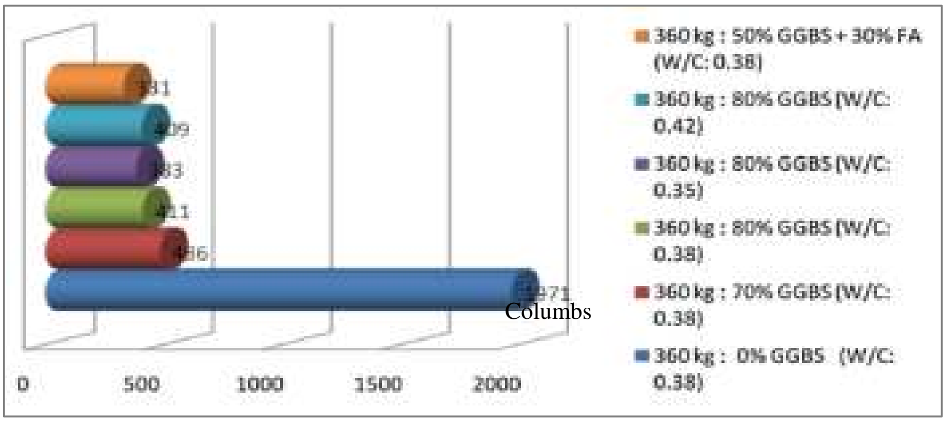


Figure 5: RCPT For Concrete with Different GGBS Proportions [8].

Carbon emissions were found to be reduced significantly by adding GGBS to concrete as shown in Figure 6 where mix 1 represents concrete without GGBS.

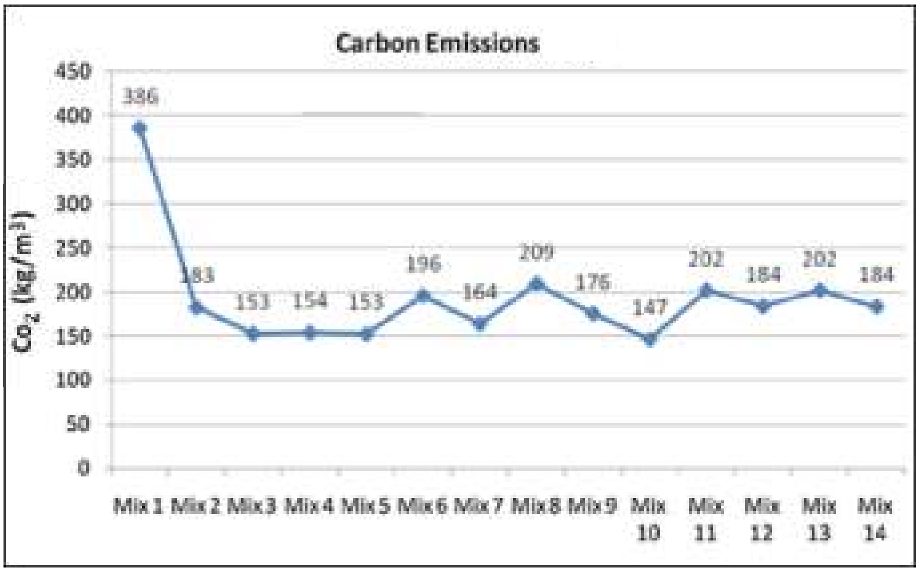


Figure 6: CO_2 Emissions for the Examined Mixes [8].

A study by Bagheri et al. [9] was conducted in 2012 to study the effect of adding silica fume to concrete on the mechanical strength and durability of concrete that contains GGBS. Results show that the mixes which contain silica fume and GGBS demand less water than mixes that contain only silica fume. Moreover, replacing 15% of cement by GGBS led to a minor reduction in compressive strength of concrete at different ages. Silica fume addition showed compensation in the strength of 15% slag mix to match the control mix strength at 28 days and to exceed it at later ages. However, the addition of silica fume could not compensate for the strength at cement replacement of 30% to 50% by GGBS compared to control mix.

In terms of durability, mixes with GGBS only show lower performance in compressive strength test than control mix at 28 days, however, they show better durability characteristics at 90 days and above. Silica fume addition improved the durability performance at all ages.

An investigation was conducted by Khana and Lynsdaleb [10] in 2002 to investigate the strength and permeability of high strength concrete. Mixes of binary and ternary cementitious materials from silica fume (5% to 15%), fly ash and OPC were used with water/cement ratio (w/c) of 0.27, 0.4 and 0.5. It was found that the addition of silica fume increases the early strength of concrete. Optimum strength and lowest permeability values were recorded at silica fume content of 8% to 12% of cement. It was also found that adding silica fume caused a slight increase in the depth of carbonation in concrete.

Yang and Chiang [11] in 2005 evaluated the relationship between the pore structure of concrete and the electrical charge that passes through concrete using RCPT and other methods. In their experiment, a cement based mortar (Concrete) with river sand as fine aggregate, crushed limestone of 10 mm maximum diameter as a course aggregate, Portland cement type 1 without mineral additives was used. Eight mixes were prepared with different proportions of water/cement ratio that was varying from 0.3 to 0.65. The average compressive strength obtained after crushing 3 concrete cylinders of each mix was in the range of 54.4 MPa for 0.3 w/c mix to 28.5 MPa for 0.65 w/c mix. The RCPT test results also varied between 2435 coulombs for the highest strength mix to 13191 coulombs for the weakest mix (in terms of compressive strength). It was concluded that the continuity and the volume of pores increase with the increment of water/cement ratio and the relationship between compressive strength and pores quantity is linear.

Another aspect of a performance test was conducted in 2007 by Oner and Akyuz [12] about the optimum usage of GGBS for highest compressive strength of concrete. GGBS was added to concrete as a partial replacement for cement at different proportions. Four main groups of control concrete mixes were poured according to their binder content with 32 different mixtures. GGBS was added as 0%, 15%, 30%, 50%, 70%, 90% and 110% of control mixes weight to mixes with 30% less cement content of control mixes by weight. Air content varies from 1.4 to 2%. Compressive strength was determined at 7, 14, 28, 63, 119, 180 and 365 days. For early strength, results show lower compressive strength compared to normal mix. However, long term results show considerable increment in strength compared to normal mixes. They have also concluded that the optimum replacement of cement by GGBS to maintain the highest strength is 55% to 59%. In addition, it was found that the workability of concrete with GGBS was better than the workability of normal concrete with the same binder content.

Another investigation was conducted in 2005 by Cheng et al. [13] to study the effect of having GGBS in reinforced concrete on the durability characteristics of the structure. Specimens were prismatic beams of size (150) x (150) x (900) mm. These specimens were exposed to chloride ions and different loading conditions while direct current was used to accelerate the corrosion of the rebars in the concrete. Results show that slag addition reduces the current that passes through the specimens and also reduces the permeability. In addition, GGBS has a significant effect on flexural rigidity and corrosion rate of reinforced concrete beams.

Dottoa et al. [14] , in 2004, studied the influence of adding silica fume to the concert mix on its mechanical properties and durability performance. Specimens of different mixes were prepared, water/binder ratio used in three batches were 0.5, 0.65 and 0.8 while the SF content was 0%, 6% and 12%. These specimens were tested to evaluate the effect of SF on compressive strength, porosity, electrical resistivity and polarization curves of concrete. The team used a high early strength Portland cement and SF from the production of a silicon metal industry. Results show that SF can be effectively used to protect reinforcement against corrosion. Protection rate correspondence is directly proportional to the amount of SF added to the mix. Moreover, SF addition increased the compressive strength of concrete noticeably when compared to normal concrete.

A review for the durability properties of concrete that contains silica fume was prepared by Khana and Siddiqueb [15] in 2011. The team summarized the various applications of using silica fume in concrete mix design. SF can be used to produce high performance concrete, high strength concrete, shotcrete concrete and other applications. Moreover, the reaction mechanism of silica fume with concrete was reviewed. SF is very active pozzolanic material. It has been noticed that silica fume addition enhances the transition phase of CH crystals by reducing its degree of orientation. Thus, it improves the mechanical properties of concrete and enhances the formation of new C-S-H particles. Moreover, studies show that permeability of chloride through concrete has been reduced by using SF. Scientists have suggested that the fine particles of silica fume reduce the pore structure in concrete by filling micro-gabs and forming more C-S-H. It has been also reported that concrete permeability has been reduced up to more than 75% by adding SF. It has been proven in the literature that 10% to 20% addition of silica fume enhances the corrosion behavior of reinforcement [15]. Concrete PH and Chloride content decrease in the presence of SF because of the decrease in $Ca(OH)_2$ due to the increase in the formation of C-S-H which helps in filling more pores and preventing penetration.

Ochbelagh et al. [16] carried out an investigation in 2012 to study the effect of adding silica fume to the compressive strength of concrete and the ability of concrete to resist gamma rays. They have used Portland cement type I with w/c ratio of 0.45 by weight, aggregate of 2400 kg/cm^3 and lead powder to produce concrete specimens with and without silica fume. Results show huge improvement in concrete strength due to adding silica fume. The team suggested that adding 15% silica fume as a cement replacement can enhance the microstructure of concrete, which can thus increase strength by about 22%.

Strength and modulus of elasticity of concrete containing silica fume were also investigated in 2013 by Sarıdemir [17]. In this study, several levels of cement replacement by silica fume were tested. The research agrees with Ochbelagh study [16] where it has been found that 15% silica fume gave the best compressive strength. Moreover, Sarıdemir found that silica fume improves the modulus of elasticity of concrete and that concrete modulus of elasticity has a liner relationship with concrete compressive strength.

A study in 2012 was conducted by O’Connell et al. [18] to investigate the performance of concrete incorporating GGBS in aggressive waste water environments. GGBS has been added to the concrete to evaluate its durability against sulfates and acids which are highly present in waste treatment plants. Several tests were conducted for that purpose. The authors concluded that the addition of GGBS to concrete will result in huge reduction in the expansion of concrete due to sulfate attack. Figure 7 shows clearly the good performance of concrete containing GGBS against sulfate attack.

A study on the effect of aggregate packing on concrete performance was conducted in 2015 by Moinia et al. [19]. Simulation, using algorithms from the literature and experiments, was used to develop concrete packing. It has been concluded that concrete packing can be used to improve compressive strength of concrete.

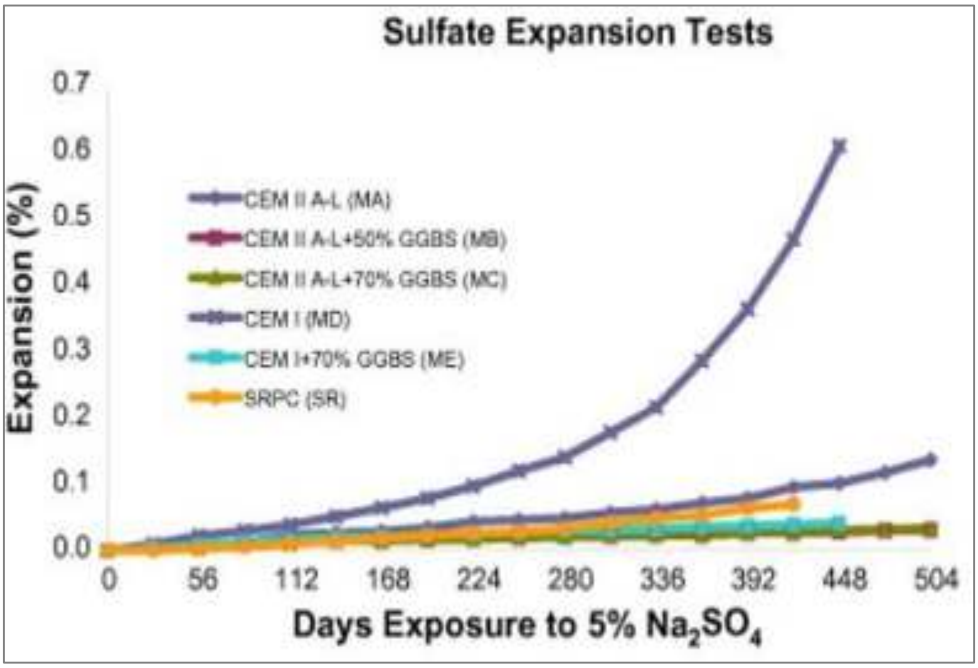


Figure 7: Sulfate Expansion Tests [18]

A PhD study was conducted by Abu Saleh M. [20] in 2014 regarding development of sustainable and environment friendly concrete. The author has worked on many aspects of sustainability in concrete. 24 Concrete mixes were designed using absolute volume method. 15 mix design contained GGBS while 3 mixes had silica fume at three different water cement ratios (0.25, 0.32 and 0.4). Cement was replaced by GGBS in 5 different proportions starting from 100 to 70 % replacement. It has been noted that concrete compressive strength with 70% GGBS is higher than concrete with higher content of GGBS ash shown in Figure 8. The study has also mentioned that a slower rate of hydration has been observed when GGBS content in the mix increases. To overcome this issue, especially for gaining early strength, the author suggested using lower w/c ratios than regular mixes.

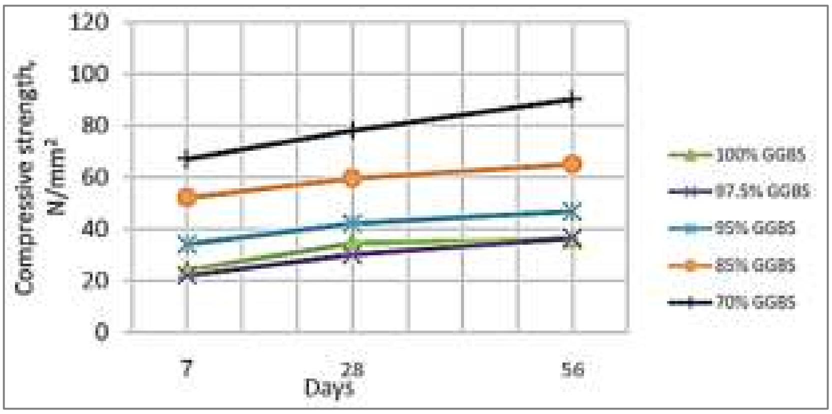


Figure 8: Compressive Strength of Concrete with Various GGBS Proportions [20]

In Abu Saleh's study, concrete mix with 70% GGBS was considered as the control mix. Mixes with 10% silica fume and rice husk were compared to the control mix and it was found that the mix with silica fume has better compressive strength than the GGBS mix.

A RCPT test was also carried out to examine the permeability of concrete that contains slag and Silica fume. Very low permeability results were obtained (all below 1000 Coulomb) using 70% to 100 % GGBS mixes and 10% silica fume mixes. In addition, Abu Saleh did microstructure analysis using scanning electron microscope for different mixes as shown in Figure 9. Some silica fume partials did not react at 7 day due to the lack of water when w/c was 0.25.

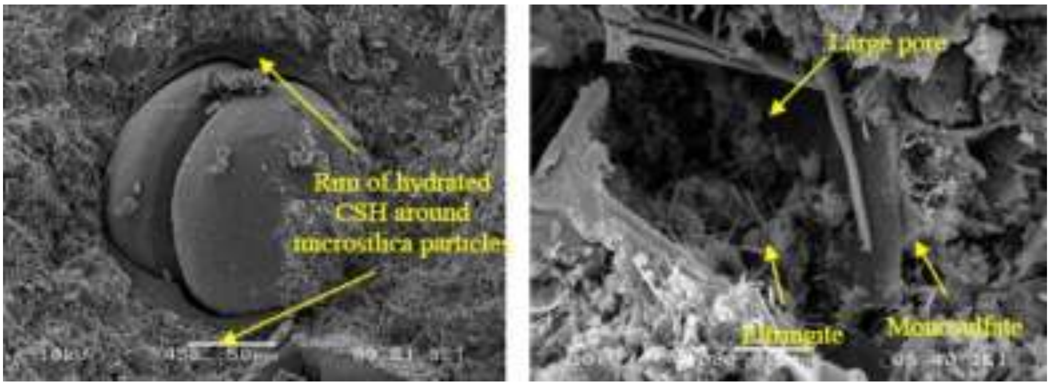


Figure 9: SEM Images of P90M10 Paste at the Age of 7 Days [20]

In 1997, Jones et al. [21] did experiments on durability of ternary blend concrete from carbonation and chloride penetration point of view. They have targeted for strength of 20, 40 and 60 MPa at 28 days of curing using concrete containing flay ash, GGBS and/or silica fume. An electrochemical chloride ingress test was conducted along with penetration test. It was concluded that ternary blend concrete has higher rate of carbonation compared to normal concrete or concrete with fly ash. This result is not matching with most of the recent literature.

Menéndez et al. [22] in 2003 conducted research on “Strength development of ternary blended cement with limestone filler and blast-furnace slag.” Cement was replaced by 10, 20 and 35% of GGBS. Compressive strength test shows that normal mix has higher compressive strength at 28 days. However, at 90 days the mixes with 20 and 35% GGBS show better strength results than regular mix.

In 2010, a study by Nochaiya et al. [23] has been done to evaluate the properties of concrete with fly ash and silica fume. Tests were conducted to study the workability, compressive strength and setting time of concrete. It has been concluded that the addition of silica fume requires more water to reach same level of slump. However and regardless of slump results, workability in general was noted to be higher than normal concrete. Moreover, setting time of concrete with silica fume seems to be shorter than normal concrete. Compressive strength of concrete with silica fume and fly ash was also tested. It showed higher values than normal concrete by approximately 145%. A microstructure analysis was conducted using SEM as shown in Figure 10 and Figure 11. The authors conducted that CH, $Ca(OH)_2$, was found in less amount in mixes that contain silica fume. This is due to the reaction of silica fume with the $Ca(OH)_2$.

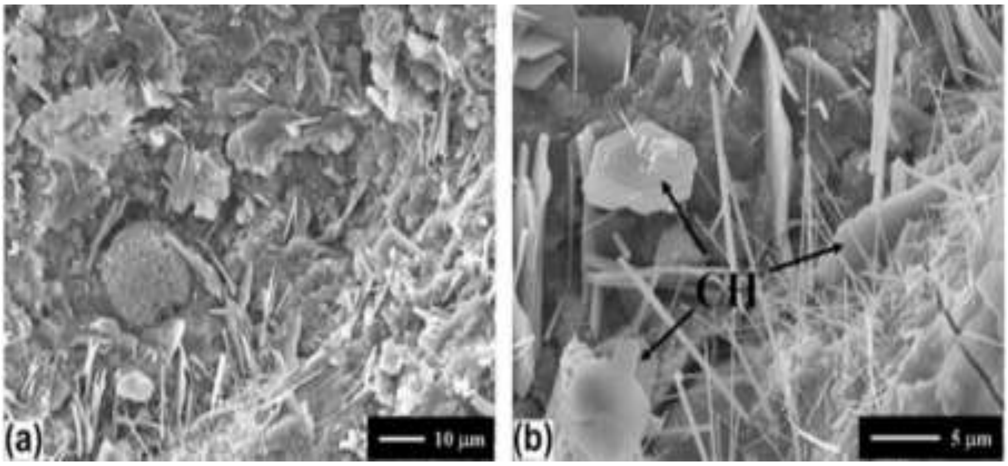


Figure 10: Microstructure of Concrete with 20% Fly Ash and without Silica Fume at (a) ×1000 and (b) ×3000 [23].

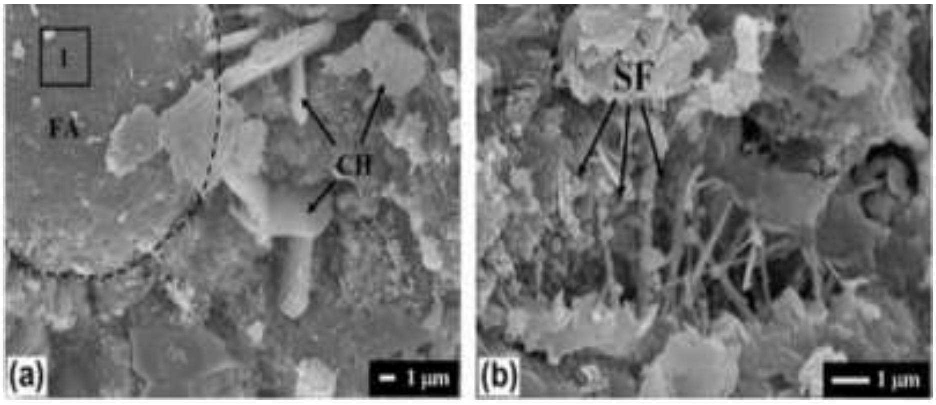


Figure 11: Microstructure of Concrete with 20% Fly Ash and 10% Silica Fume at (a) ×4000 and (b) ×10,000 [23].

In the current research, a new modeling technique will be used to densify the particles packing of concrete ingredients. Improvement in the rheology, mechanical and durability of the resulted green/sustainable concrete is anticipated due to this technique. A microstructural analysis will be conducted to validate these improvements. Furthermore, cost analysis will be carried out to justify the use of green/sustainable concrete in the UAE.

Chapter 2: Experimental Program

Ten concrete mixes were prepared using computer modeling techniques, EMMA software. These mixes were poured, cured and tested for fresh and hardened physical and mechanical properties.

2.1 Material Properties

Materials were chosen from local suppliers. All materials have been certified by local municipality for quality requirements. Details of the specific gravity (SG) and chemical compositions for some materials are as in Table 1, Table 2 and Appendix B.

Table 1: Specific Gravity of Concrete Ingredient

Material	Cement	Dune sand	Crushed Rock sand (5mm)	Aggregates (10mm)	Aggregates (20mm)	GGBS	Silica fume
SG	3.14	2.66	2.67	2.92	2.94	2.18	2.2

Table 2: Chemical Composition of Concrete Ingredients

Chemical composition	Cement (%)	GGBS (%)
SiO_2	20.5	33.8
IR (insoluble residue)	0.34	0.37
Al_2O_3	4.7	13.6
Fe_2O_3	4	0.7
CaO	64.1	39.4
MgO	1.8	6.2
SO_3	2.4	0.09
S	-	0.92
Na_2O	0.58	0.46
Mn_2O_3	-	0.27
LOI (Loss On Ignition)	1.5	2.0
Cl^-	0.02	0.01
C_3A	5.7	-

Material particles size distribution analysis has been imported into EMMA program. A particle size distribution of GGBS is shown in Figure 12 and a particle size distribution of aggregates (Figure 13). Appendix E and Appendix B contains more details of the properties and particle size distribution of the concrete materials used.

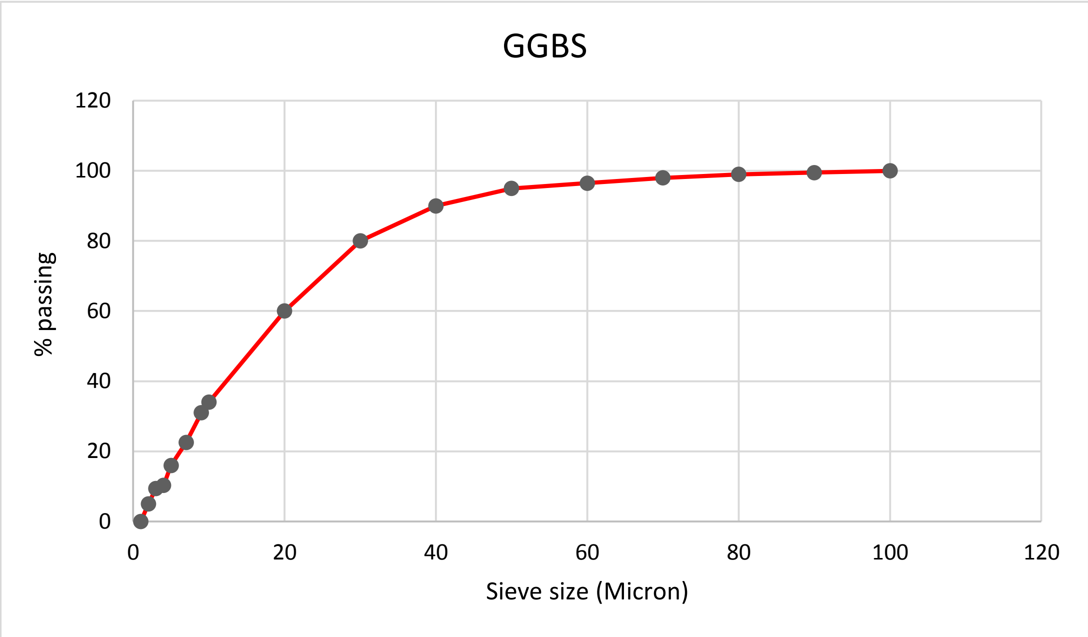


Figure 12: Particle Size Distribution of GGBS

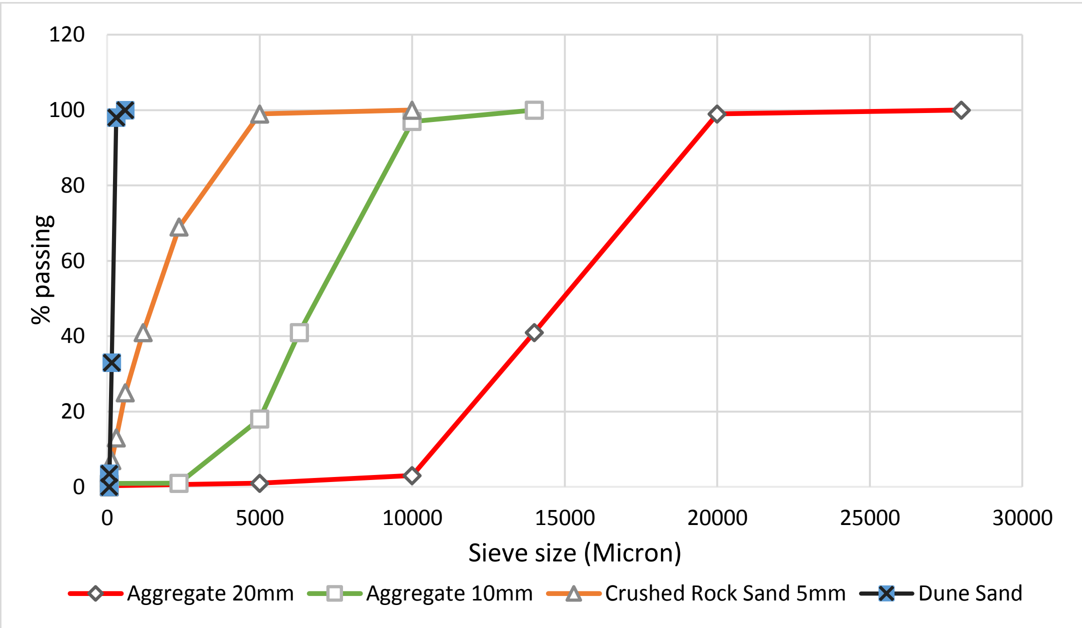


Figure 13: Sieve Analysis of the Fine and Course Aggregates

2.2 Particle Packing Using EMMA

Mix design was prepared using EMMA program. One of the objectives of this study was to use software to test the particles packing of the concrete. The steps of using EMMA are explained in details in section 2.2.2.

2.2.1 EMMA modeling.

Elkem team has done studies on the packing of the particles of materials to enhance its performance by making the most possible compacted and air-free mixes. Investigations were carried on varying the particle size distributions in pourable materials. Developers have referred to previous studies that supported the research efforts. Andreassen model was found to be perfect for their aim.

Andreassen suggested that optimal packing occurs when the particle size distribution can be described by this model:

$$\mathrm{CPFT} = \left(\frac{d}{D}\right)^{q^*} .100$$

Where q* means q is the exponent and q is the distribution coefficient,

CPFT is the Cumulative (Volume) Percent Finer Than,

d is the particle size,

D is the Maximum particle size. [24]

Based on the Andreassen equation, particles modeling software called EMMA (Elkem Materials Mix Analyzer) was developed. Users have to enter the particle size distribution (PSD) of each material of the mix, and then EMMA will calculate the particle size distribution of the mix and compare it to Andreassen model. Andreassen model has been presented by a linear line that shows the packing relation between particle passing specific sieves and the quantity of those particles. For ultra-fine particles, EMMA has an improved model that can be also used.

2.2.2 Using EMMA for packing concrete particles.

EMMA, as modeling software, gives the required tools to evaluate the packing density of any material. EMMA is a very useful tool to visualize and adjust the particle size distribution of the entire mix by modifying the quantity of each ingredient until the whole mix gets the best fit with the perfect solid material model, Andreassen model. Appendix F shows the details of how the software was used to obtain the mix design. Figure 14 and Figure 15 show EMMA software and the fields were the materials and quantities were added.

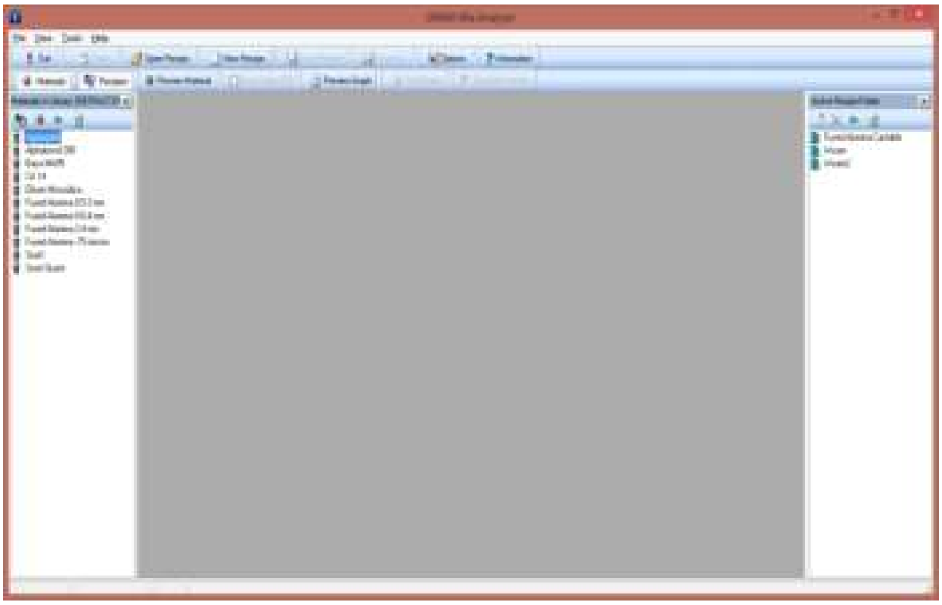


Figure 14: EMMA Mix Analyzer User Interface

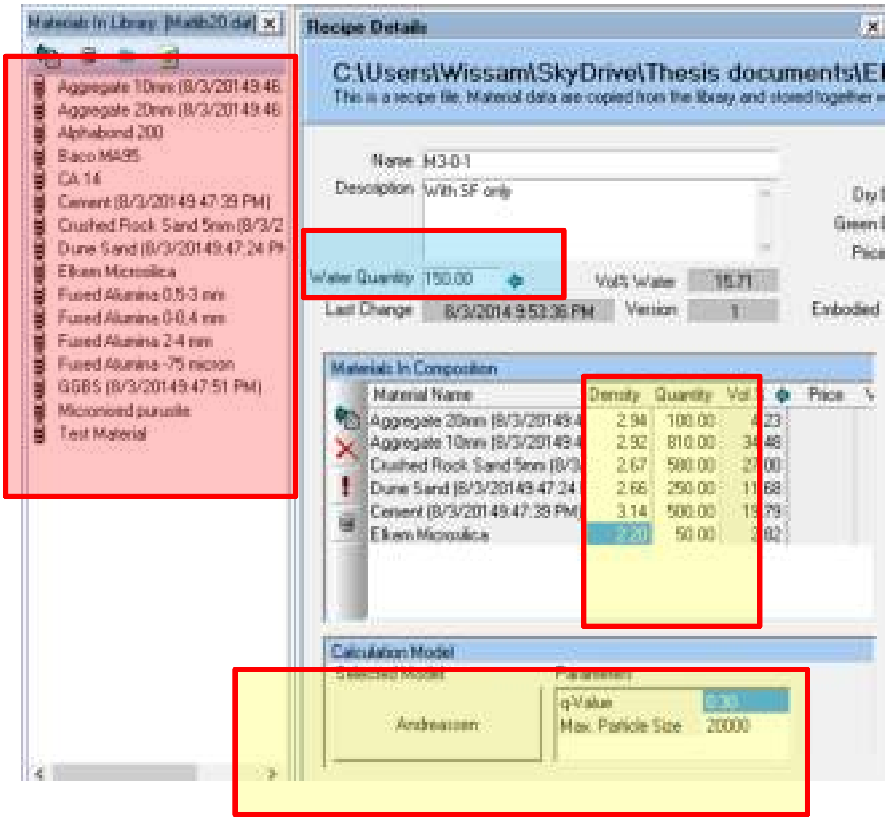


Figure 15: Green Mix Design Inputs in EMMA

The materials quantities were changed in loop until best match between recipe model and Andreassen model was obtained as shown in Figure 16 and Figure 17.

Figure 16 shows the particle size distribution for mix C500-S0-G0 where there is clear drop at the ultra-fine particle sizes. On the contrary, Figure 17 shows mix C320-S50-G180, which contains GGBS and SF that cover the fine and ultra-fine area.

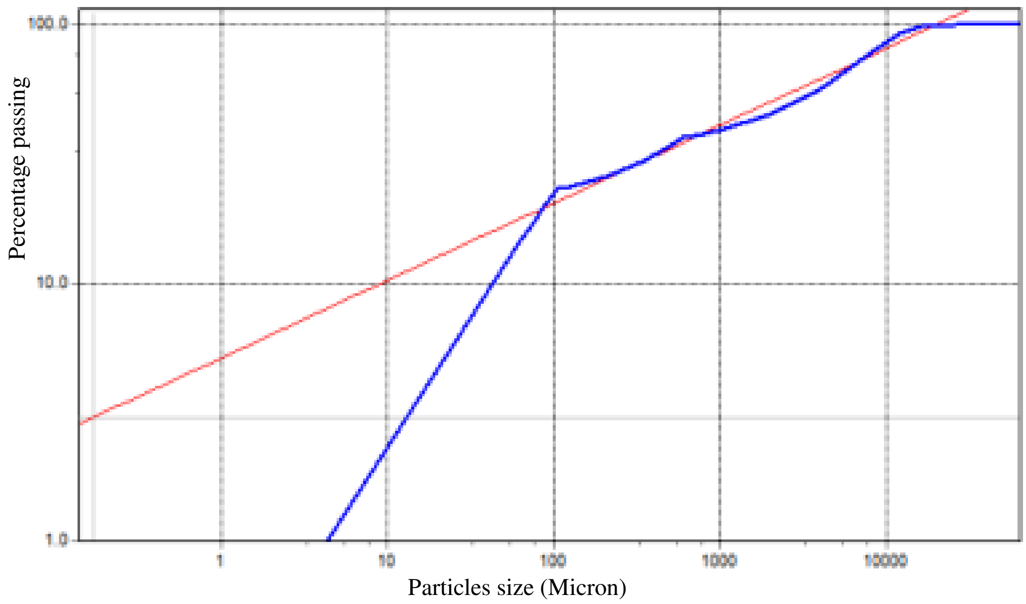


Figure 16: EMMA Particles Size Distribution Modeling of Mix C500-S0-G0 (Control Mix without Additives)

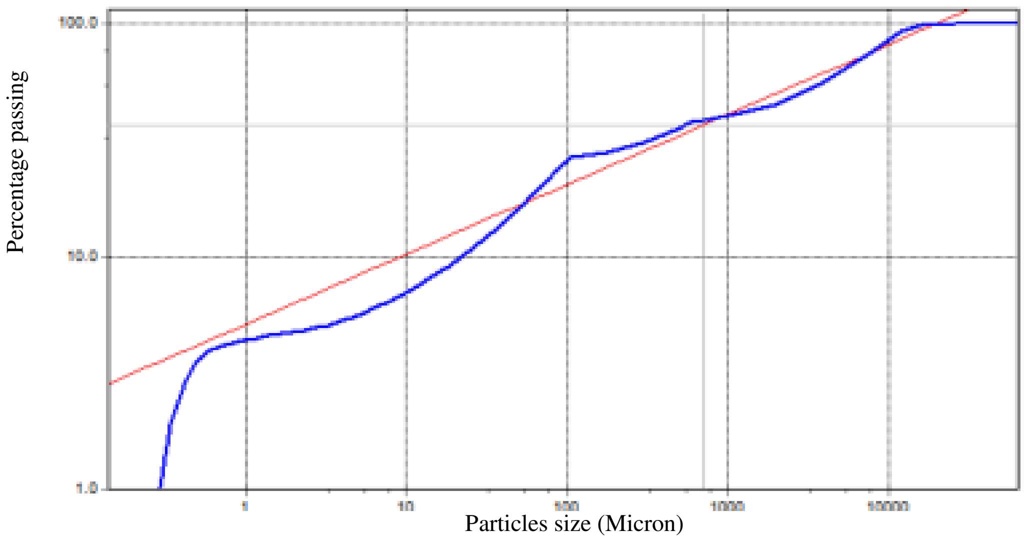


Figure 17: EMMA Particles Size Distribution Modeling of mix C320-S50-G180 (with Silica Fume)

Final mix proportions were concluded to be as close as possible to Andreassen model.

2.3 Specimens Preparation

Cubes and cylinders were prepared in the laboratory to be applied for several concrete tests. 100 cubes of 150x150x150mm were prepared of several mixes. Nine cylinders of 150 diameters by 300 mm length were also prepared. 20 concrete beams of 150x150x500mm were prepared.

After deciding on the material to be used and the time frame, work started by pouring concrete using molds fabricated at the workshop and others that are readymade. Preparation started for concrete pouring by arranging all required concrete molds at the casting yard. Also, fresh concrete testing tools, such as air content, slump and thermometer testing equipment were prepared. Concrete proportions were fed to plant mixers by computer and the mixes supplied inside truck mixer. Then, it was poured in trolley.

Temperatures for all mixes were tested at the site immediately after pouring the concrete as shown in Figure 18. This was the first experimental test at site.

Figure 18: Measuring Temperature of the Concrete

Concrete cubes molds of 150x150x150mm inner dimension were used to form the test cubes as shown in Figure 19.

Figure 19: Filling Cubes and Layering Concrete in the Molds.

2.3.1 Slump test.

A slump test was held to measure the workability of concrete mix for all the mixes according to ASTM C143, as shown in Figure 20.

Figure 20: Slump Test Before Casting Concrete in The Molds.

2.3.2 Air content test.

Air content test was held according to ASTM C231, as shown in Figure 21.

Figure 21: Air Content Test

2.3.3 Specimens curing.

Concrete specimens were demolded after 24 hours of casting. Then, concrete cubes were tagged with the casting date and mix group number to make it easier for the later stage to recognize the required cubes for tests. Tagging was placed at the rough surface of the cubes (the casting side). Cubes were cured for period of 7 and 28 days to gain the required compressive strength, and to prevent shrinkage cracks due to lack of moisture. Concrete curing was conducted at the Conmix concrete batching plant yard. Curing pool was shaded and built inside an air conditioned room with temperature of around 25 degree. Also, all specimens were completely submerged in water as shown in Figure 22.

Figure 22: Concrete Curing at Conmix Plant

2.3.4 Concrete compressive strength test.

Compressive strength test was conducted at 7 and 28 days according to BS EN 12390-2:2009 standard [25]. Each concrete cube was weighted before the test. Then, it was moved to the compression machine for the test. Cubes were positioned in the machine, such that the face of casting concrete was perpendicular to the machine. In other words, smooth surfaces were in touch with machine). Specimen was aligned to the center of the plate in the machine (Figure 23). Results were recorded for each mix, and an average strength of 3 cubes was considered.

Figure 23: Compressive Strength Test

2.3.5 Flexural strength test.

A flexural strength test was performed to measure the tensile strength of concrete according to ASTM C293. Unreinforced concrete beams of 150X150x500mm were tested against flexural strength at 28 days of curing. Center point load was applied at each beam and an average of 2 beams was considered for each mix. Top point was applied at the center of the beam. Other 2 points were marked at 25mm from the edge of the beam as shown in Figure 24 where this arrangement complies with ASTM C293 requirements to have length that is equal or is greater than 3 times of the depth.

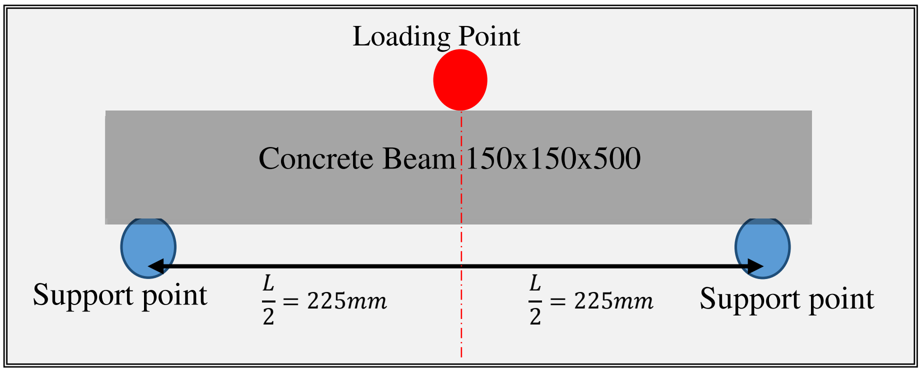


Figure 24: Flexural Strength Test Arrangement

The load was applied at constant rate until failure as shown in Figure 25. Failure load was recorded for calculating modulus of rupture using ASTM equation:

$$R = \frac{3PL}{2bd^2} \qquad (1)$$

where:

R = modulus of rupture,

P = vertical load,

b = length of the long side of the specimen,

d = height of the specimen.

Figure 25: Broken Beams Under Point Load

2.3.6 Modulus of elasticity (MOE) test for concrete.

The stress to strain ratio of 28 days age concrete cylinder (150mm diameter and 300mm length) was measured using the elasticity test of concrete apparatus at AUS laboratory as shown in Figure 26. Gauges were installed and calibrated around the diameter of the cylinder.

Figure 26: Elasticity Test of Concrete

The test started by applying constant force rate at the flat surface of the cylinder (Longitudinal compressive stress) that equals to 20% of the ultimate compressive stress of cubes. The specimens were loaded twice as shown in Figure 27; the first loading was mainly for calibrating, adjusting and ensuring the performance of gauges. Computer recorded the values for stress and strain with time till failure.

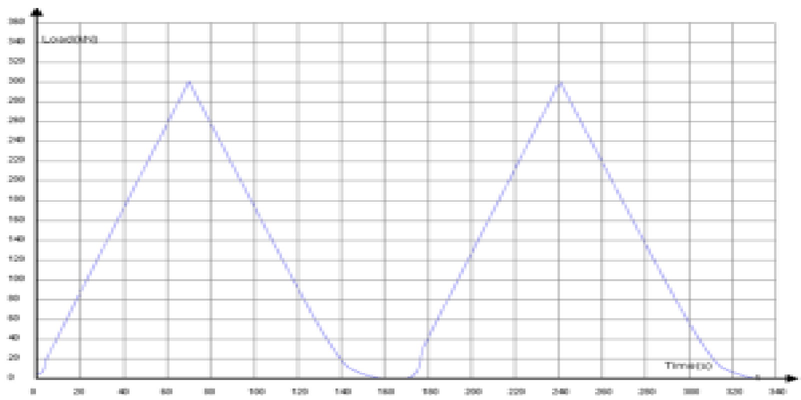


Figure 27: Load vs Time Graph by the Testing Machine at the Laboratory.

For normal weight concrete (with or without supplementary materials) MOE can be calculated using ACI-318M Equation:

$$E_c = 4700\sqrt{f_c'} \qquad (2)$$

2.3.7 Rapid chloride permeability test.

The rapid chloride permeability test (RCPT) was conducted in the laboratory according to AASHTO T277 and ASTM C1202. Concrete cylinders of 90mm diameter by 150mm length were cored from concrete cubes and tested for RCPT as shown in Figure 28.

Figure 28: Specimens Preperation for RCPT

The test aimed to measure the electrical connectivity of concrete by placing a 50mm concrete specimen between two electrical poles. Each electrical pole is represented by a solution reservoir of 0.25 liter. One side was filled with a 3.0% (NaCl) solution by weight while the other side was filled with 0.3 molar concentration of NaOH. Each reservoir has a stainless steel mesh on the inner side adjacent to the specimen as shown in Figure 29. Then, system was subjected to 60 volt of electrical direct current potential for six hours.

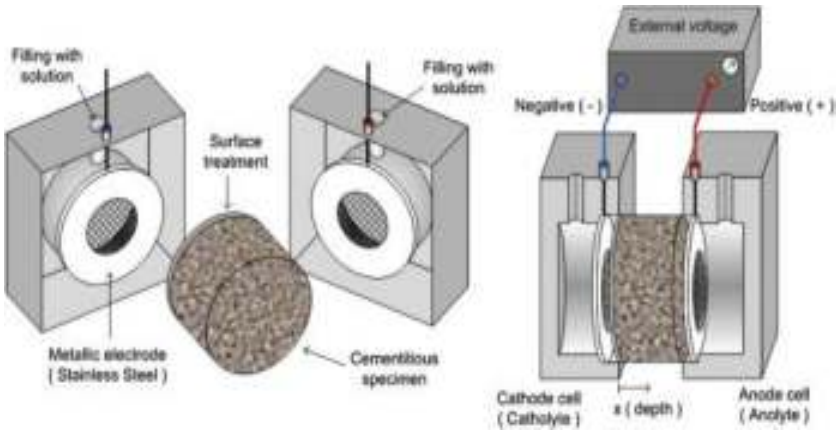


Figure 29: Illustration of the Test Arrangement [26]

The electrical current passing through the specimen has been measured in milliamps by the RCPT instrument. The area under the curve of milliamps vs. time represents the columbs values. Values were then compared to the ASTM C1202 (Table 3) to identify the level of permeability.

Table 3: Chloride Permeability Limits [27]

Chloride permeability	Charge (C)	Type of concrete	Total integral chloride to 41 mm depth after 90-day ponding test
High	>4000	High water-to-cement ratio (>0.6) conventional Portland cement concrete	>1.3
Moderate	2000–4000	Moderate water-to-cement ratio (0.4–0.5) conventional Portland cement concrete	0.8–1.3
Low	1000–2000	Low water-to-cement ratio (<0.4) conventional Portland cement concrete	0.55–0.8
Very low	100–1000	Latex-modified concrete, internally sealed concrete	0.35–0.55
Negligible	<100	Polymer-impregnated concrete, polymer concrete	<0.35

- Experimental steps:

Concrete cylinder of 90mm diameter by 150mm length was taken from concrete cubes to be tested for RCPT. A sow-cut machine was used for taking a concrete sample of 50mm thickness and 90mm diameter from the center of the concrete cylinder to avoid heterogeneity due to casting on the sides of the cylinder as shown in Figure 30 and Figure 31.

Figure 30: Cutting Specimen Using Diamond Sow-Cut

After cutting the sides of the cylinder, each specimen was tagged according to concrete mix it belongs to, as shown in Figure 32. Fine diamond saw-cut was used to avoid breaking the edges of the specimen. ResiGrand NT epoxy from commix was

Figure 31: Specimens after Cutting

used to coat the sides of the specimen in order to seal it against air or water penetration as shown in Figure 32. Epoxy was applied carefully to avoid any extension to the top or bottom side of the specimen. The specimens were left to dry for half an hour.

Figure 32: Epoxy Coating for the Sides of Each Specimen

The samples were placed in a desiccation chamber; the chamber was connected with vacuum pump by a hose. Silicon oil around the edge of the chamber was applied before closing its cover to ensure there is no air leakage. Then pumping was started and the stopcock valve on the chamber was opened as shown in Figure 33.

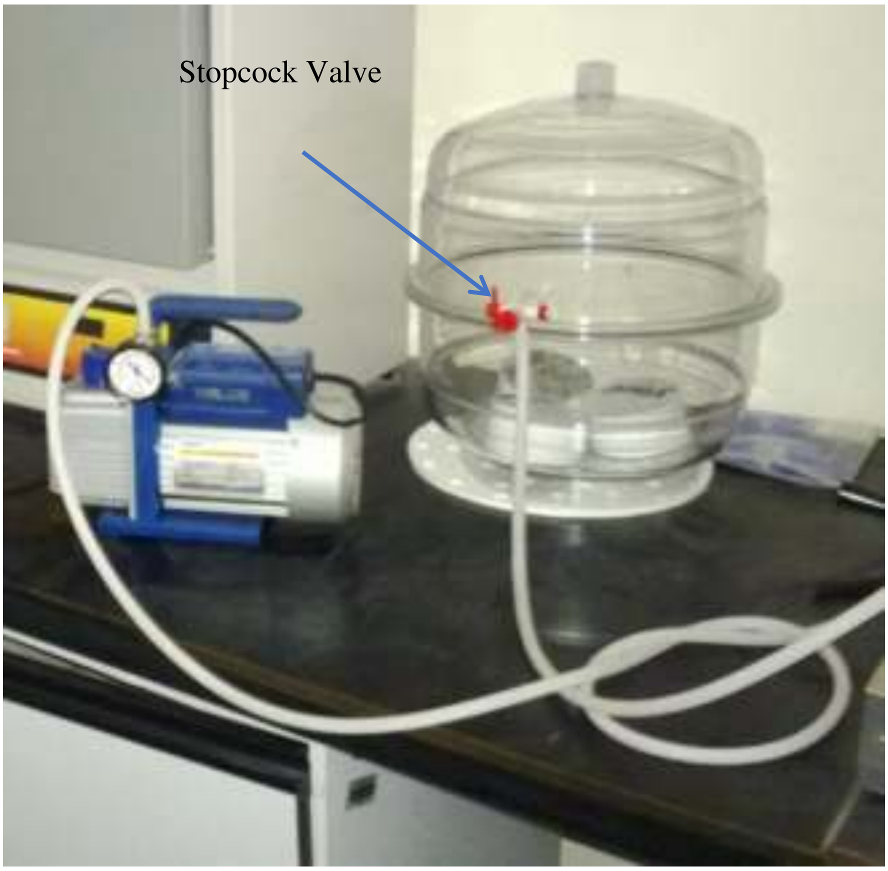


Figure 33: Specimens were Subjected to Vacuum of Less Than 133Pa

The pump was kept running for 3 hours to guarantee the removal of all the air from the specimens. The vacuum pump was able to maintain less than 133 Pa of pressure as shown in Figure 34.

Figure 34: Vacuum Pump Gauge

Distilled water was prepared in the laboratory as shown in Figure 35. Around 10 liters were required for the experiment. The water was heated for half an hour before it was used to guarantee the removal of all air content.

Figure 35: Preparing Distilled Water in the Laboratory

After the vacuum stage was completed, the stopcock valve was closed, and the vacuum pump was turned off to prevent any air leakage into the desiccation chamber. The hose was then removed from the pump end and submerged in the distilled water container. Then, the stopcock valve was opened again. Due to the difference in pressure, water started moving from the container to the desiccation chamber in a relatively high speed as shown in Figure 36. When the specimens were covered completely with water as shown in Figure 37, the stopcock valve was closed again. The hose was removed from the water, cleaned and connected to the vacuum pump. The pump was turned on for another hour. Note that no air was allowed to enter to the desiccation chamber during this process. After that the stopcock valve was closed and the pump was turned off. The specimens were kept in the water for 18 hours.

Figure 36: Submergence of specimens in Distilled Water

Figure 37: Specimens Totally Covered with Water

On the next day, the desiccation chamber was opened, and the specimens were ready for performing the test as shown in Figure 38. The specimens were placed between the reservoirs and rubber gaskets which were fixed at both ends as shown in Figure 39.

Figure 38: Opening the glass chamber after 18 hours

Figure 39: Fixing the specimens in the testing equipment

Silicon was applied between the gasket and the specimen to close any path for leakage. The specimens were lifted for an hour in order for the silicon to dry. Silicon oil was applied between the reservoir and the gasket for better sealant as shown in Figure 40.

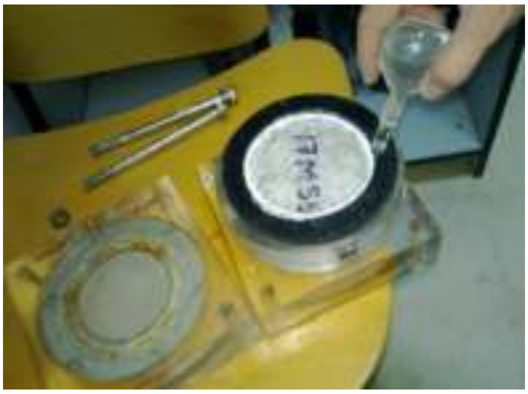


Figure 40: Silicon Application to Ensure Good Sealant

The specimens were tightened between the reservoirs using bolts as shown in Figure 41 and Figure 42.

Figure 41: Tightening the Screws to Avoid Leakage

Figure 42: Specimens Tightened between the Reservoirs

A reservoir of 0.25 liter was filled with a solution of 3% of NaCl by weight and distilled water of 0.25 liter. Similarly, a solution of 0.3 molar concentration of NaOH was used to fill the positive reservoir as shown in Figure 43. The reservoirs then was connected to the RCPT device as shown in Figure 44.

Figure 43: Weighting the Sodium Chloride and Sodium Hydroxide

Figure 44: Connecting the Reservoirs to the RCPT Equipment

Reservoirs were connected to the logging device. Then, test started after inputs were entered to the device software ('Prove it') as the following:

- Voltage = 60 DC
- Test time = 6 hours
- Specimen diameter = 90 cm
- Max test Temperature = 90 °C

Results were recorded and analyzed in the next chapter.

2.3.8 Microstructural analysis.

Microstructure analysis is being widely used in the literature to explain the relation between micro and macro structures of concrete. Microstructure investigations help in having a better understanding of concrete particles distribution. Using the electron microscope, the particles can be seen with up-to 2 micron magnification. Researchers can follow the changes on the particles of a specimen with time (more hydration of cement), so they can judge the effect of curing and the effect of additives on concrete physical and mechanical properties. Moreover, many properties and phenomena of concrete macrostructure can be explained using microstructure analysis, such as permeability, reinforcement corrosion, air content…etc. In addition to that, the formation of new layers such as C-S-H and CH can be visualized and clearly studied.

Following the casting and curing of the concrete cubes for 7 and 28 days, selected samples were taken for the SEM analysis. The samples were taken from the center of the cubes to be representative, containing different components of concrete. These samples were taken from the center of the cubes to ensure that they have all the different components of the concrete. A piece of concrete was cut down in a regular shape with a diameter of approximately 10mm and 5mm thickness with flat surface for the observation. A flat surface was obtained using the regular grinder with concrete cutting desk. Samples were polished using special fine polishing disk in the laboratory to have as smooth as possible surface. After that, the samples were vacuumed for 30 minutes in a vacuum chamber to get clearer images.

A scanning electron microscope "SEM" shown in Figure 45 was used to study microstructural details of concrete ingredients. The SEM was used to study the morphology of particles for different components of concrete. The SEM directs an ultra-fine beam of electrons with an accelerating voltage of 10 kV or 30 kV at the sample to scan it [28]. The electronic signals reflected from the surface of the sample are divided into:

- Backscattered electrons: high energy electrons.
- Secondary electrons: low energy electrons.
- Auger electron: low energy reflected electrons caused by excitation of some atoms.

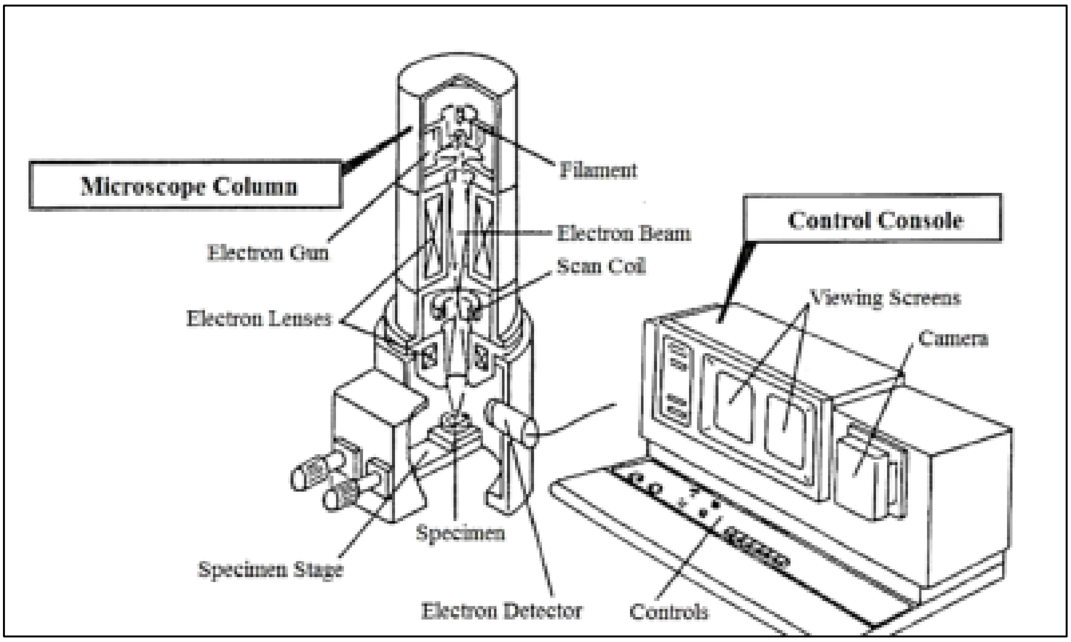


Figure 45: General Sketch of SEM and Its Components [29]

The specimens were placed in special tray and well-fixed by screws to ensure that there will not be any movement during the test inside the SEM as shown in Figure 46.

Figure 46: Prepared Samples were Fixed in the Tray of SEM.

The SEM test was performed on selected samples using the SEM at AUS as shown in Figure 47 to study the effect of particles packing on the microstructure of concrete.

Also, the test was carried out to study the effect of adding GGBS and silica fume to concrete mix on the morphology of concrete.

Figure 47: SEM Device at the Laboratory of AUS.

After several trials, the backscattered mode was chosen to obtain the micrograph images and to analyze the microstructure of the specimens. The Backscattered mode does not require ultra-smooth and thin slices. SEM is controlled using computer (Figure 48) and can take micro images that exceed 20kX of magnification. Morphology of concrete microstructure under SEM is shown in Figure 49.

Figure 48: Computer Software to Control the SEM

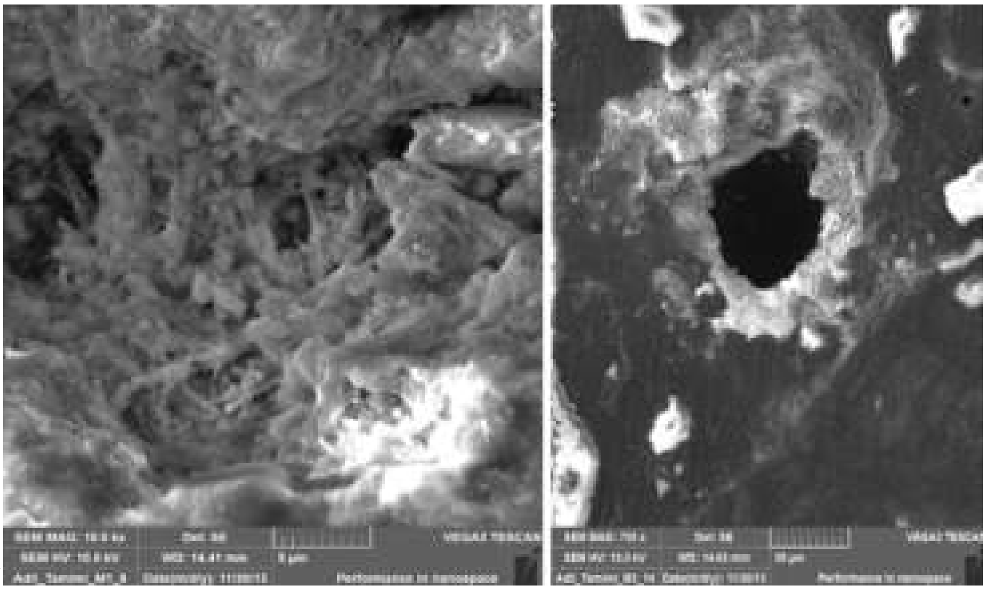


Figure 49: SEM Images of the Microstructure of Concrete

Analysis of the chemical composition of some areas in the concrete specimens was carried using the X-ray analysis feature in the SEM.

2.3.9 Mixes numbering system.

Each mix modeled in EMMA was given a unique number to be easily identified. The numbering system took the following format:

Cx-Sx-Gx

where:

C = cement,

S = silica fume,

G = GGBS,

x = the quantity of each binder in kg.

Chapter 3: Results and Discussion

3.1 Modeling Analysis by EMMA Program

Mixes from earlier study [30] were modeled, and the proportions were adjusted using EMMA as per Table 4.

Table 4: Mixes of 40 MPa and 60 MPa without Supplementary Materials

Material	20mm Aggregate (kg)	10mm Aggregate (kg)	5mm Crushed Rock (kg)	Dune Sand (kg)	Cement (kg)	w/c ratio
C40	720	360	520	220	410	0.3
C60	720	390	540	220	500	0.3

The results of several iterations in the EMMA program leads to the mixes shown in Table 5, which represent the best match between the proposed model and the actual particle size distribution of the materials.

Table 5: Mix Proportions Adjusted by EMMA

Material	C500-S0-G0	C320-S0-G180	C500-S100-G0	C320-S50-G180	C250-S0-G250	C275-S0-G275	C250-S50-G250	C500-S50-G0
20mm Aggregate (kg)	100	100	100	100	100	100	100	100
10mm Aggregate (kg)	810	810	810	950	810	810	950	810
5mm Crushed Rock (kg)	580	580	580	580	580	580	580	580
Dune Sand (kg)	280	280	250	250	280	250	250	250
Cement (kg)	500	320	500	320	250	275	250	500
GGBS (kg)	0	180	0	180	250	275	250	0
Silica fume (kg)	0	0	100	50	0	0	50	50
W/C ratio	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

The C40 and C60 mixes were prepared using the traditional methods. The proportions of each mix were entered into EMMA to produce visualized curves of particles size distribution for the entire mix. The particle size distribution of C40 mix is close to Andreassen model as shown in Figure 50, and the mix is well graded. However, an area of improvements in particles packing can be clearly identified in the graph. Cement and GGPS area can be improved significantly by adding smaller particles to cover the gap in the area of 1 to 10 microns. Also, a small additional amount of 10mm aggregate can adjust the drop in the quantity to have better grading.

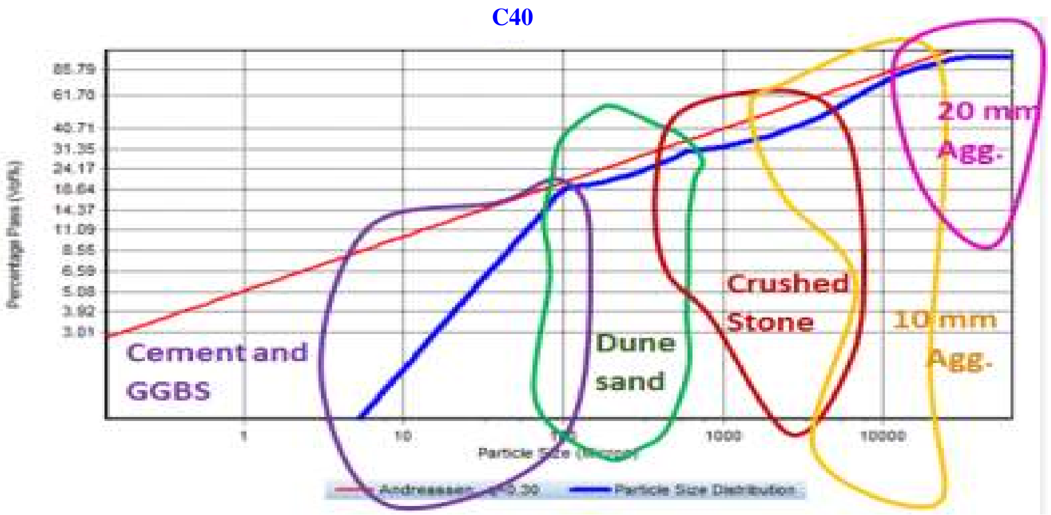


Figure 50: PSD and Illustration of the Area Covered by each Component of C40 Mix.

Similarly, C60 mix, as shown in Figure 51, can be adjusted for a better fitting on the model by adding ultra-fine particles; (see the yellow highlighted part of Figure 51 which clearly lacks ultra-fine particles).

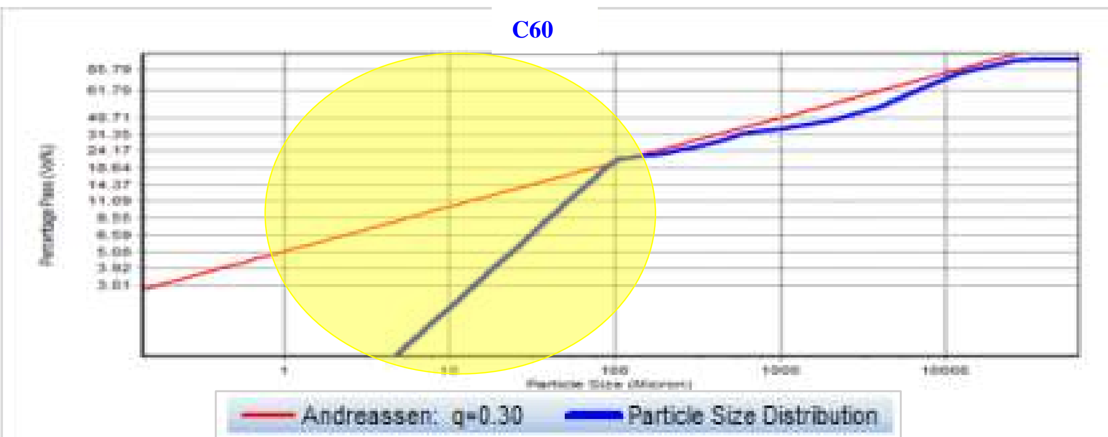


Figure 51: PSD of C60 Mix.

C500-S0-G0 is the improved revision of C60 mix. The area between 100 to 10000 microns has been well adjusted in the improved mix. Particles distribution of C500-S0-G0 is shown in Figure 52.

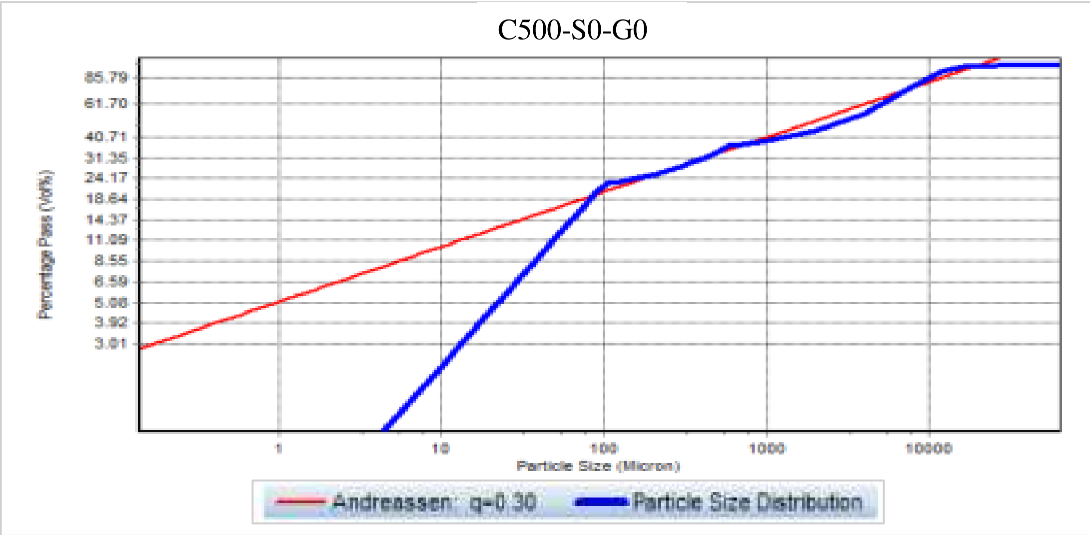


Figure 52: PSD of Mix C500-S0-G0.

After reaching good PSD proportions that best match with Andreassen model (the red line in Figure 53), these proportions were fixed, except for slight changes, among other mixes to control observation of the effect of fine and ultra-fine materials.

A new mix C320-S0-G180 that contains GGBS which has replaced 180 kg of cement in mix C500-S0-G0 was modeled as shown in Figure 53. GGBS Particle size

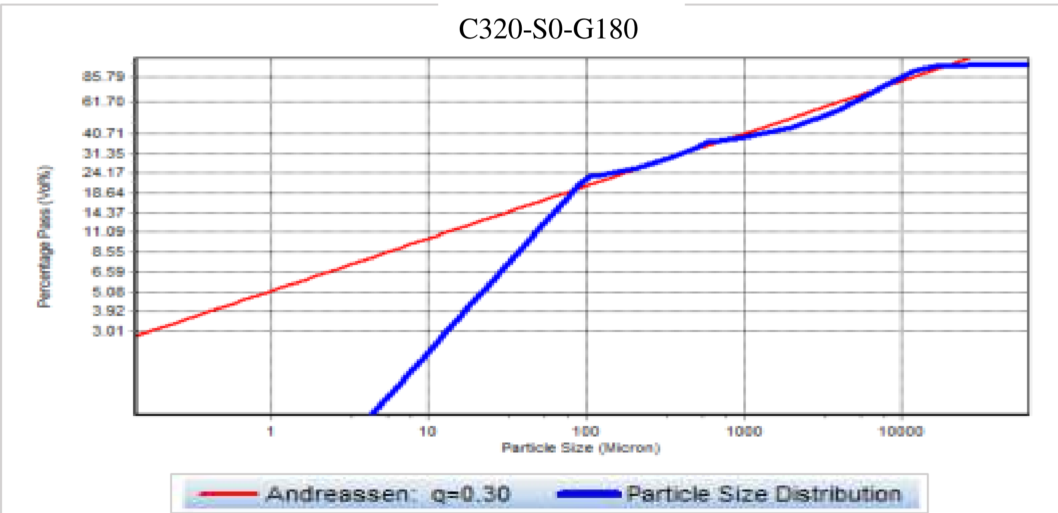


Figure 53: PSD of Mix C320-S0-G180.

distribution is very similar to cement. Thus, there was no noticeable change in the graph compared to C500-S0-G0 mix.

The addition of SF is presented in mix C500-S100-G0. Figure 54 shows great improvement in the grading of the mix design. SF filled the gap in the area from 0.5 to 62.2 Microns.

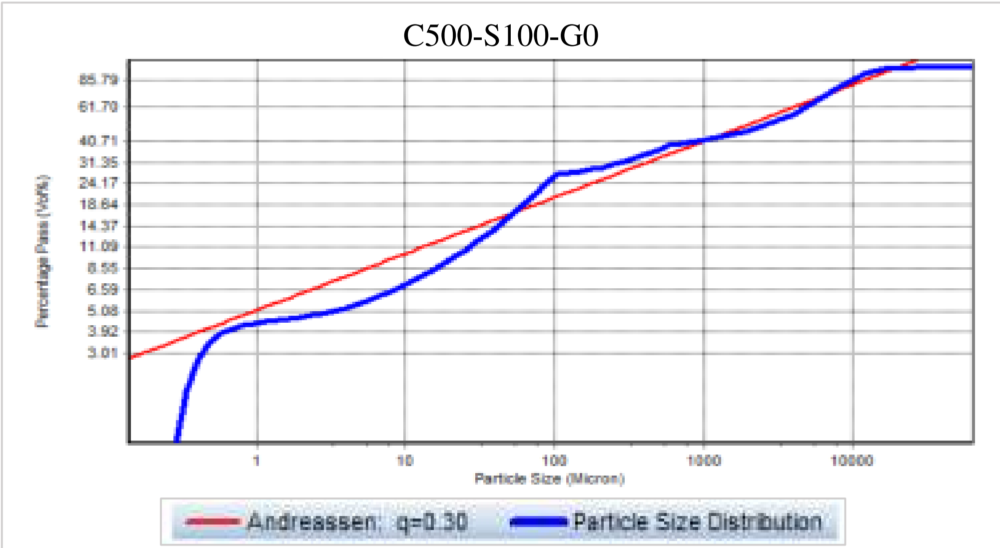


Figure 54: PSD of Mix C500-S100-G0

Mix C320-S50-G180 with GGBS and less SF is shown in Figure 55.

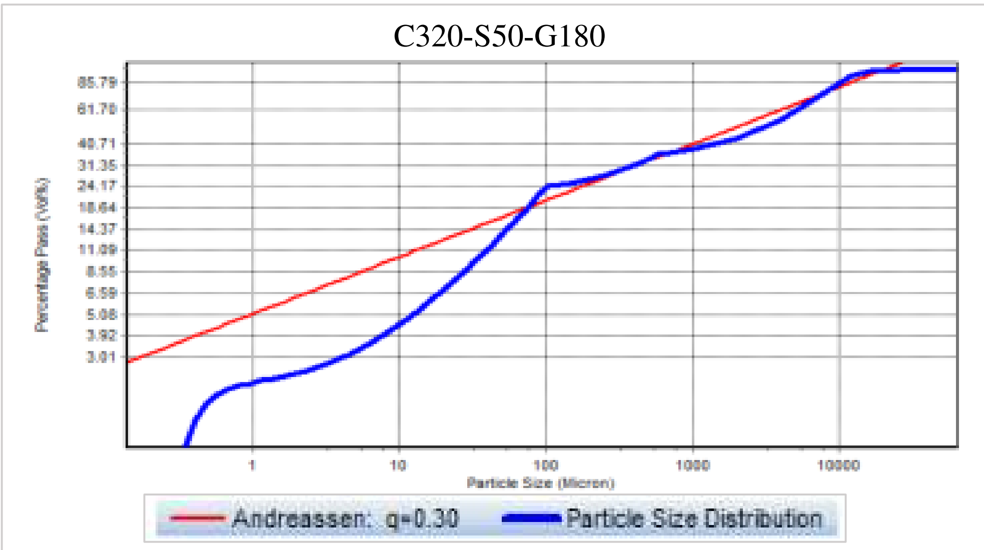


Figure 55: PSD of C320-S50-G180 (With GGBS and SF)

From these figures, it can be concluded that SF mixes are much better graded compared to mixes without SF. Silica fume is making concrete more solid by filling the micro gaps in concrete's microstructure. Mixes with reduced amount of cement have been modeled. Figures 56, 57 and 58 are showing mixes that are having 50% replacement of Cement.

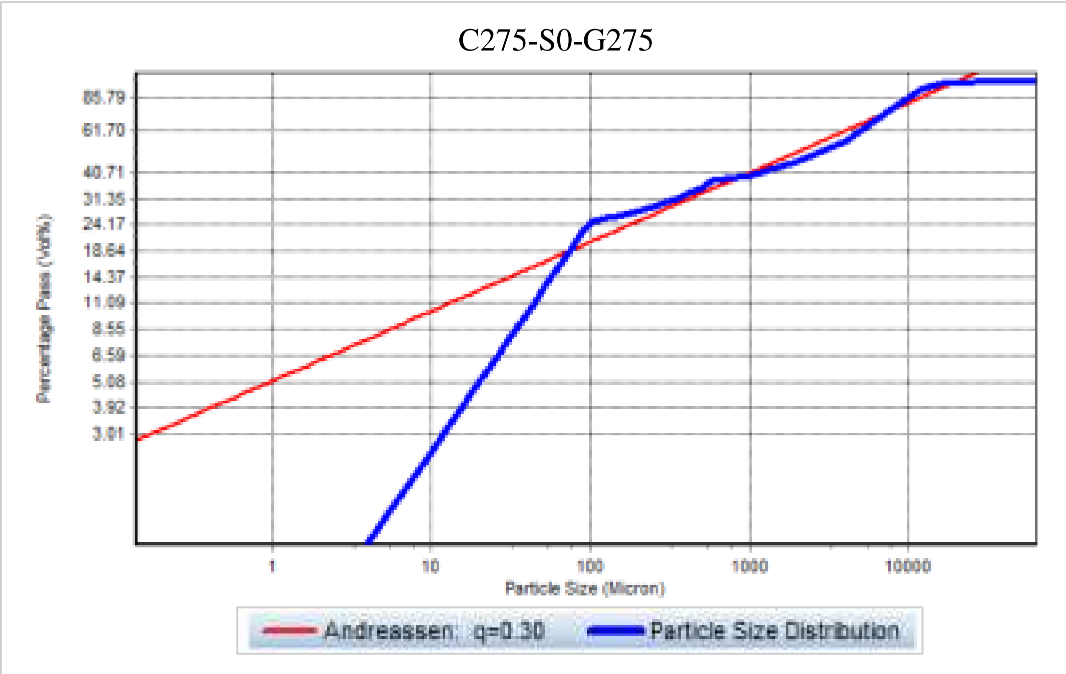


Figure 56: PSD of C275-S0-G275 (with GGBS Only)

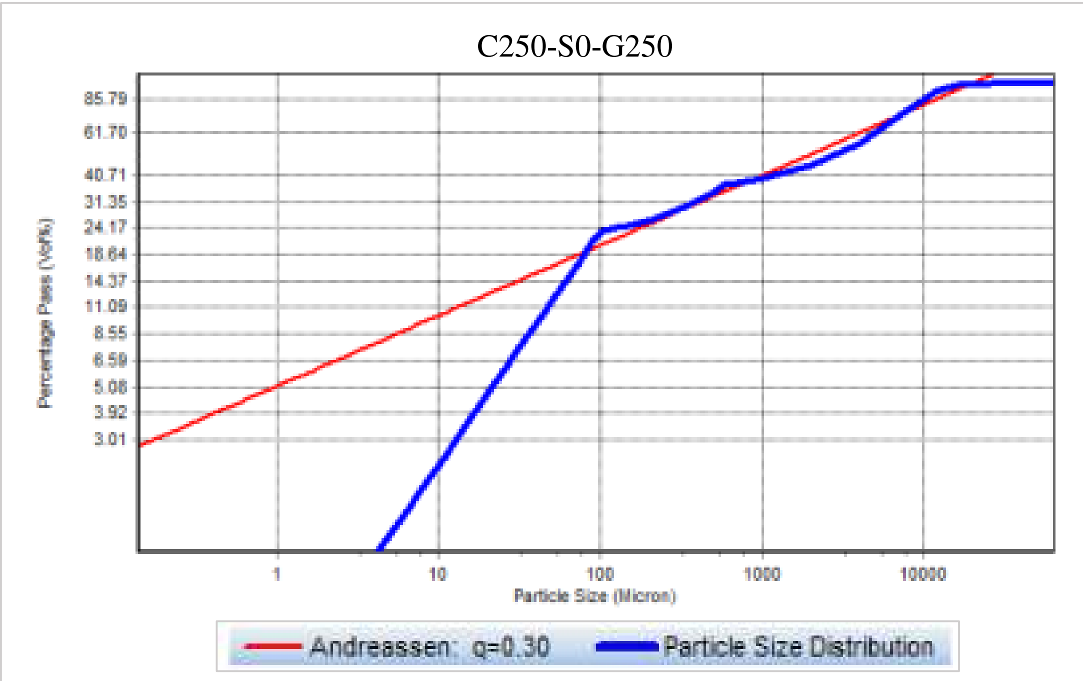


Figure 57: PSD of C250-S0-G250 (with GGBS Only)

SF has been added to the previous mixes and modeled as shown for mix C250-S50-G250 in Figure 58 and mix C500-S50-G0 in Figure 59.

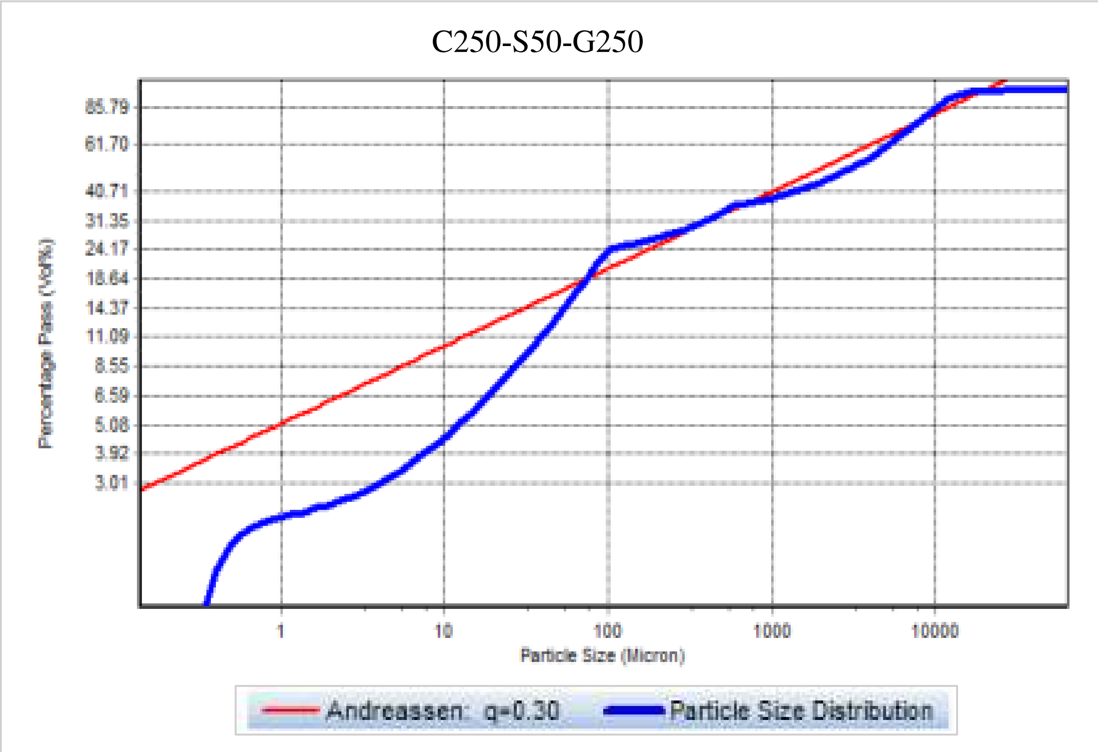


Figure 58: PSD of C250-S50-G250 (with GGBS and SF)

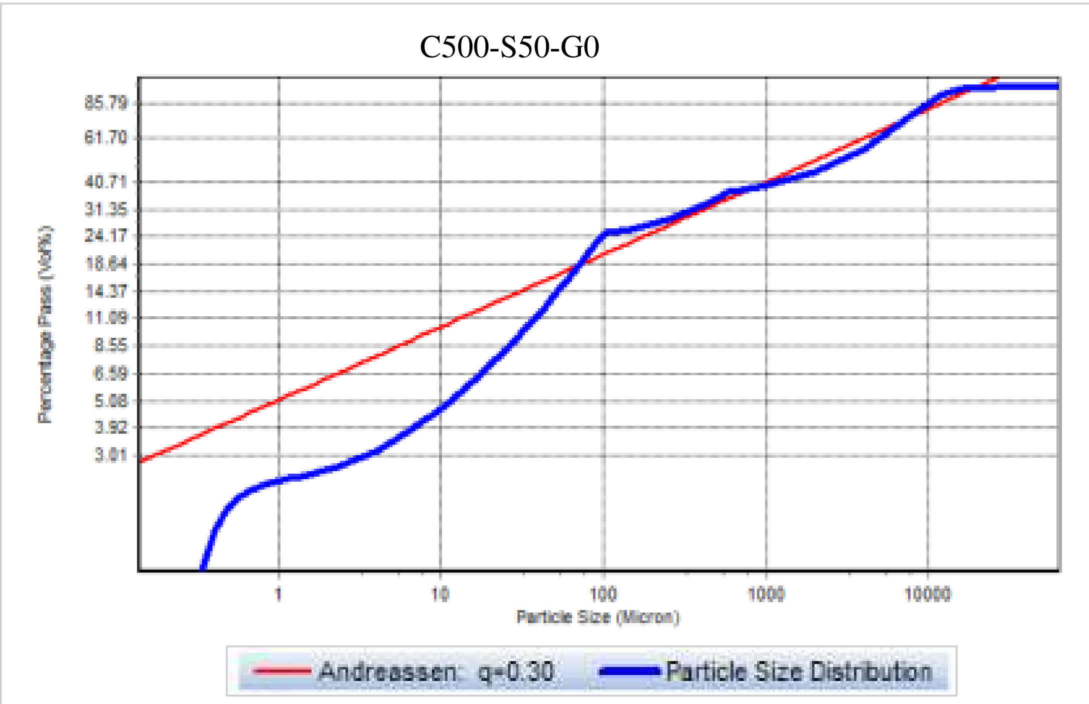


Figure 59: PSD of Mix C500-S50-G0

3.2 Checking Proportions of Mix Design Using Absolute Volume Method

Checking the proportions using the Absolute Volume Method for mix C320-S50-G180, given that:

Binder = 500 kg, w/c = 0.3, Silica Fume = 10%, GGBS = 35%

Water = (Binder/ (w/c)) = 500/0.3 = 150 kg

GGBS = 0.35 x 500 = 175 kg
SF = 0.1 x 500 = 50 kg
Cement = 500 – 175 – 50 = 325 kg

The volume of these materials is shown in Table 6. For each material, volume is calculated using the following formula:

$$V = \frac{W}{SG \times g_w} \qquad (3)$$

where:

V = Volume,
W = Weight,
SG = Material specific gravity,
g_w = Specific gravity of water.

Table 6: Cementitues Ingredients of Concrete Volume in 1 Cubic Meter

Material	Specific gravity	Volume (out of $1m^3$)
Cement	3.14	0.1035
GGBS	2.81	0.0623
SF	2.2	0.0227
Water	1	0.1500
Total		0.3385

Thus, Binder and water = 33.8% of the mix,

Aggregate = 100- 33.8 = 66.2%,

Coarse aggregate = 55% of total aggregate = 0.55*66.2 = 36.4% of total mix, Fine aggregate = 45 % = 0.45*66.2 = 29.8% of total mix,

Weight = (Volume x SG x gw). Thus, a total aggregate weight will be as per Table 7.

Table 7: Aggregate of Concrete Volume in 1 Cubic Meter

Material	Specific gravity	Weight (kg)
Aggregate 20mm	2.94	1062
Aggregate 10mm	2.92	
Crushed Rock Sand 5mm	2.67	792
Dune Sand	2.66	
Total		1854

Adding the total binder weight = 1854 + 500 + 150 = 2504 kg/m^3 of concrete. Table 8 shows comparison between EMMA and absolute volume method results for mix C320-S50-G180.

Table 8: Comparison between EMMA and Absolute Volume Method

Material	C320-S50-G180 (EMMA)	C320-S50-G180 (A.V.M.)
20mm Aggregate	1050	1062
10mm Aggregate		
5mm Crushed Rock	830	792
Dune Sand		
Cement	500	500
GGBS		
Silica fume	50	
Total weight	2430	2504

The modification in proportions using EMMA caused a slight change in the weight of the materials compared to the absolute volume method. That change comes to make the mix denser and better graded.

3.3 Results of Fresh Concrete Properties

Slump, temperature and air content tests were conducted on the fresh concrete of the mixes. Results are shown in Table 9.

Table 9: Slump, Temperature and Air Content Tests Results

Mix	Slump (cm)	Temperature (°C)	Air content (%)	Average Density of cubes (kg/m^3)
C40	12.8	31.2	1.9	2533
C60	15.1	30.5	1.6	2604
C500-S0-G0	12.7	32	1.3	2510
C320-S0-G180	12.2	31	1	2551
C500-S100-G0	16.8	29	1.1	2495
C320-S50-G180	14.2	30.2	1.1	2477
C250-S0-G250	13.5	31.6	1.4	2542
C275-S0-G275	15.3	28.9	1.2	2536
C250-S50-G250	14.2	30.1	1.3	2507
C500-S50-G0	15.4	29.8	1.3	2524

Slump test shows slight loss of workability (in general) with mixes that contain SF over other mixes. This is due to the higher hydration in the presence of SF.

Air content test shows very low air values (from 1% to 1.4%) in all the new mixes compared to C40, C60 and the literature [12] where normal air content varies from 1.4% to 2%. All mixes were well packed as expected from modeling.

3.4 Compressive Strength Test

The test was conducted according to BS EN 12390-2: 2009 / BS EN 12390-3:2009. Results of the compressive strength test are shown in Table 10. Compressive strength results show high strength concrete for all mixes.

Results of the compressive strength test for 7 days were above 50 MPa which is good indicator as concrete is still gaining strength. Concrete is expected to gain about 70% of its compressive strength at 7 days. However, results did not meet the expectations for 28 days test due to the limitation of the coarse aggregate strength.

Satisfactory shape of failure as per BS EN 12390-2:2009 for concrete specimen was noticed after the compressive strength test which indicates proper conditions of compressive strength test.

Table 10: Compressive Strength Test Results at 7 and 28 Days

Mix No	Compressive strength at 7 days (Average of 3 cubes)-MPa	Compressive strength at 28 days (Average of 3 cubes)- MPa
C40	29.01	42.00
C60	59.61	67.00
C500-S0-G0	51.30	56.92
C320-S0-G180	54.37	65.85
C500-S100-G0	59.47	68.09
C320-S50-G180	53.25	57.31
C250-S0-G250	50.62	62.30
C275-S0-G275	50.13	56.47
C250-S50-G250	53.91	66.63
C500-S50-G0	51.93	65.66

The results of 28 days did not meet expectations. This was due to the weakness of the coarse aggregates. Studying the crushed cubes showed that there was clear shear failure in the aggregate of these specimens as shown in Figure 60.

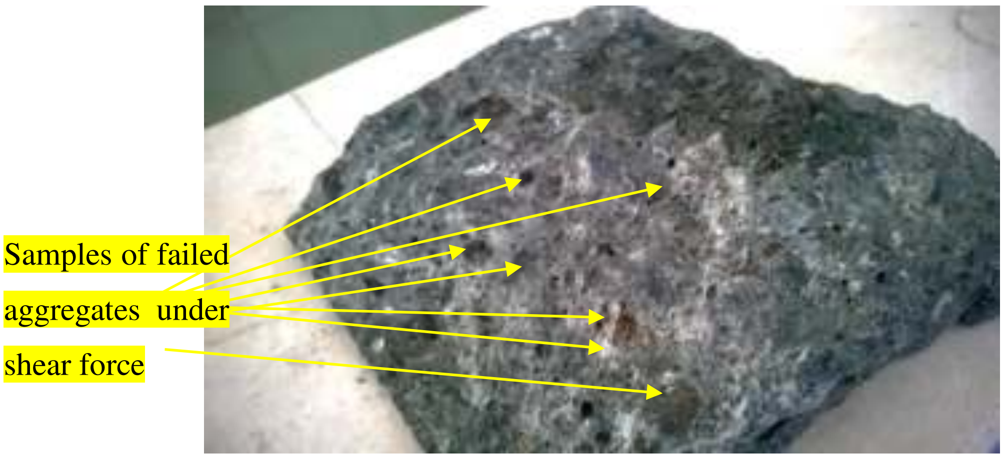


Figure 60: Shear Failure in the Aggregate of the Tested Specimen

Failure shape was common satisfactory failure shape [25], [31] for concrete cubes as shown in Figure 61 where all sides were broken equally towards the center of the specimen.

Figure 61: Failure Shape of the Specimens (Satisfactory)

3.5 Permeability Test

Rapid Chloride Permeability Test (RCPT) was conducted to measure the porosity level of concrete by passing amount of electrical current to travel through 5cm specimen of each concrete mix. Table 11 shows the results of RCPT test for 28 days cured specimen.

Table 11: RCPT Results at 28 Days

Mix	RCPT Columbs	RCPT Reading
C40	6451	High
C60	3189	Moderate
C500-S0-G0	2744	Moderate
C320-S0-G180	392	Very low
C500-S100-G0	1856	Low
C320-S50-G180	684	Very low
C250-S0-G250	1553	Low
C275-S0-G275	2517	Moderate
C250-S50-G250	903.6	Very low
C500-S50-G0	614.9	Very low

RCPT results shows that all green concrete mixes have less permeability than normal mixes (C40 and C60). RCPT readings for most green mixes are between low and very low. While normal mixes are between high and moderate which shows how well are the green mixes packed. Two green mixes got moderate reading but still having lower Columbs values than C60 and C40.

Figure 62 shows the RCPT results versus air content. Green mixes with supplementary materials show lower RCPT values. Air content (which is low for all green mixes as mentioned earlier) recorded the lowest values with addition of GGBS. Generally the RCPT results where higher with the mixes that have higher air content. Furthermore, C320-S0-G180 showed the lowest combination of air content and porosity.

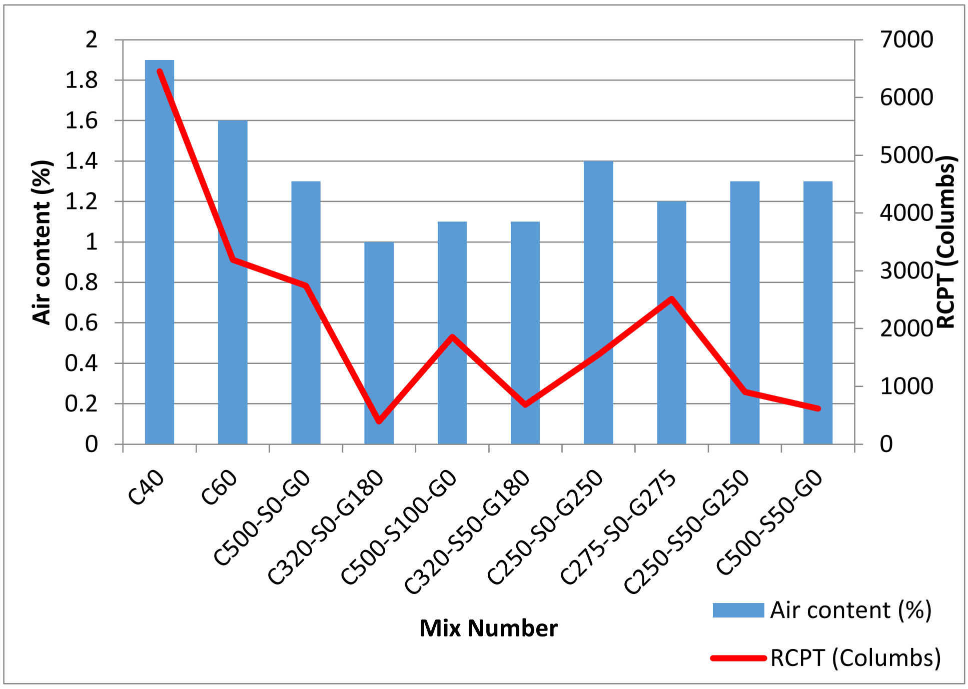


Figure 62: RCPT Results Versus Air Content

3.6 Flexural Strength Test

The results of flexural strength test are shown in Table 12.

Applying Equation 1 to mix C250-S0-G250 where the Load at failure = 63 kN:

$$R = \frac{3 \times 63 \times 450}{2 \times 150 \times 150^2} = 0.0126 \, \frac{kN}{mm^2} = 12.6 \, MPa$$

Recalculate modulus of rupture based on Equation from ACI-318M code:

$$M_{cr} = \frac{f_r I_g}{y_t} \qquad (4)$$

thus:

$$f_r = \frac{M_{cr} y_t}{I_g} \qquad (5)$$

where:

y_t= half the height of specimen cross section = 75mm,

I_g= moment of inertia of specimen cross section = $\frac{150^4}{12} = 42187500$ mm^4,

Substituting inputs in the above equation:

$$f_r = \frac{63 \times 1000 \times 75}{42187500} = 12.6\ \frac{N}{mm^2} = 12.6\ MPa$$

Table 12: Flexural Strength Test Results and Modulus of Rupture

Mix	Load (kN)	Modulus of Rupture (MPa)
C40	28	5.5
C60	43	8.5
C500-S0-G0	51.5	10.5
C320-S0-G180	55.5	11
C500-S100-G0	58.5	12
C320-S50-G180	53	10.5
C250-S0-G250	63	12.5
C275-S0-G275	57	11.5
C250-S50-G250	44	9
C500-S50-G0	44	9

The modulus of rupture is an indicator of the required force to initiate the first crack in concrete. As shown in Figure 63, green concrete mixes show significant improvement in the modulus of rupture which indicates better tensile strength of green mixes compared to normal ones.

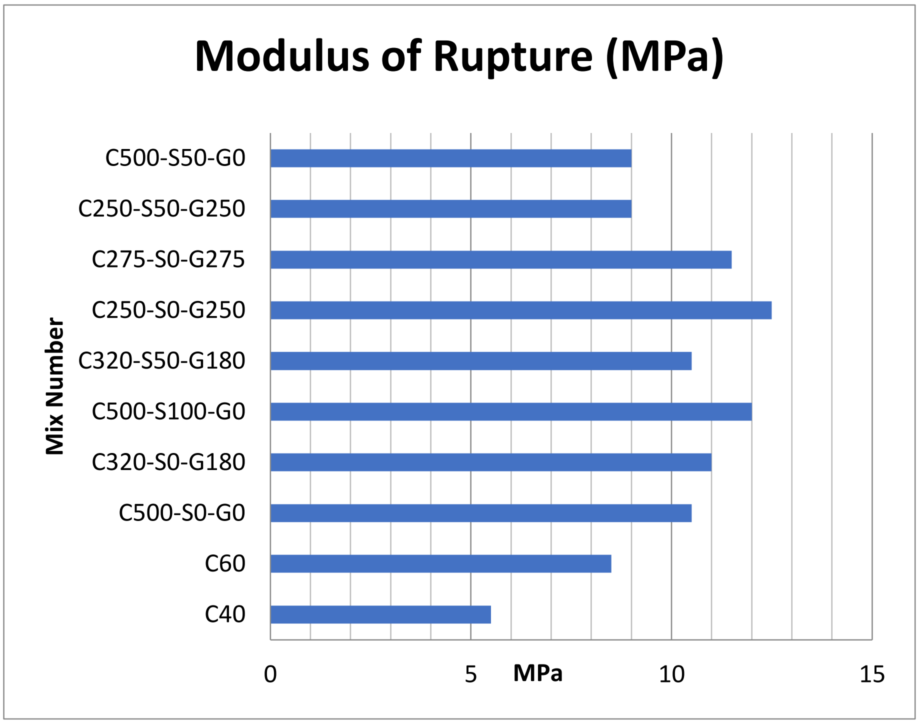


Figure 63: Modulus of Rupture (MPa) for Green and Normal concrete

The density of the beams were between 2500 and 2700 kg/m^3 as shown in Table 13. The difference in density reflects the randomization of particles distribution in each mix. Heavier samples are having more fine particles (more binder) and fewer aggregates than lighter ones.

Table 13: Beams Average Density (kg/m^3)

Mix	Concrete density (kg/m3)
C40	2557
C60	2608
C500-S0-G0	2655
C320-S0-G180	2565
C500-S100-G0	2495
C320-S50-G180	2487
C250-S0-G250	2735
C275-S0-G275	2545
C250-S50-G250	2513
C500-S50-G0	2597

3.7 Modulus of Elasticity (MOE)

MOE test was conducted on the mixes shown in Table 14.

Table 14: List of Tested Mixes for MOE

Mix No.	Density (kg/m^3)	Compressive strength (MPa)
C250-S50-G250	2595	67
C500-S50-G0	2455	67

Using $E_c = 4700\sqrt{f_c'}$ for C250-S50-G250, $E_c = \frac{4700\sqrt{66.63}}{1000} = 38.36$ GPa

Using$E_c = 4700\sqrt{f_c'}$ for C500-S50-G0, $E_c = \frac{4700\sqrt{65.66}}{1000} = 38.08$ GPa

The experimental results were very close to the numerical calculation. The slope of the lines in Figure 64 and Figure 65 from 0 to 0.5 and from 1 to 1.5 strain was calculated. Then, the average of the 2 slopes was considered as the MOE for the mix. (Refer to Appendix D for the list of stress/strain values).

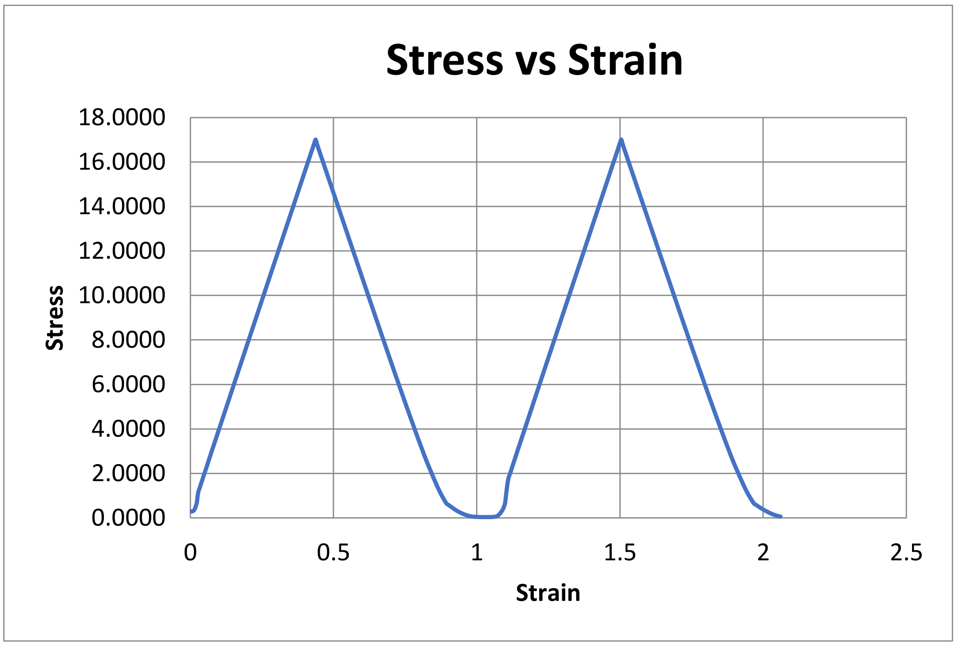


Figure 64: Stress vs. Strain Graph of Mix C250-S50-G250.

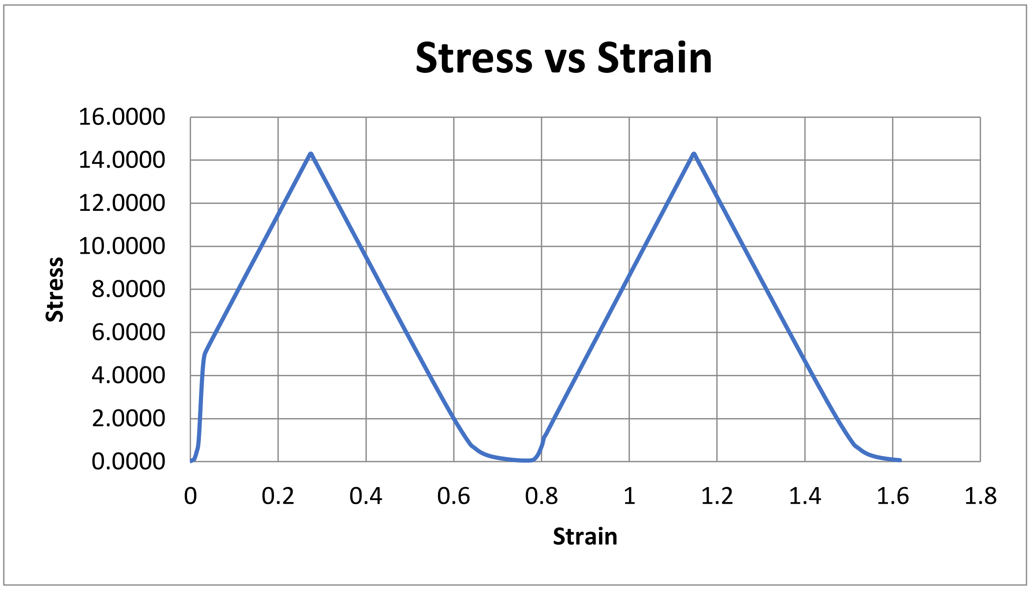


Figure 65: Stress vs. Strain Graph of Mix C500-S50-G0

Average $E_c$for C250-S50-G250 which includes GGBS & SF = 37.15 GPa

Average $E_c$for C500-S50-G0 which includes only GGBS= 36.20 GPa

Results show that the modulus of elasticity is not affected by addition of GGBS or SF. The results of the two specimens were very close to MOE obtained by Equation 2 as shown in Table 15.

Applying the MOE formula $E_c = 4700\sqrt{f_c'}$ from ACI 318, MOE can be obtained for the mixes as following:

Table 15: MOE using ACI 318 Equation

Mix No	Compressive strength at 28 days (Average of 3 cubes) MPa	MOE (GPa)
C40	42	30.46
C60	67	38.47
C500-S0-G0	56.92	35.46
C320-S0-G180	65.85	38.14
C500-S100-G0	68.09	38.78
C320-S50-G180	57.31	35.58
C250-S0-G250	62.3	37.10
C275-S0-G275	56.47	35.32
C250-S50-G250	66.63	38.36
C500-S50-G0	65.66	38.08

Table 15 shows the values for MOE for different concrete mixes. Concrete with optimum binder ratios can handle more stresses before having change in dimensions and thus has higher modulus of elasticity. The relationship between MOE and compressive strength is linear [32]. Higher MOE values at early ages reduce cracks (shrinkage and thermal) [33].

3.8 Microstructural Analysis and Discussion

The SEM analysis reveals various microstructures and morphologies of concrete specimens. Figure 66 shows the SEM images for mix C500-S0-G0 without supplementary materials.

The images that were taken with Secondary Electron Mode were not clear (see Figure 66). This mode requires very special specimen preparation such as ultra-thin layers with very well polished surfaces. However, in the case of concrete, it is required to visualize the morphology of the surface as it is, without any damage caused by specimen preparation.

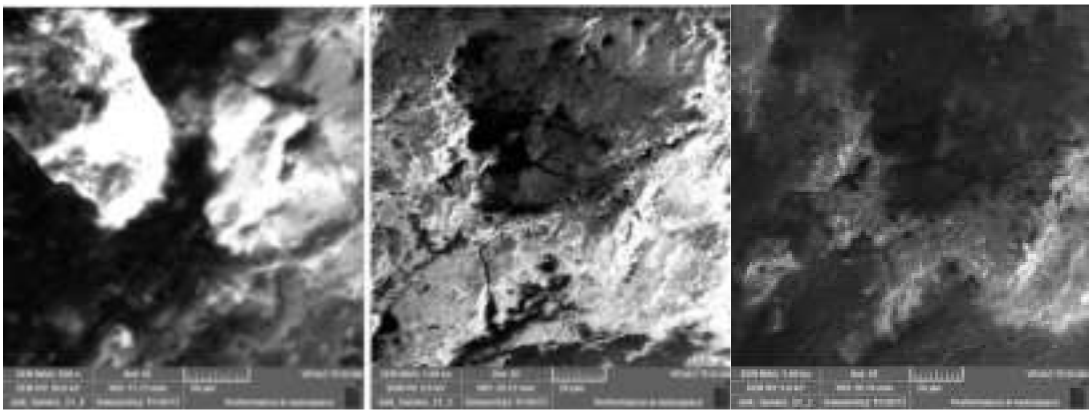


Figure 66: Image of Concrete Microstructure Using Secondary Electron Mode

On the other hand, Backscatter mode was tested and showed much clearer pictures for the morphology of the concrete surface. Thus, Backscatter mode was used throughout the experiments. Three specimens were tested using the SEM; one without supplementary materials, while the other two are with supplementary materials. Figure 67 shows the details of the concrete of mix C500-S0-G0 under SEM at various magnification levels.

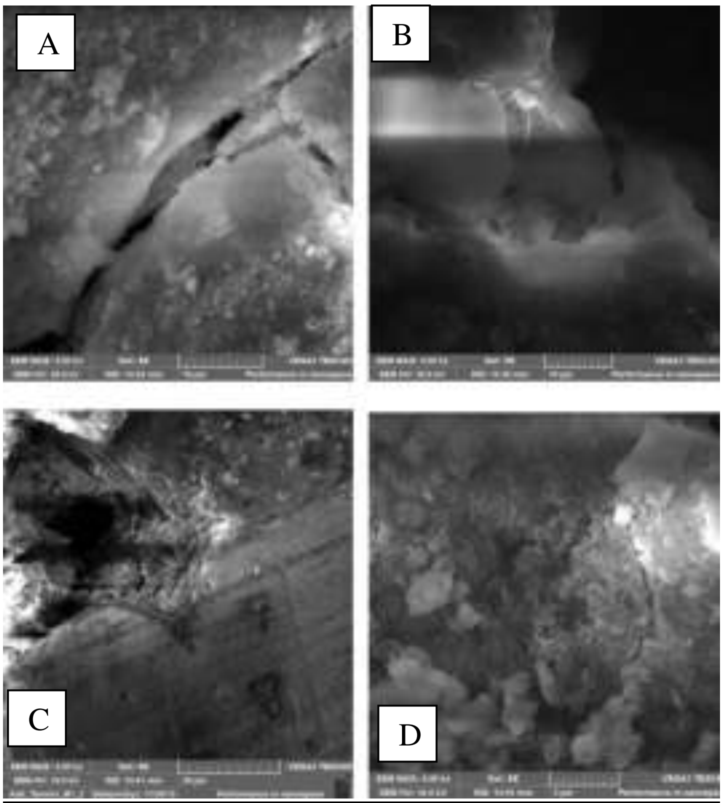


Figure 67: C500-S0-G0 at Different Magnifications A) 5kx, B) 4kx, C) 3kx, D) 8kx

Figure 68 shows SEM image of mix C500-S0-G0 where ettringites (hexacalcium aluminate trisulfate hydrate) can be detected. Ettringites can be clearly shown on the concrete along with continuous micro-cracks. Voids are relatively big and deep which obviously increase the porosity of concrete and produced open microstructure.

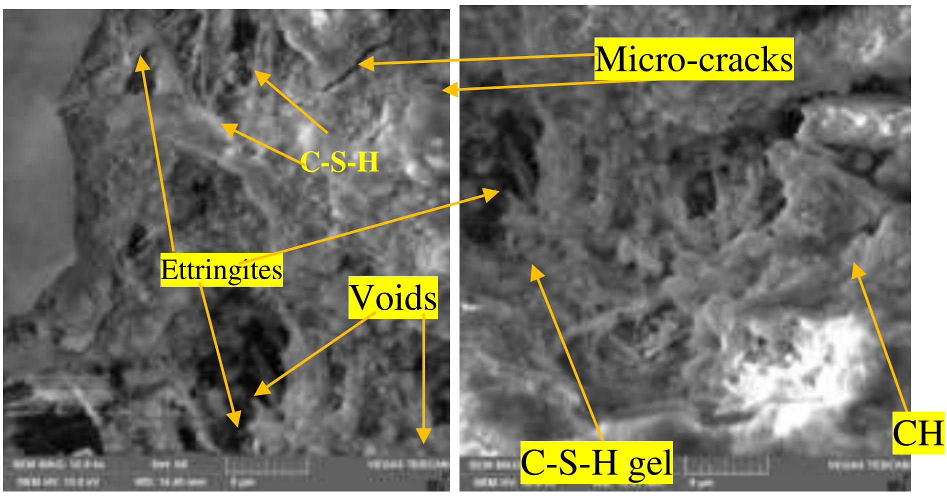


Figure 68: C500-S0-G0 at 28 days Curing and 10kx Magnification

Ettringites are formed due to the reaction between calcium aluminate $3CaO.Al_2O_3$ (C3A) with calcium sulfate CaSO4. They are very weak component of concrete. Figure 69 shows another spot of the C500-S0-G0 mix sample. Open microstructure also shows voids and ettringites close to each other with 2.5 to 5 micron diameter. Calcium hydroxide (CH), which appears in Figure 70 as crystal shells covered with C-S-H gel, is one of the main hydration process products. However, its contribution in concrete strength is minimal.

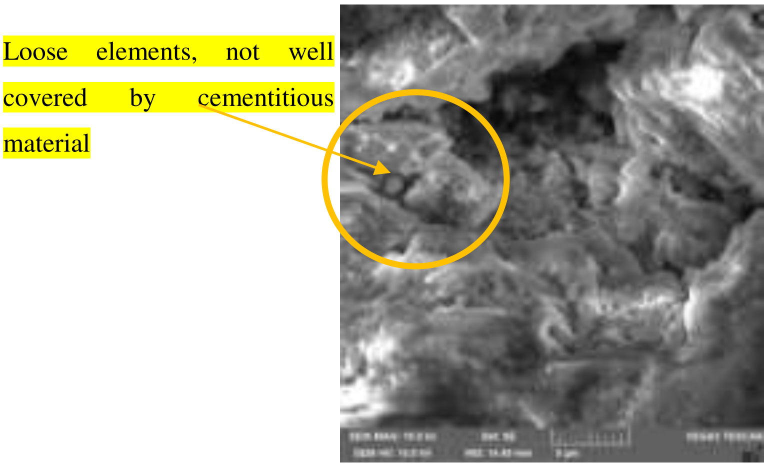


Figure 69: C500-S0-G0 at 28 days Curing and 10k Magnification

Loose particles, voids and micro-cracks shown in Figure 69 were formed due to lack of C-S-H gel formation. At 10kx magnification, ettringites of 2 micron of length can be clearly seen in Figure 70. The existence of calcium hydroxide (CH), ettringites, and voids is an evidence of concrete weakness.

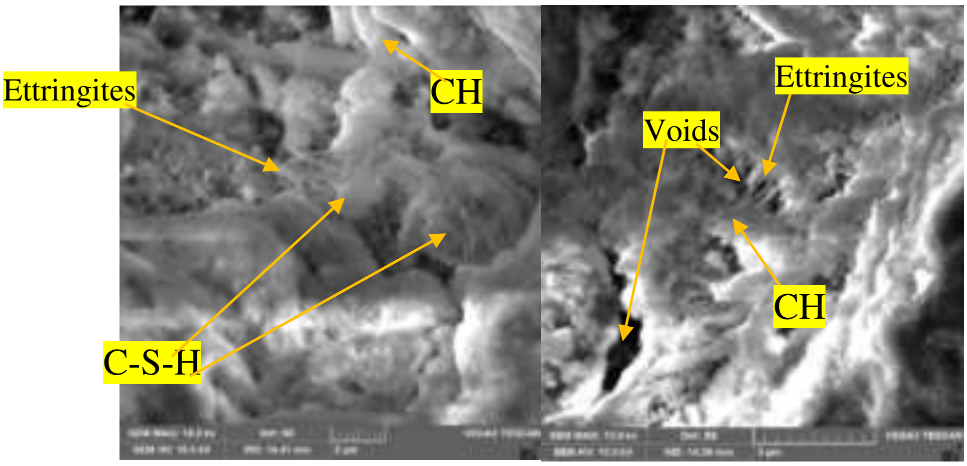


Figure 70: C500-S0-G0 at 28 days Curing and 10k Magnification

Figure 68 to Figure 70 show concrete without supplementary materials. Morphology of concrete surface using SEM shows evidence of ettringites which is a very weak product of cement hydration. Moreover, caves-shape voids are also present in all SEM produced images. Most voids are taking deep shape. Micro-cracks are present in different widths and lengths. Also, it can be seen that not all particles are well adherent to each other. Some particles (hydration product or raw material) can be seen having separate conditions from the other components.

The Sample that contains GGBS from the mix C320-S0-G180 has been tested under the SEM. A sample piece is shown in Figure 71a. Compared to Figure 70, the C320-S0-G180 mix with GGBS shows a much better microstructure (refer to Figure 71b). Fewer voids, smaller cracks and more homogenous structure can be observed. An X-ray analysis has been conducted to study the chemical composition of each sample. The chemical analysis for each spectrum in Figure 72 was shown in Figure 73 to Figure 76. The ratio of Ca to Si in C-S-H component of hydrated cement varies from approximately 1.6 to 2 according to Kurdowski [34]. Ca/Si ratio in Figure 73 is 3.02,

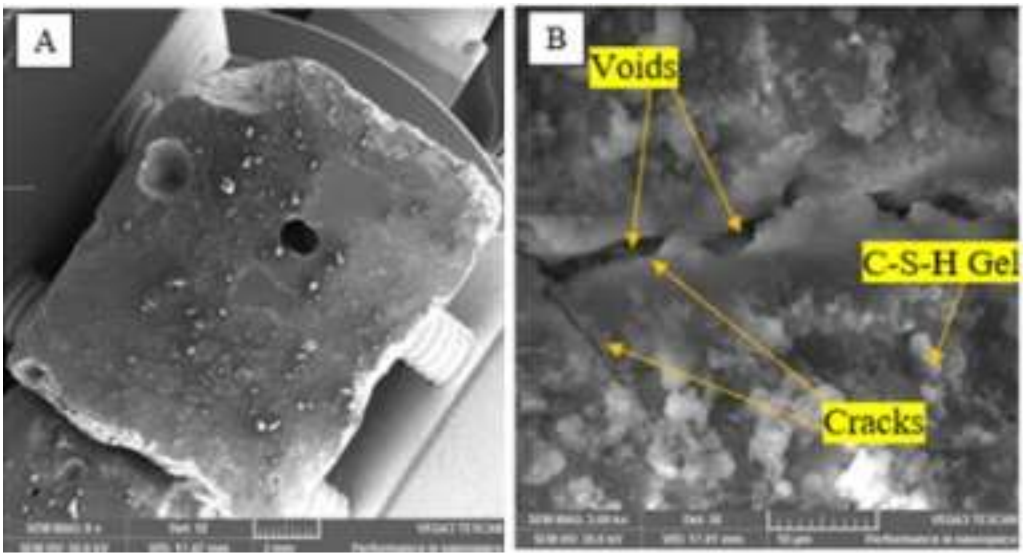


Figure 71: a) Tested Sample b) C320-S0-G180at 3k Magnification

which means that there are more calcium particles in that particular area. Thus, most probably, this spectrum represents calcium hydroxide $Ca(OH)_2$. Figure 75 to Figure 76 has Ca/Si ratio of approximately 1.8 to 2. Thus these spectrums represent C-S-H gel. The calcium hydroxide particle (Portlandi) is surrounded by C-S-H gel with less voids and smaller cracks than what was shown on C500-S0-G0. C-S-H amount is obviously more in the mix containing slag. These remarks explain the better performance of concrete containing GGBS in RCPT test where microstructure of concrete shows less and smaller voids and cracks than regular mix.

Figure 72 shows a micrograph for concrete morphology at 7000x magnification using the SEM. Five spots were taken for X-ray analysis to study the chemical components of these spots.

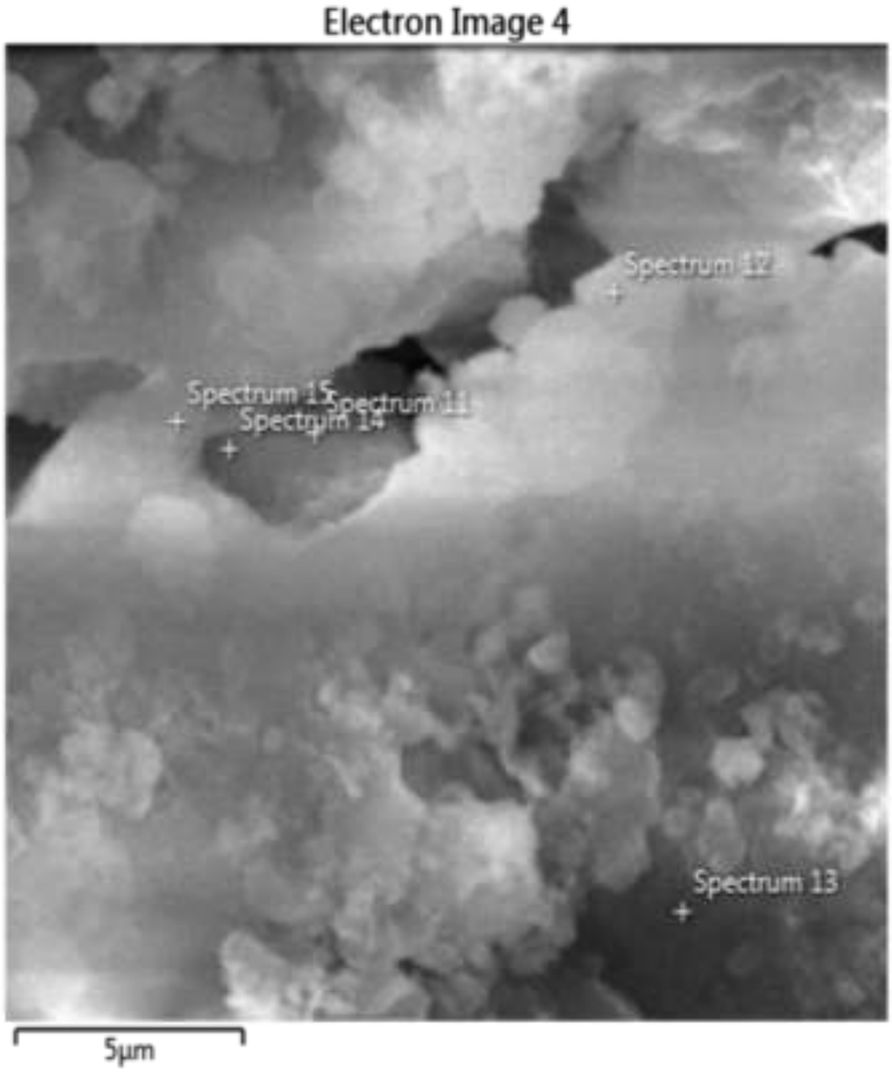


Figure 72: Spectrums for X-ray Analysis

Figure 73 shows the X-ray analysis of the spectrum 11. Many chemical components can be observed in the spectrum. However, C-S-H is the main component in the presence of calcium. The ratios between the quantity of calcium (Ca) and silicon (Si) can show good indication of the hydration product type.

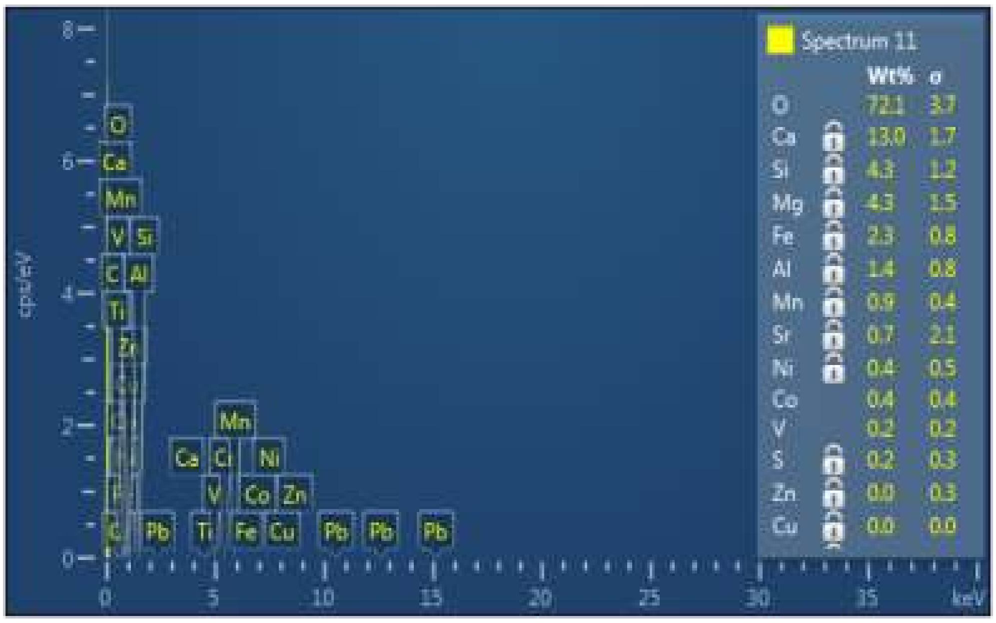


Figure 73: Spectrum 11, Analysis of Chemical Components

Spectrum 11 represents CH ($Ca(OH)_2$), which is main component of cement hydration process. The importance of presence of CH is that GGBS particles will react with CH and create C-S-H. With time, concrete keeps gaining strength and durability throughout the formation of C-S-H. Spectrum 12 shows C-S-H gel where the Ca/Si ratio is 1.5.

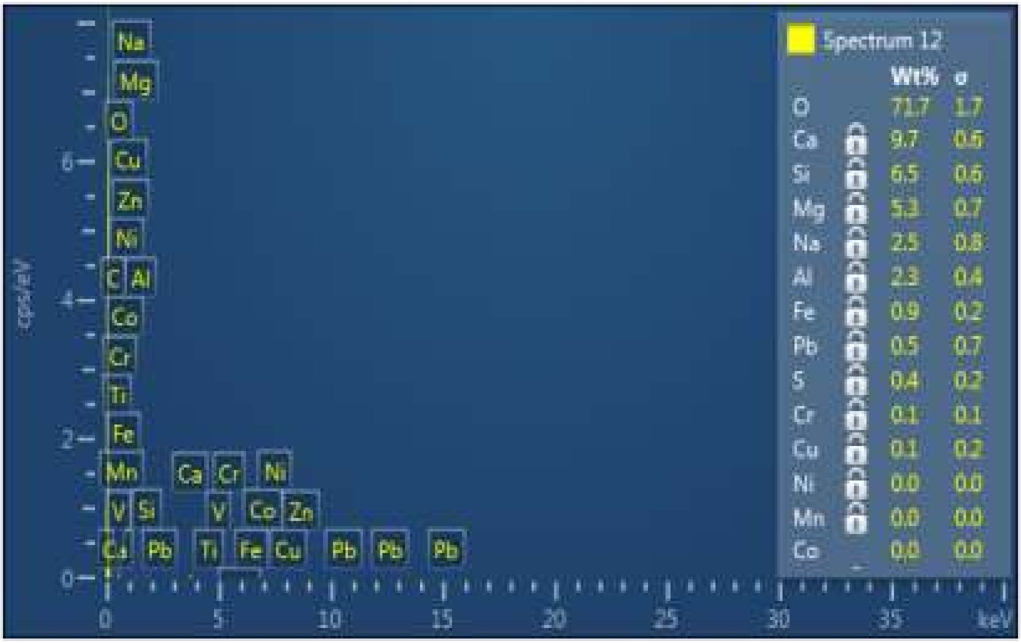


Figure 74: Spectrum 12, Analysis of Chemical Components

Spectrum 13 in Figure 75 shows C-S-H gel where the Ca/Si ratio is 1.8.

Figure 75: Spectrum 13, Analysis of Chemical Components

Spectrum 15 in Figure 76 shows C-S-H gel where the Ca/Si ratio is 1.9.

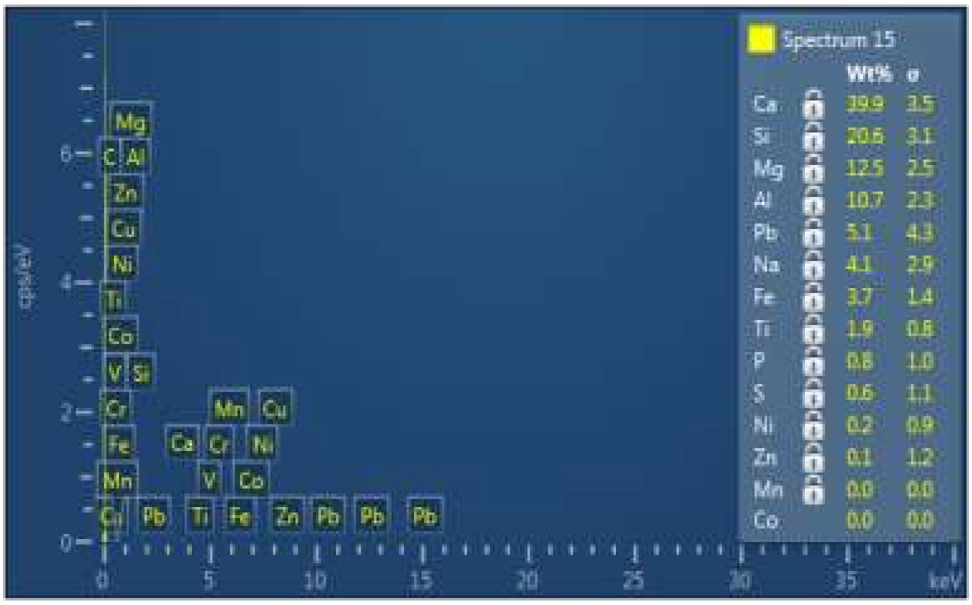


Figure 76: Spectrum 15, Analysis of Chemical Components

Figure 77 shows a dense structure microstructure for a mix containing GGBS at 2000x magnification. Cracks and voids are visible, however, voids are not together and cracks are shallow. There are fewer voids that are isolated compared to the microstructure of mix C500-S0-G0.

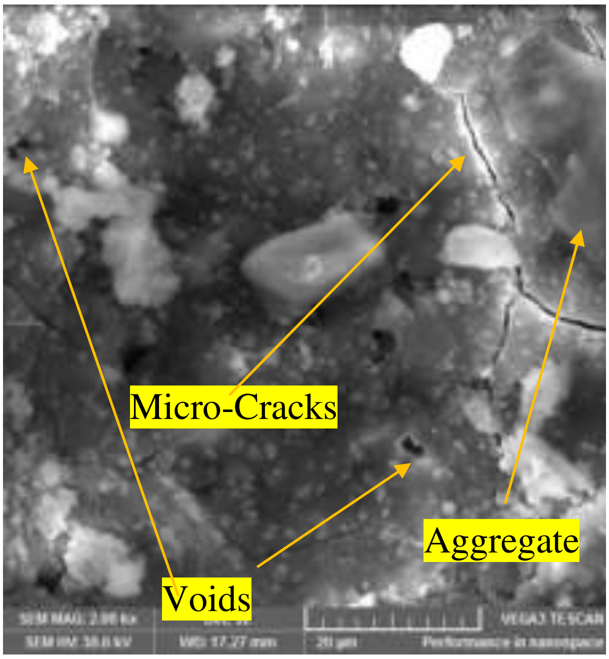


Figure 77: C320-S0-G180 at 2kx Magnification

Figure 78 for Mix C320-S0-G180 shows a broken edge of the specimen. C-S-H layers can be clearly seen. No ettringites and very few voids can be observed.

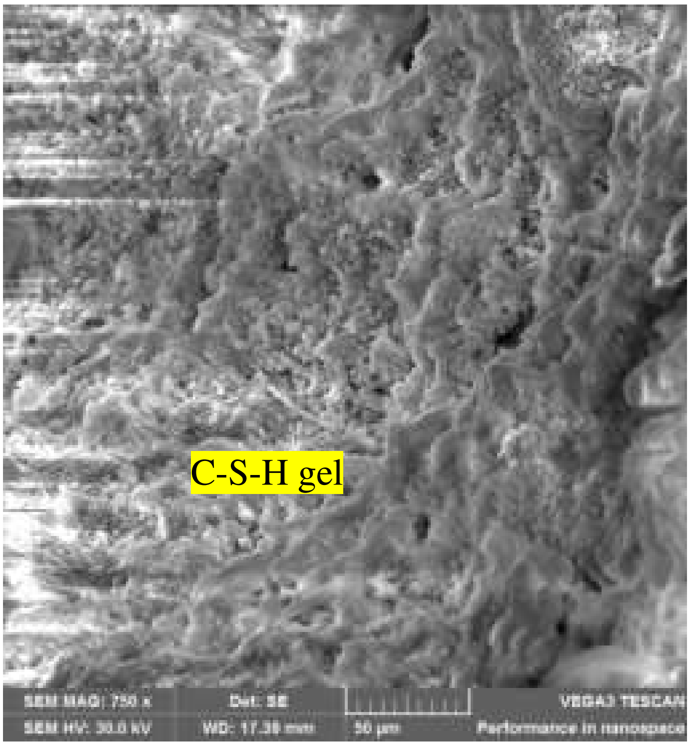


Figure 78: C320-S0-G180 at the Broken Edge of the Specimen

Another Sample, which contains only silica fume, was tested under the SEM. As shown in Figure 79, the sample piece was taken from mix C500-S100-G0.

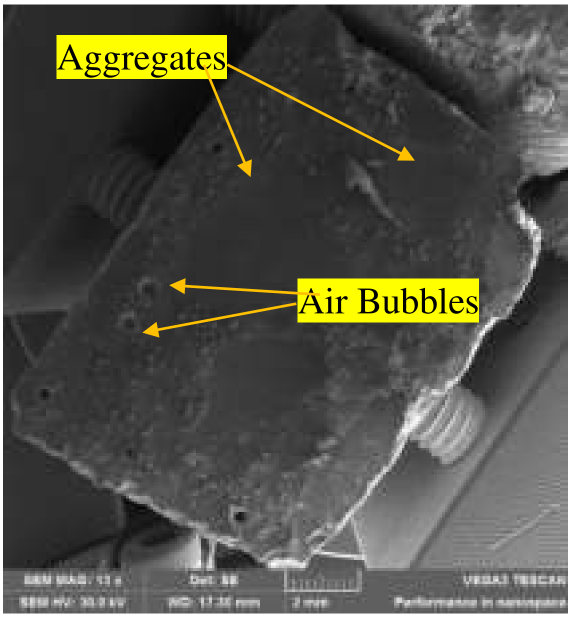


Figure 79: C500-S100-G0 with SF Under SEM

Very small and discontinued voided areas can be seen in mixes that contain silica fume, (refer to Figure 80).

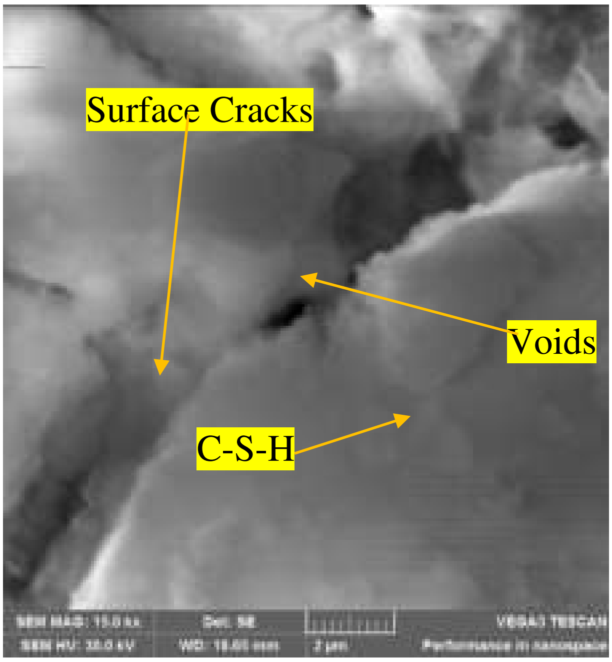


Figure 80: Cracks with SF Specimen

Very dense microstructure is shown in Figure 80 and Figure 81. Cracks of 2 micron or less are visible. However, due to the high density of the mix, those cracks have negligible depth. Voids also are very small in size and quantity. Figure 80 and Figure 81 have dense microstructure compared to Figure 68 which shows open microstructure. Therefore, RCPT results of mix C500-S100-G0 in Figure 80, which has a very low permeability, can be justified. The smaller voids and denser microstructure make it hard for any fluid to penetrate through concrete and reach reinforcement.

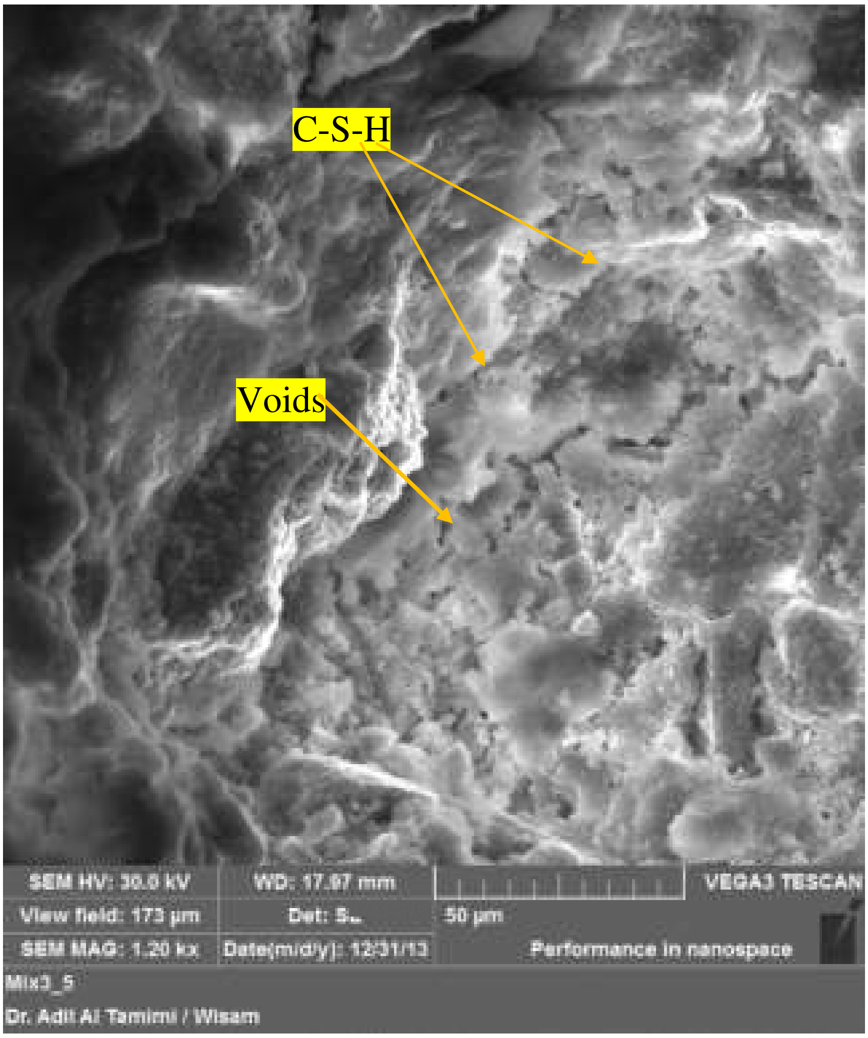


Figure 81: C500-S100-G0 SEM image Shows a More Dense Areas than Other Mixes.

Silica fume addition reduces the ratio of Ca/Si of C-S-H in concrete where in some cases it reaches 1 [34]. Spectrums in Figure 83 to Figure 87 show a clear effect of silica fume addition in terms of Si presence in X-ray analysis of Figure 82. Ca/Si ratio was reduced significantly in C-S-H due to the high presence of silica fume. It has been noticed that magnicume also reacts with silica fume in some cases in a similar manner of CaO. Concrete with silica fume produced denser microstructure. A noteworthy discontinuity in the cracks can be observed.

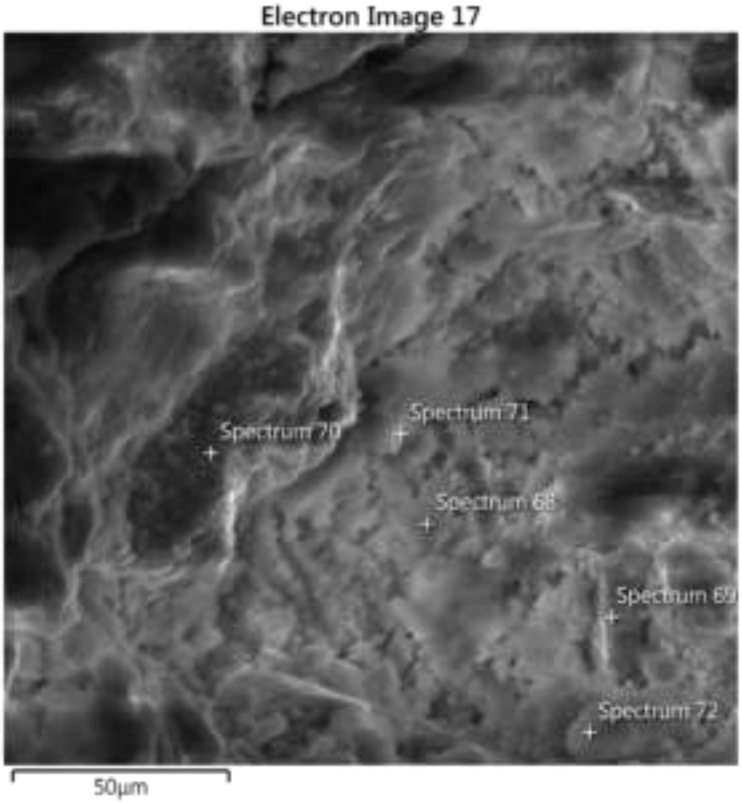


Figure 82: Micrograph for X-ray analysis

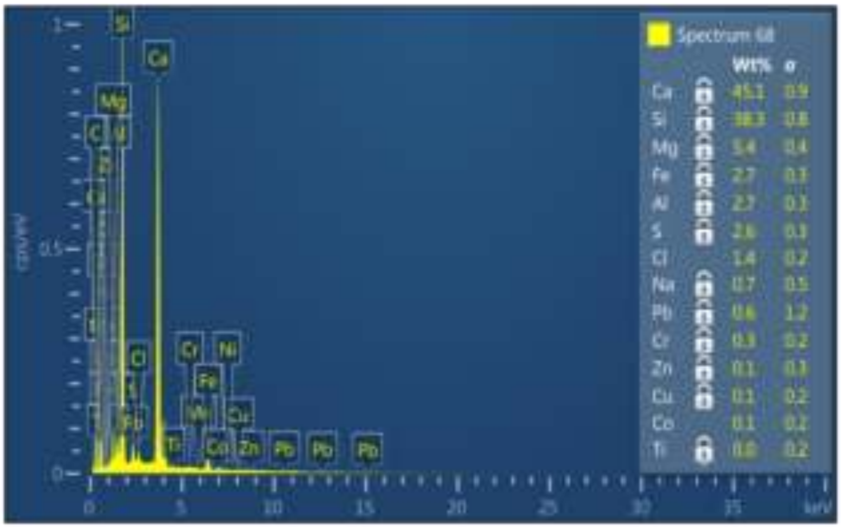


Figure 83: Spectrum 68, analysis of chemical components

When Ca/Si ratio is 1.17, it means that there are almost equal amount of calcium and silicon particles. Thus, this spectrum represents C-S-H gel.

High percentage of Si combined with low percentage of calcium and magnesium in Figure 84 represents a sand particle.

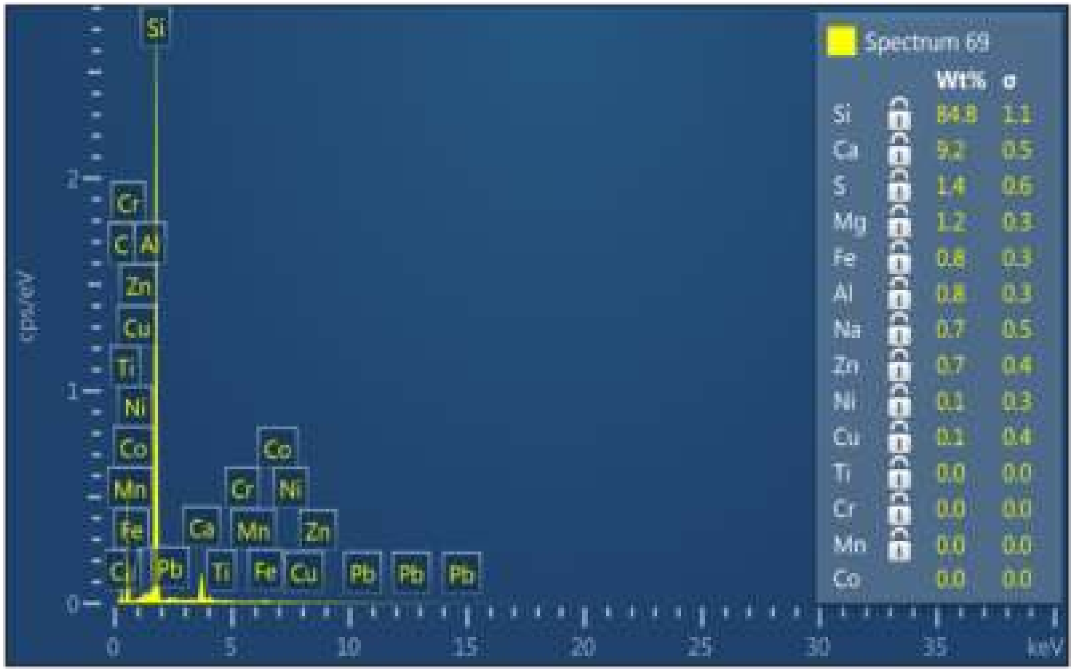


Figure 84: Spectrum 69, Analysis of Chemical Components

Magnesium silicate hydrate (M-S-H) is presented by spectrum 70 shown in Figure 85. (M-S-H) gel is identified when Mg/Si ratio falls in the range of 0.7 to 1.5 [35]. (M-S-H) is main hydration product and was only found with specimens that has silica fume.

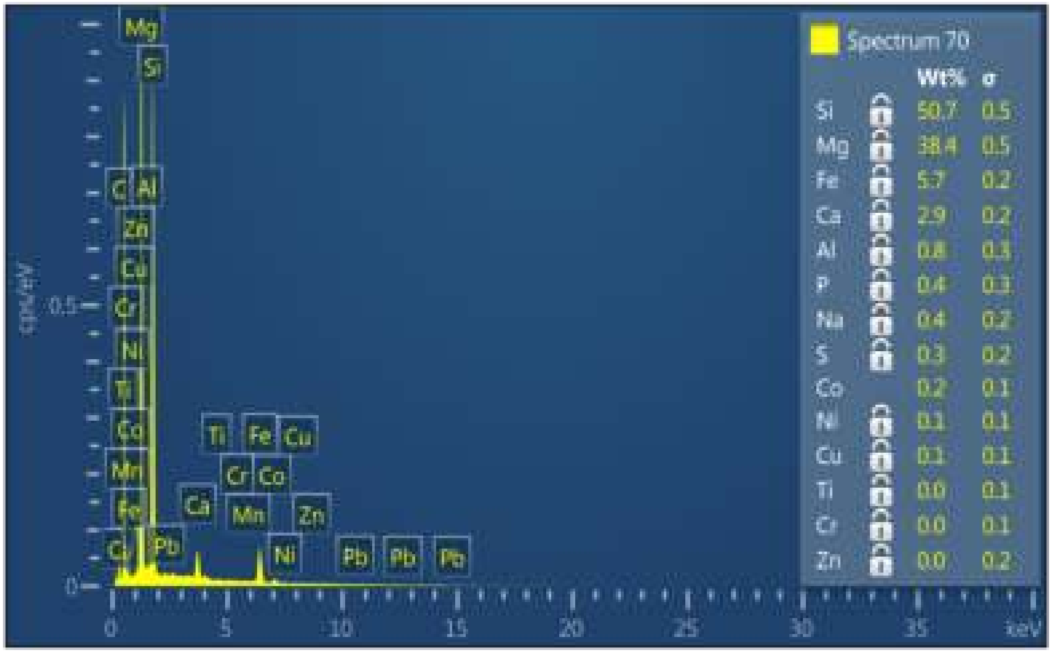


Figure 85: Spectrum 70, Analysis of Chemical Components

In Spectrum 71 (Figure 86) and Spectrum 72 (Figure 87), Ca/Si ratio is 0.9 and 1.23, which also means this spectrum represents C-S-H gel.

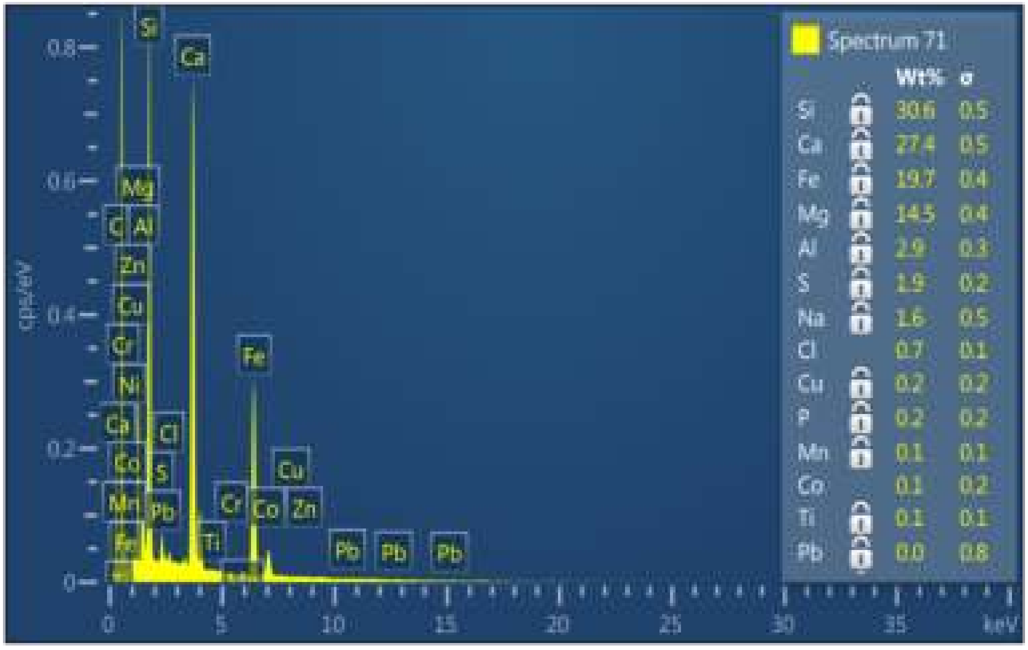


Figure 86: Spectrum 71, Analysis of Chemical Components

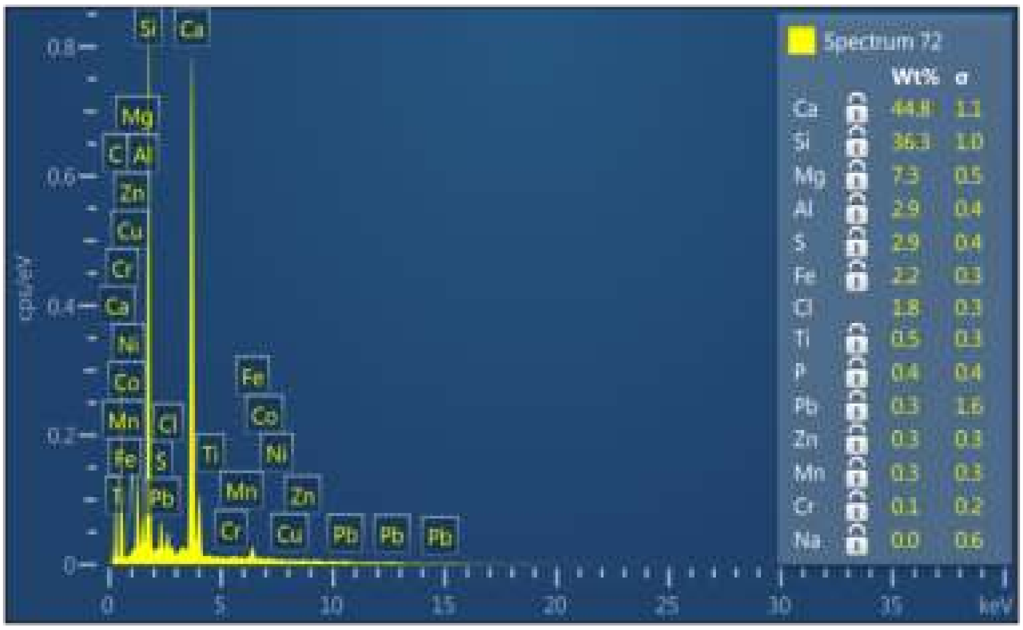


Figure 87: Spectrum 72, Analysis of Chemical Components

Enhanced layers of concrete microstructure can be seen in SEM images that contain SF, (See Figure 88), of concrete which contributes in better packing and less voids.

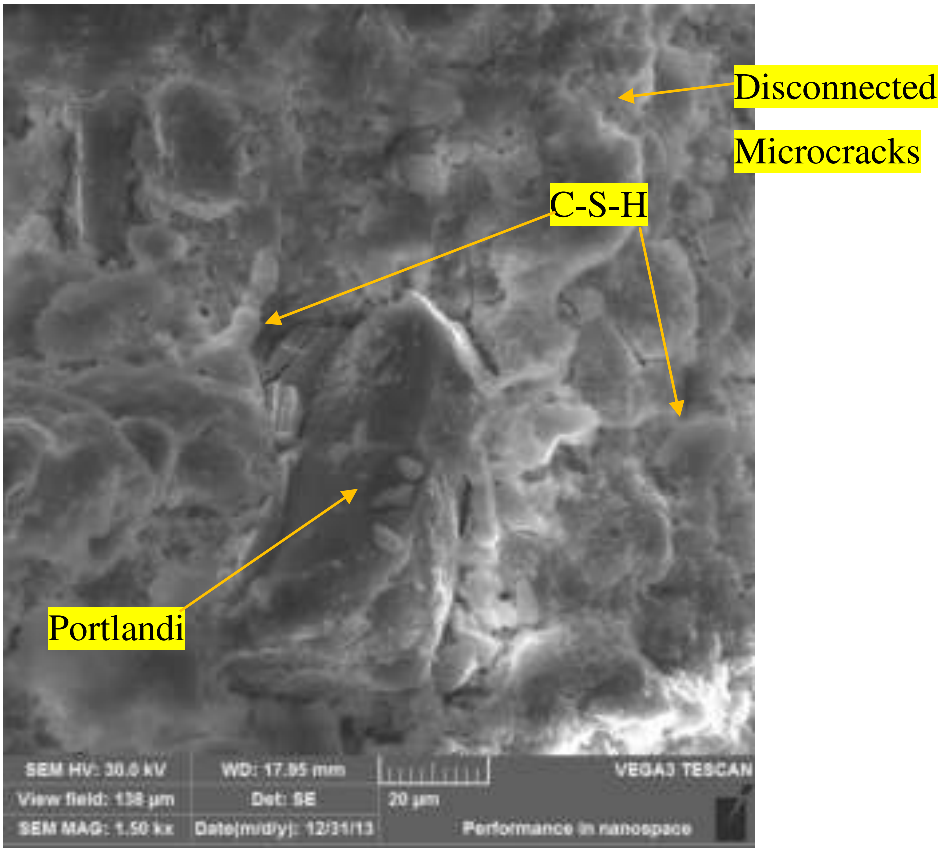


Figure 88: Portlandite Particle Imbedded in Concrete with SF

3.9 Cost analysis of Using Green Concrete in the UAE

A feasibility study was conducted to evaluate the performance of green concrete in terms of cost. The prices of the different components of concrete in the UAE markets were collected and reported. Table 16 shows the cost of each mix.

Table 16: Cost of Concrete Individual Items per m^3

Material	20mm Agg. (m^3)	10mm Agg. (m^3)	5mm Crushed Rock (m^3)	Dune Sand (m^3)	Cement (ton)	GGBS (ton)	Silica fume (ton)	Water (m^3)	Super-Plasticizer (liter)
Cost (AED/unit)	29.5	29.5	30	22	220	225	1000	10.56	1.5

These prices were taken by site survey on some concrete batching plants. Materials transportation cost is also included in the above table.

3.9.1 Calculating concrete cost per cubic meter.

Calculation of the cost per cubic meter of concrete was conducted by summing the price for each component of the concrete:

1- Since aggregate is delivered using truck of 21m^3 capacity, bulk density was used to calculate the cost of aggregates.

Example of C500-S0-G0 for 20mm aggregate:

100 (kg) / (1.7*1000 (Bulk density)) = 0.0588 m^3 Volume of aggregate

0.0588 * (29.5 AED/m^3) = 1.74 AED.

2- Other materials (which are delivered by weight, tons), a direct multiplication of price into the used quantity will give the cost of that material.

Example of C500-S0-G0 for Cement:

(500 kg) * (220AED/1000kg) = 110 AED.

3- After summing the cost of each mix materials, the cost per mix was obtained. However, the required cost is per cubic meter. Thus, linear interpolation was used to obtain cost per cubic meter of concrete.

Example of C500-S0-G0 mix: Total volume of the mix based on particles density = 0.945 m^3 which costs 156 AED. One cubic meter cost= $\frac{156}{0.945} = 165$ AED . Table 17 and Figure 89 illustrate the cost of all mixes.

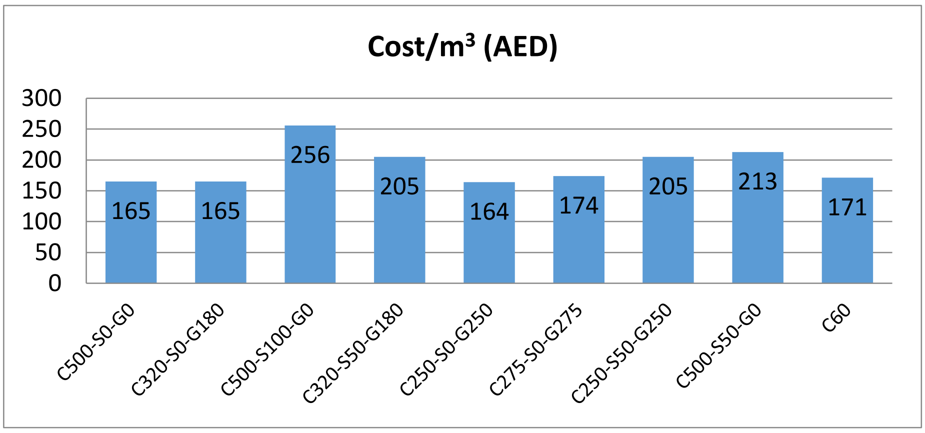


Figure 89: Cost of Mix per Cubic Meter

Table 17: Cost (AED) Matrix for Normal and Green Concrete

Ref. Mix # / Material	C500-S0-G0	C320-S0-G180	C500-S100-G0	C320-S50-G180	C250-S0-G250	C275-S0-G275	C250-S50-G250	C500-S50-G0	C60
20mm Aggregate	1.74	1.74	1.74	1.74	1.74	1.74	1.74	1.74	18.85
10mm Aggregate	14.06	14.06	14.06	16.49	14.06	14.06	16.49	14.06	12.56
5mm Crushed Rock	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	0.00
Dune Sand	3.42	3.42	3.06	3.06	3.42	3.06	3.06	3.06	0.00
Cement	110.00	70.40	110	70.40	55.00	60.50	55.00	110.00	110.00
GGBS	0.00	40.50	0.00	40.50	56.25	61.88	56.25	0.00	0.00
Silica fume	0.00	0.00	100.	50.00	0.00	0.00	50.00	50.00	0.00
water	1.48	1.48	1.77	1.63	1.48	1.63	1.63	1.63	1.48
Super-plasticizer	15.00	15.00	18.00	16.50	15.00	16.50	16.50	16.50	15.00
material cost/Mix (AED)	156	157	259	210	157	169	211	207	158
Cost/m^3 (AED)	165	165	256	205	164	174	205	213	171

3.9.2 Discussion.

From Table 17, it can be noted that green concrete can be obtained in the UAE using GGBS as a cement replacement without any additional costs. Silica fume addition enhanced concrete properties in terms of permeability and early strength. Moreover, according to the literature [36], silica fume enhances the compressive strength of concrete. The addition of 10% silica fume increased the cost of the concrete by approximately 20%. Silica fume can be used as a partial replacement for cement, and in this case, the price will be affected by approximately 13% only.

3.10 Carbon Dioxide Emissions and Heat of Hydration

Green concrete replaced part of the cement in the mixes that contain GGBS. The approximate values of carbon dioxide emissions are shown in Figure 90.

Heat of hydration generated by the hydration process of the reaction between cement and water will also be reduced by the same percentage of cement replacement. Reduction in heat of hydration reduces the internal stresses in concrete and thus decrease early stage cracks such as shrinkage cracks.

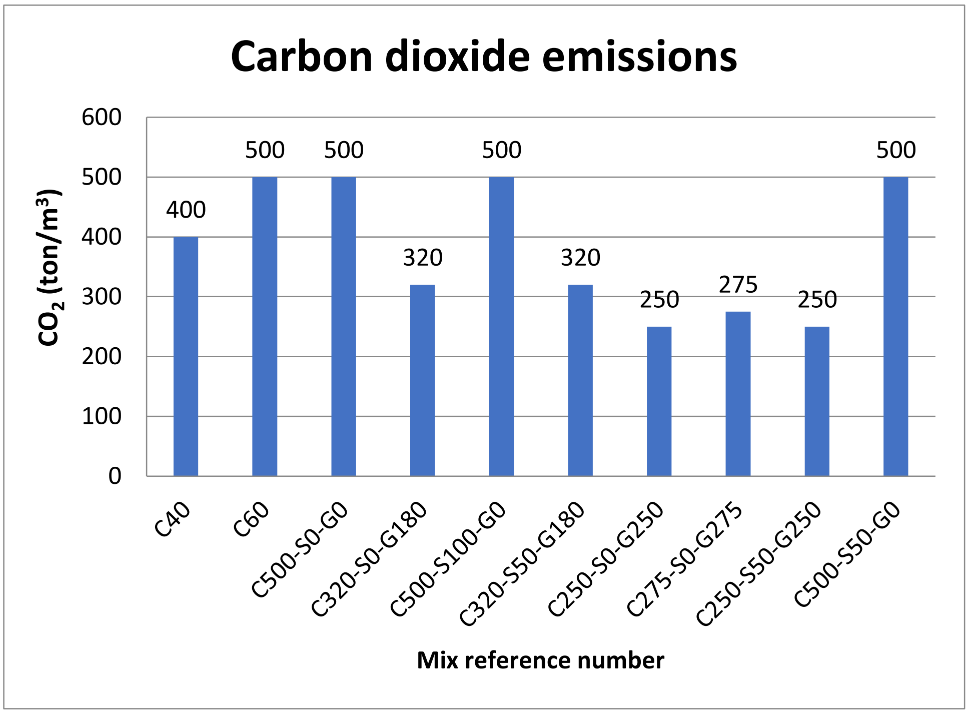


Figure 90: Carbon Dioxide Emissions (ton/m^3)

3.11 Summary of Results

Among 10 mixes, mix C320-S0-G180 which contains 500 kg of binder where GGBS replaced 36% of cement content, results in the best performance. As shown in Table 18, the mix has excellent durability properties such as very low RCPT value and air content, high modulus of elasticity and high modulus of rupture. These properties help to increase the life span of the structure and reduce the cracks due to the internal stresses by heat of hydration or loading. In addition, mix C320-S0-G180 costs the same cost as normal concrete. Table 18 below summarizes tests and investigation results.

Table 18: Summary of Experimental Results

Mix No / Test	C40	C60	C500-S0-G0 (Control mix)	**C320-S0-G180**	C500-S100-G0	C320-S50-G180	C250-S0-G250	C275-S0-G275	C250-S50-G250	C500-S50-G0
Slump (cm)	12.8	15.1	12.7	**12.2**	16.8	14.2	13.5	15.3	14.2	15.4
Temp (°C)	31	30.5	32	**31**	29	30	32	29	30	30
Air content (%)	1.9	1.6	1.3	**1**	1.1	1.1	1.4	1.2	1.3	1.3
Average density of cubes (kg/m^3)	2533	2604	2510	**2551**	2495	2477	2542	2536	2507	2524
Compressive strength at 7 days	29	59.5	51.5	**54.5**	59.5	53.5	50.5	50	54	52
Compressive strength at 28 days	42	67	57	**66**	68	57.5	62.5	56.5	67	66
RCPT Reading	High	Mod-erate	Mod-erate	**Very low**	Low	Very low	Low	Mod-erate	Very low	Very low
Modulus of Rupture (MPa)	5.5	8.5	10.5	**11**	12	10.5	12.5	11.5	9	9
MOE	30.5	38.5	35.5	**38**	39	35.5	37	35	38.5	38
Cost/m^3	148	171	165	**165**	256	205	164	174	205	213

Chapter 4: Conclusion and Future Studies

In this research new green concrete mixes were designed using new computer modeling techniques and locally available materials to produce high performance concrete. Investigations and findings can be concluded in the following points:

- A site investigation was carried out in some concrete batching plants in the UAE to study the availability of concrete supplementary materials and the feasibility of using them in the research. It was concluded that GGBS and silica fume are the best concrete supplementary materials to be used in the UAE. Fly ash seems to be avoided by concrete batching plants due to its high cost and special storage requirements.
- New concrete mixes were modeled using the EMMA software. Modeling identified the locations of drops in particle size distribution of concrete mix which were rectified. Thus, 8 mixes were prepared for best possible particles packing in order to have less voids and more durable concrete.
- Slump, temperature and air content tests were conducted on fresh concrete. Slump test results vary for different mixes from 12 to 16 cm depending on the binder blend content and the amount of super plasticizer used. The range was within the workable range, and concrete was easily molded. Concrete temperature at pouring was around 30 ^{o}C and air content was between 1 and 1.4%. The low values of air content represent the good packing of the concrete.
- Rapid chloride permeability test was carried out to evaluate the permeability levels of the new mixes. Results show a large drop in concrete permeability with the addition of GGBS and SF. Green concrete has at least 2 times less pores than normal concrete. Also, the low results of permeability for concrete containing GGBS and SF cannot be obtained unless there are good particles packing. Again, RCPT proves that modeling using the EMMA program was effective.
- Compressive strength test results show a decrease in strength from the C60 mix to C500-S0-G0 (Control mix). However, both mixes have the same cement content. This decline in compressive strength can be explained as a

weakness in the 10mm aggregate. Mix C60 contains 720 kg of 20mm aggregate and 390kg of 10mm aggregate versus 100kg of 20mm aggregate and 810 of 10mm aggregate in C500-S0-G0. The same case happened at 28 days where compressive strength of the new mix C500-S0-G0 was less than the C60. Actually, the weakness of 10mm aggregate has affected all the mixes since the aggregate content was almost fixed among the 8 mixes which were modified using EMMA. The broken part of the concrete cubes by compressive strength test shows clear failure in the aggregates. In addition, mix C500-S100-G0 got compressive strength of 59.47 MPa at 7 days. Therefore, it couldn't exceed 68 MPa at 28 days. Thus, there was a limit of compressive strength due to weakness of 10mm aggregate. An important point to mention for future research is to study the strength of aggregates before using in concrete mix design to ensure getting the required strength.

- Modulus of Rupture (MOR) shows higher results with presence of GGBS and SF. The MOR also indicates higher tensile strength (from 5% to 32%) for green mixes compared to normal ones.
- Microstructural and X-ray analyses were conducted to study the morphology of concrete surface and the relation between microstructures and macrostructure. SEM images indicated many pores with large size in normal concrete mixes and less C-S-H gel. Concrete with GGBS and SF shows enhanced microstructure that reflects the reasons of having better durability performance. Less and smaller cracks were found in blended concrete. Moreover, ettringites could not be observed in SF and slag mixes and more C-S-H gel was found.
- A cost analysis study of using green concrete in local construction was conducted and the cost of each individual concrete ingredient was calculated. Feasibility study proved that green concrete can be made within the same price range of normal concrete in the UAE. That is on the short term; however, on the long term, green concrete can help to extend the life span of structures by increasing concrete durability. Thus, green concrete is a cheaper option for construction.
- This study shows the benefit of using green concrete in the UAE in terms of durability, mechanical properties and environmental impact.

Based on this research outcomes and results, it is recommended for future studies to test the strength of aggregate before mixing the concrete. The reason for doing the test is that aggregate has significant effect on the mechanical strength of the concrete. Moreover, the effect of supplementary materials on reducing chloride and sulfate attack for packed concrete can be conducted to provide the industry with more reasons for using green/sustainable concrete.

References

[1] S. A. Khedr and A. F. Idriss, "Resistance of Silica-Fume Concrete to Corrosion-Related Damage," *Materials in Civil Engineering,* vol. 7, no. 2, p. 102–107, 1995.

[2] P. Chindaprasirt, C. Jaturapitakkul and T. Sinsiri, "Effect of fly ash fineness on microstructure of blended cement paste," *Construction and Building Materials,* vol. 21 , no. 1, p. 1534–1541, 2007.

[3] C. Prinya, C. Jaturapitakkul and T. Sinsiri, "Effect of fly ash fineness on microstructure of blended cement paste," *Construction and Building Materials,* vol. 21, p. 1534–1541, 2007.

[4] A. A. Ramezanianpour, Cement Replacement Materials Properties, Durability, Sustainability, Heidelberg New York Dordrecht London: Springer Geochemistry / Mineralogy, 2014.

[5] R. Siddique and M. Iqbal Khan, Supplementary Cementing Materials, Heidelberg Dordrecht London New York: Springer, 2011.

[6] Estidama, "Building Rating System Design & Construction," *Pearl Building Rating System for Estidama,* no. 1.0, pp. 1-223, 2010.

[7] K. G. Babu and V. S. R. Kumar, "Efficiency of GGBS in concrete," *Cement and Concrete Research ,* vol. 30, pp. 1031- 1036, 2000.

[8] M. Elchalakani, A. Tarek and E. Abu-Aisheh, "Sustainable concrete with high volume GGBFS to build Masdar City," *Case Studies in Construction Materials,* vol. 1, p. 10–24, 2014.

[9] A. R. Bagheri, H. Zanganeh and M. M. Moalemi, "Mechanical and durability properties of ternary concretes containing silica fume and low reactivity blast furnace slag," *Cement & Concrete Composites,* vol. 34, p. 663–670, 2012.

[10] M. Khana and C. Lynsdaleb, "Strength, permeability, and carbonation of high-performance concrete," *Cement and Concrete Research ,* vol. 32 , p. 123–131, 2002.

[11] C. Yang and C. Chiang, "On the relationship between pore structure and charge passed from RCPT in mineral-free cement-based materials," *Materials Chemistry and Physics,* vol. 93, p. 202–207, 2005.

[12] A. Oner and S. Akyuz, "An experimental study on optimum usage of GGBS for the compressive strength of concrete," *Cement & Concrete Composites ,* vol. 29, p. 505–514, 2007.

[13] A. Cheng, R. Huang, J.-K. Wu and C.-H. Chen, "Influence of GGBS on durability and corrosion behavior of reinforced concrete," *Materials Chemistry and Physics,* vol. 93, no. 2-3, p. 404–411, 2005.

[14] J. Dottoa, A. Abreub, D. Dal Molinb and I. Müller, "Influence of silica fume addition on concretes physical properties and on corrosion behaviour of reinforcement bars," *Cement and Concrete Composites,* vol. 26, no. 1, p. 31–39, 2004.

[15] M. I. Khana and R. Siddiqueb, "Utilization of silica fume in concrete: Review of durability properties," *Resources, Conservation and Recycling,* vol. 57, p. 30–35, 2011.

[16] R. Ochbelagh, S. Azimkhani and H. G. Mosavinejad, "Shielding and strength tests of silica fume concrete," *Annals of Nuclear Energy,* vol. 45, p. 150–154, 2012.

[17] M. Sarıdemir, "Effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete," *Construction and Building Materials,* vol. 49, p. 484–489, 2013.

[18] M. O’Connell, C. McNally and M. G. Richardson, "Performance of concrete incorporating GGBS in aggressive wastewater environments," *Construction and Building Materials,* vol. 27, no. 1, p. 368–374, 2012.

[19] M. Moinia, I. Flores-Viviana, A. Amirjanovb and K. Soboleva, "The optimization of aggregate blends for sustainable low cement concrete," *Construction and Building Materials,* vol. 93, p. 627–634, 2015.

[20] M. A. u. Z. Abu Saleh, "Development of Sustainable and Low Carbon Concretes for the Gulf Environment," University of Bath, Department of Architecture and Civil Engineering, Bath, UK., 2014.

[21] M. Jones, R. Dhir and B. Magee, "Concrete containing ternary blended binders: Resistance to chloride ingress and carbonation," *Cement and Concrete Research,* vol. 27, no. 6, p. 825–831, 1997.

[22] G. Menéndez, V. Bonavetti and E. Irassar, "Strength development of ternary blended cement with limestone filler and blast-furnace slag," *Cement and Concrete Composites,* vol. 25, no. 1, p. 61–67, 2003.

[23] T. Nochaiya, W. Wongkeo and A. Chaipanich, "Utilization of fly ash with silica fume and properties of Portland cement-fly ash-silica fume concrete," *Fuel,* vol. 89, no. 3, pp. 768-774, 2010.

[24] Elkem, *EMMA User Guide Version 1,* Elkem.

[25] CEN, "Part 3: Compressive strength of test specimens - EN 12390-3:2009," in *British Standards*, UK, BSI, 2011, p. 8.

[26] S. Yoona, S.-g. Oh, J. Ha and P. M. Monteiro, "The effects of surface treatments on rapid chloride permeability tests," *Materials Chemistry and Physics,* vol. 135, no. 2-3, p. 699–708, 2012.

[27] C. Shi, "Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results," *Cement and Concrete Research,* vol. 34, no. 3, p. 537–545, 2004.

[28] S. Marusin, "Sample Preparation - the Key to SEM Studies of Failed Concrete," *Cement & Concrete Composites,* vol. 17, pp. 311-318, 1995.

[29] JEOL, Scanning Electron Microscopy A to Z, Tokyo: JEOL.

[30] L. L., W. Y.L. and P. C.S., "Effect of Fly Ash and Silica Fume on Compressive and Fracture Behaviors of Concrete.," *Cement and Concrete Research,* vol. 28 1998, no. 2, p. 271–283., 1998.

[31] A. Neville and J. Brooks, Concrete Technology, Harlow: Pearson, 2010.

[32] M. Nematzadeh and M. Naghipour, "Compressive strength and modulus of elasticity of freshly compressed concrete," *Construction and Building Materials,* vol. 34, p. 476–485, 2012.

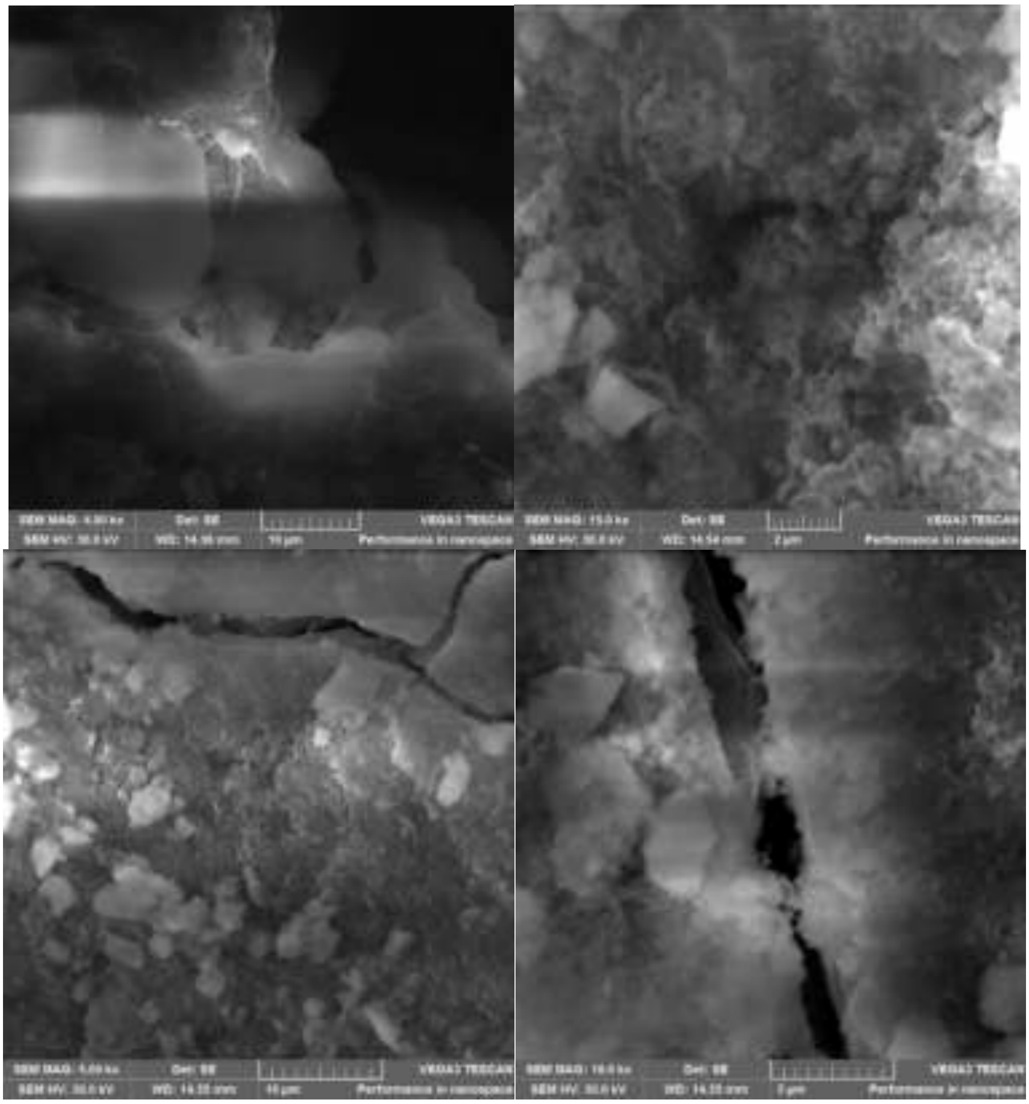
[33] İ. B. Topçu, T. Bilir and A. R. Boğa, "Estimation of the modulus of elasticity of slag concrete by using composite material models," *Construction and Building Materials,* vol. 24, no. 5, p. 741–748, 2010.

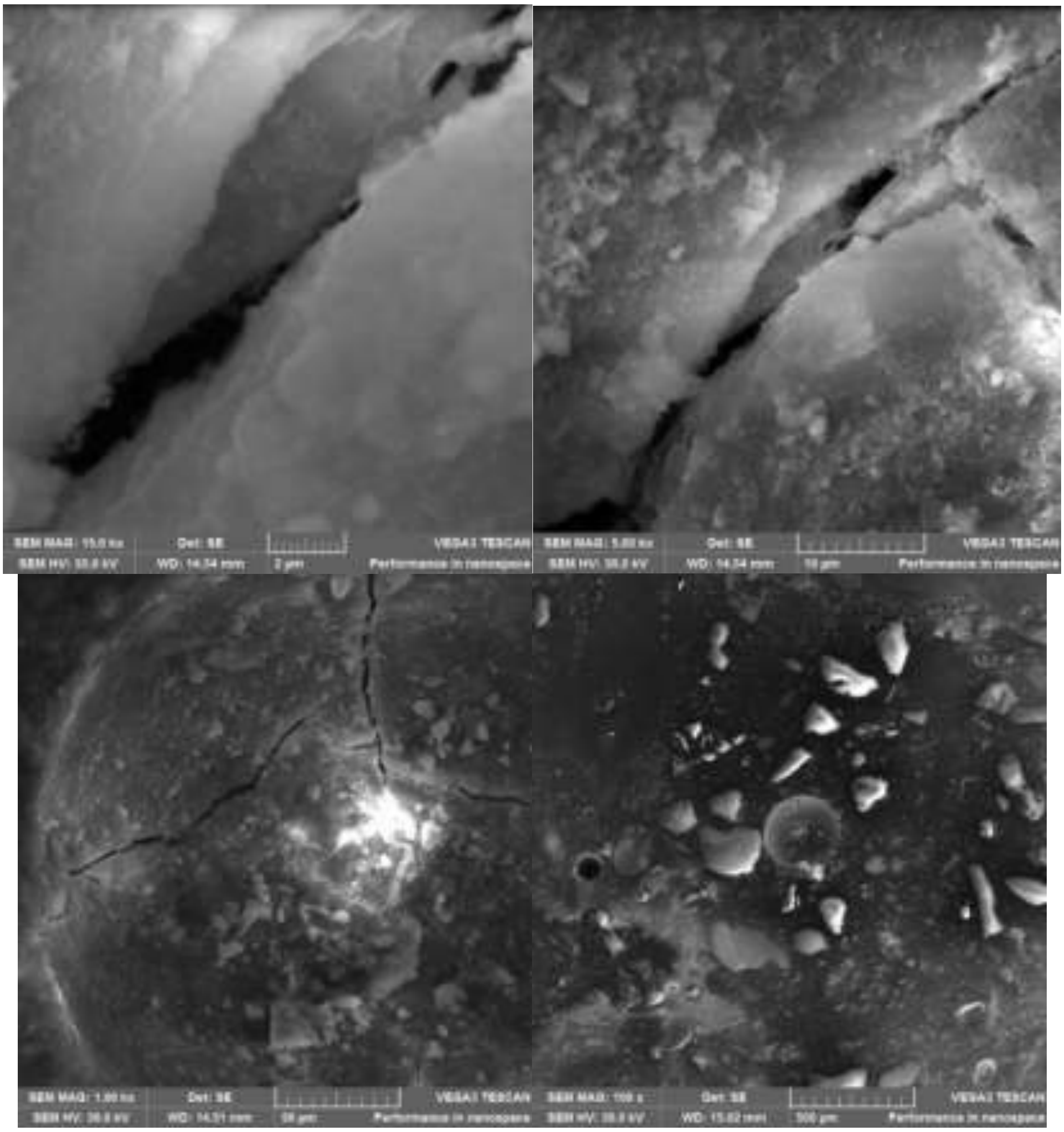
[34] W. Kurdowski, Cement and Concrete Chemistry, Dordrecht Heidelberg New York London: Springer, 2014.

[35] D. Nieda, K. Enemark-Rasmussenc, E. L'Hopitalb, J. Skibstedc and B. Lothenbachb, "Properties of magnesium silicate hydrates (M-S-H)," *Cement and Concrete Research,* vol. 79, p. 323–332, 2015.

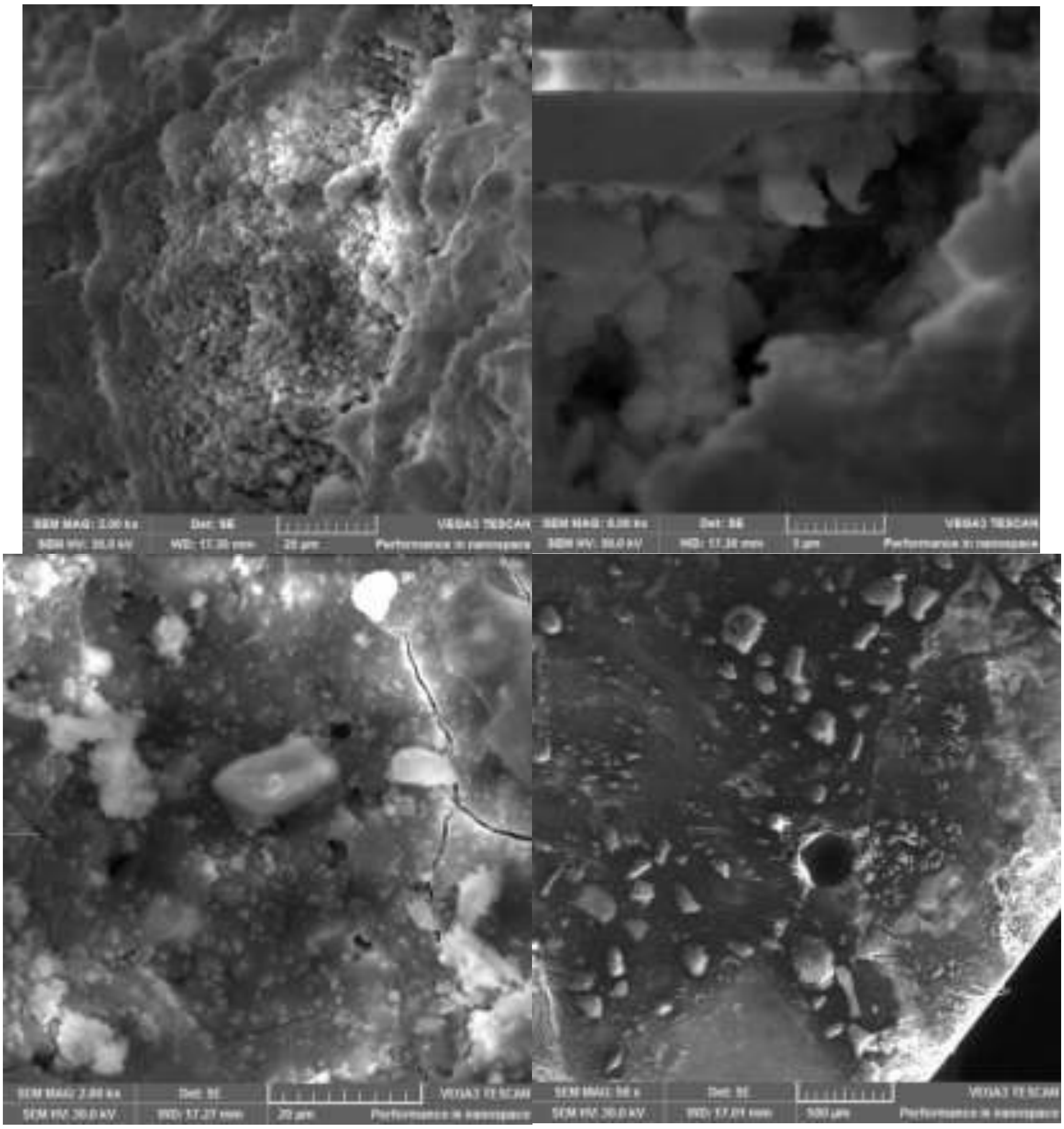
[36] M. S. Mamlouk and J. S. Zaniewski, Materials for Civil and Construction Engineers 3rd edition, New Jersey: PEARSON, 2011.

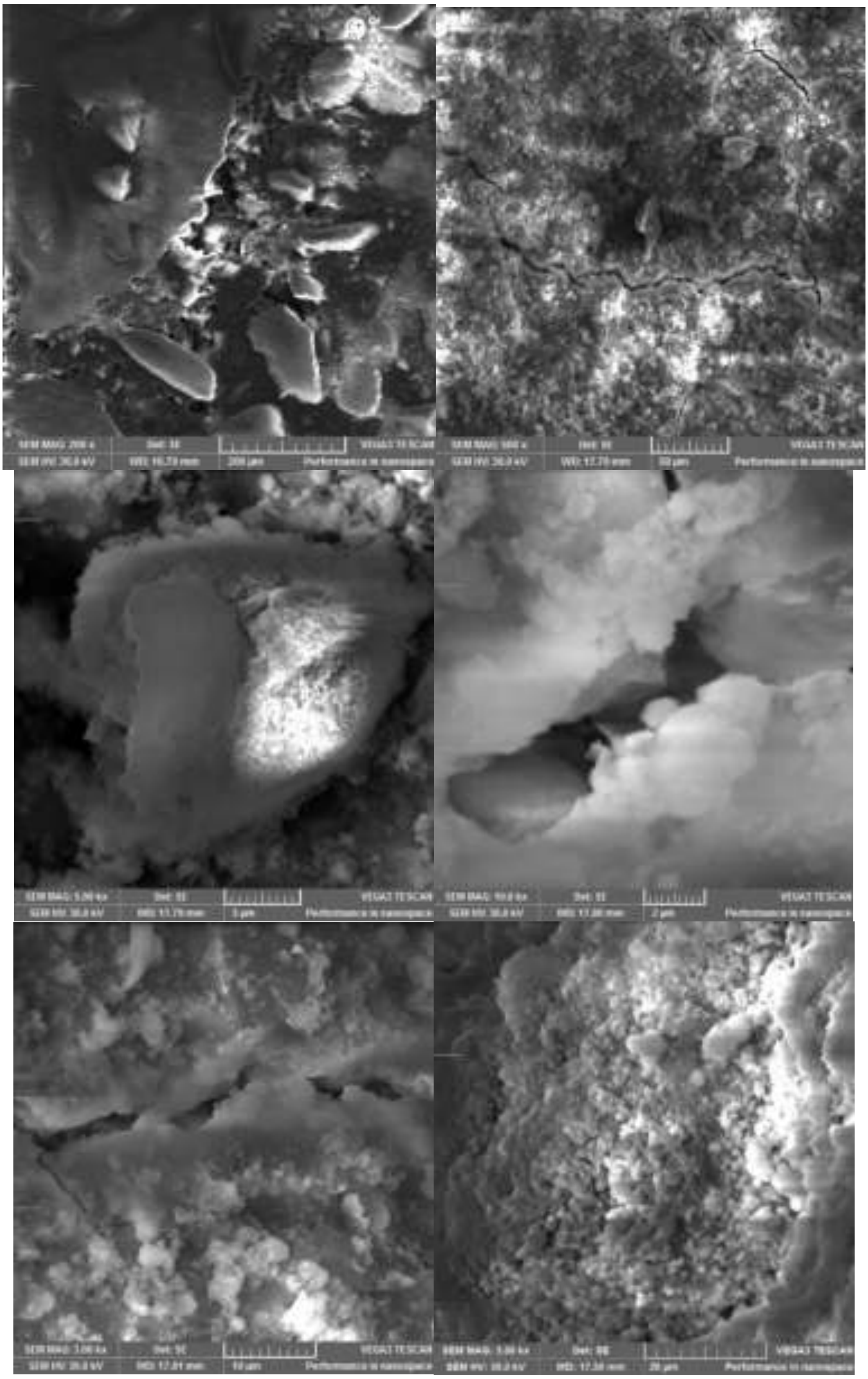
Appendix A: Additional Microstructural Images for Mix C500-S0-G0





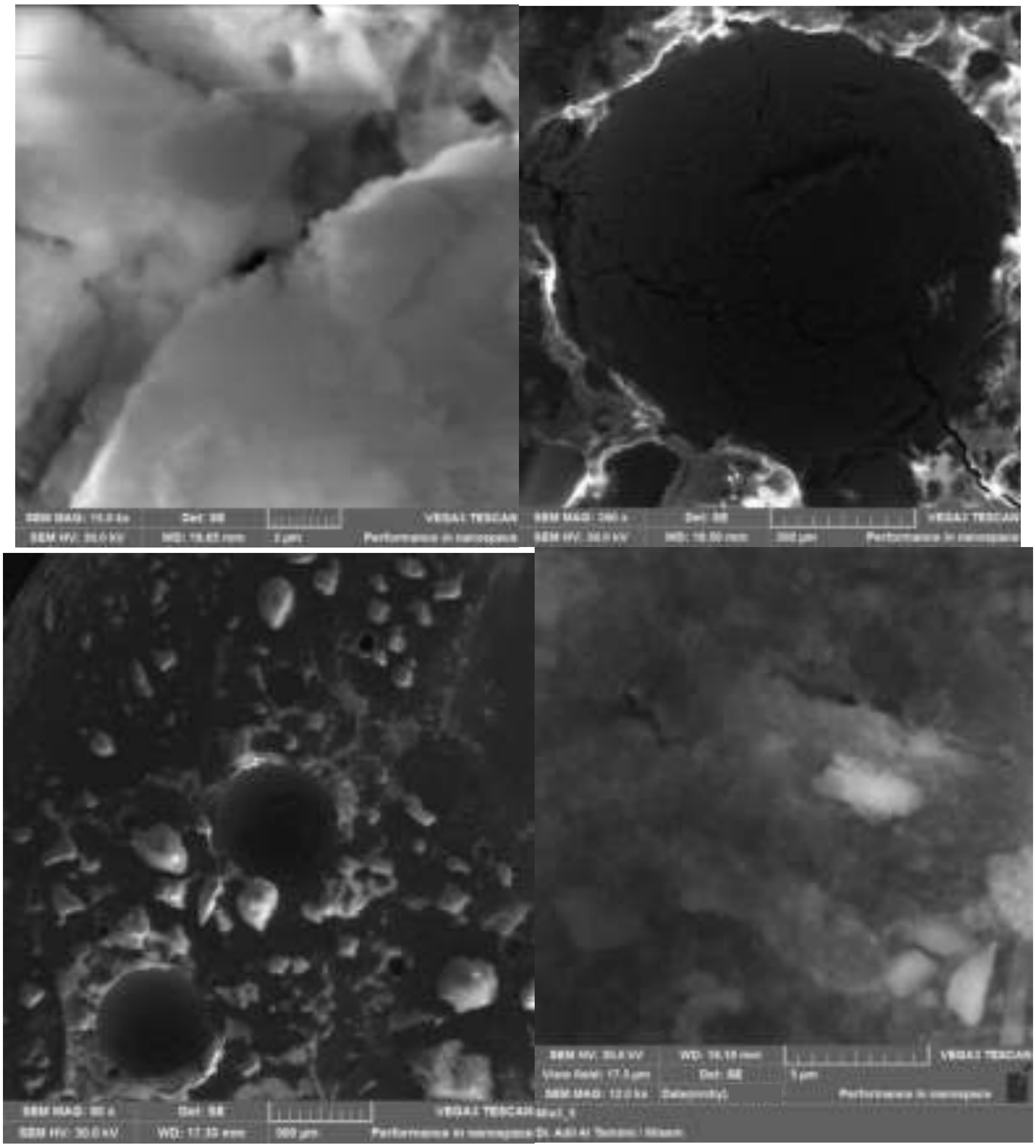
Appendix B: Additional Microstructural Images for Mix C320-S0-G180

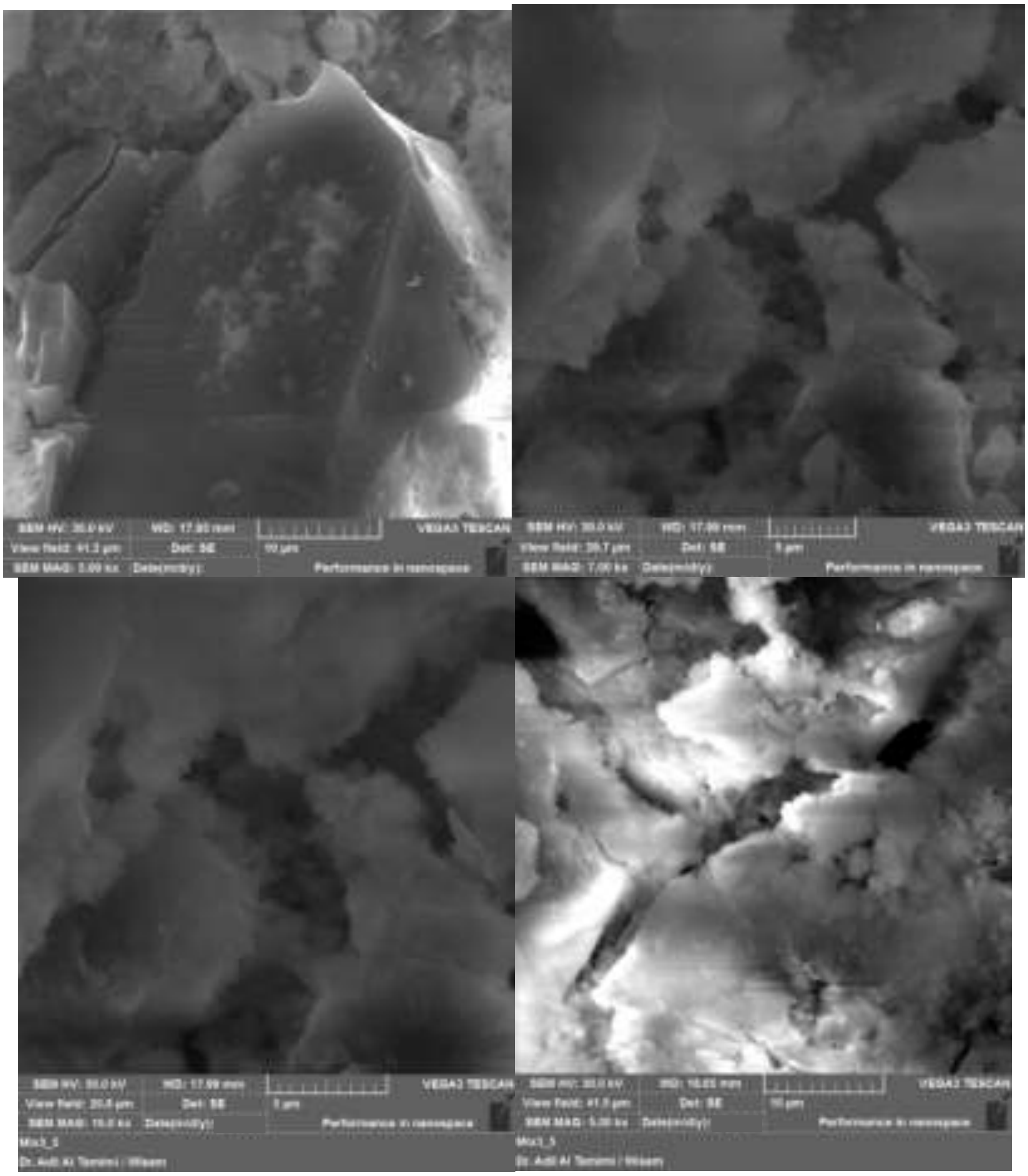




Appendix C

Additional microstructural images for mix C500-S100-G0




VEGA3 TESCAN
Det: SE
Performance in nanospace

Appendix B: Materials Properties

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REPORT ON	: **COARSE AGGREGATE**	
LABORATORY	: **AGGREGATE**	**Date :29.03.2015**
REPORT NO.	: **2015-130139**	

CONTRACT NO. : -
MANUFACTURER : CONMIX
CONSULTANT :
PROJECT NAME : QUALITY CONTROL
LOCATION : INDL. AREA #6, SHARJAH
DESCRIPTION : 20 mm CRUSHED ROCK AGGREGATE
SOURCE : AL JABER CRUSHER

RELATIVE DENSITY & WATER ABSORPTION ASTM C 127 - 01	APPARENT RELATIVE DENSITY	2.94
	RELATIVE DENSITY ON OVEN DRY BASIS	2.85
	RELATIVE DENSITY ON S.S.D. BASIS	2.87
	WATER ABSORPTION (%)	0.7
SIEVE ANALYSIS BS 812-103.1:Method 7.2:1985,Amended 1989	FINES (% PASSING 0.075 mm SIEVE) (BS 812 - 103.1:Method 7.2 : 1985,Amended 1989)	0.3
	SULPHATE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 118 : 1988)	0.07
	CHLORIDE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 117 : 1988) (AS Cl)	0.02
	FLAKINESS INDEX (% BY MASS OF DRY SAMPLE) (BS 812 - 105.1 : 1989)	11
	ELONGATION INDEX (% BY MASS OF DRY SAMPLE) (BS 812 - 105.2 :1990)	27
	AGGREGATE CRUSHING VALUE(% BY MASS OF DRY) SAMPLE) (BS 812 - 110 : 1990)	12
	CLAY LUMPS & FRIABLE PARTICLES (% BY MASS OF DRY SAMPLE) (ASTM C 142-97)	0.1
	MAGNESIUM SULPHATE SOUNDNESS (% LOSS BY MASS OF DRY SAMPLE) (ASTM C 88 – 99a)	2
	DRYING SHRINKAGE OF AGGREGATE IN CONCRETE (BS 812-120:1989) (% BY MASS OF DRY SAMPLE)	0.065

SIEVE SIZE (mm)	% PASSING
28.0	100
20.0	98
14.0	49
10.0	8
5.00	0.6
2.36	0.4
0.075	0.3

SAMPLE BROUGHT IN BY : C.M. LAB. SECTION

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REPORT NO.	: **2015-130139**	

CONTRACT NO. : -
MANUFACTURER : CONMIX
CONSULTANT : --
PROJECT NAME : QUALITY CONTROL
LOCATION : INDL. AREA #6, SHARJAH
DESCRIPTION : 10 mm CRUSHED ROCK AGGREGATE
SOURCE : AL JABER CRUSHER

RELATIVE DENSITY & WATER ABSORPTION ASTM C 127 - 01		APPARENT RELATIVE DENSITY	**2.92**
		RELATIVE DENSITY ON OVEN DRY BASIS	**2.85**
		RELATIVE DENSITY ON S.S.D. BASIS	**2.87**
		WATER ABSORPTION (%)	**0.8**
SIEVE ANALYSIS BS 812-103.1:Method 7.2:1985,Amended 1989		FINES (% PASSING 0.075 mm SIEVE) (BS 812 - 103.1:Method 7.2 : 1985, Amended 1989)	**0.4**
SIEVE SIZE (mm)	% PASSING	SULPHATE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 118 : 1988)	**0.08**
		CHLORIDE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 117 : 1988) (AS Cl)	**0.02**
		FLAKINESS INDEX (% BY MASS OF DRY SAMPLE) (BS 812 - 105.1 : 1989)	**18**
		ELONGATION INDEX (% BY MASS OF DRY SAMPLE) (BS 812 - 105.2 :1990)	**34**
14.0	**100**	AGGREGATE CRUSHING VALUE(% BY MASS OF DRY) SAMPLE) (BS 812 - 110 : 1990)	**11**
10.0	**89**		
6.30	**27**	CLAY LUMPS & FRIABLE PARTICLES (% BY MASS OF DRY SAMPLE) (ASTM C 142-97)	**0.1**
5.00	**8**		
2.36	**0.6**	MAGNESIUM SULPHATE SOUNDNESS (% LOSS BY MASS OF DRY SAMPLE) (ASTM C 88 - 99A)	**3**
0.075	**0.4**		

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REPORT NO.	: **2015-130139**	

CONTRACT NO. : -
MANUFACTURER : CONMIX
CONSULTANT : --
PROJECT NAME : QUALITY CONTROL
LOCATION : INDL. AREA #6, SHARJAH
DESCRIPTION : (0-5)mm WASHED CRUSHED ROCK SAND
SOURCE : AL SHAMSI CRUSHER

RELATIVE DENSITY & WATER ABSORPTION BS 812 : PART 2 : 1995 CLS. 5.5		APPARENT RELATIVE DENSITY	2.67
		RELATIVE DENSITY ON OVEN DRY BASIS	2.54
		RELATIVE DENSITY ON S.S.D. BASIS	2.59
		WATER ABSORPTION (%)	1.9
SIEVE ANALYSIS BS 812-103.1:Method 7.2:1985,Amended 1989		FINES (% PASSING 0.075 mm SIEVE) (BS 812 - 103.1:Method 7.2 : 1985, Amended 1989)	4.3
SIEVE SIZE (mm)	% PASSING	SULPHATE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 118 : 1988)	0.13
		CHLORIDE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 117 : 1988) (AS Cl)	0.03
6.3	100		
5.00	100	CLAY LUMPS AND FRIABLE PARTICLES (% BY MASS OF DRY SAMPLE [ASTM C 142-78(REAPPROVED 1990)]	0.1
2.36	67		
1.18	38	MAGNESIUM SULPHATE SOUNDNESS (% BY MASS OF DRY SAMPLE) (ASTM C 88 – 99a)	6
0.600	23		
0.300	13	ORGANIC IMPURITIES TEST (ASTM C 40 - 04)	NIL
0.150	7		
0.075	4.3		

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LABORATORY	: **AGGREGATE**	**Date :29.03.2015**
REPORT NO.	: **2015-130139**	

CONTRACT NO. : -
MANUFACTURER : CONMIX
CONSULTANT : --
PROJECT NAME : QUALITY CONTROL
LOCATION : INDL. AREA #6, SHARJAH
DESCRIPTION : UNCRUSHED SAND (DUNE SAND)
SOURCE : AL AIN

RELATIVE DENSITY & WATER ABSORPTION BS 812 : PART 2 : 1995 CLS. 5.5	APPARENT RELATIVE DENSITY	**2.66**
	RELATIVE DENSITY ON OVEN DRY BASIS	**2.59**
	RELATIVE DENSITY ON S.S.D. BASIS	**2.62**
	WATER ABSORPTION (%)	**1.1**
SIEVE ANALYSIS BS 812-103.1:Method 7.2:1985,Amended 1989	FINES (% PASSING 0.075 mm SIEVE) (BS 812 - 103.1:Method 7.2 : 1985, Amended 1989)	**4.9**
	SULPHATE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 118 : 1988)	**0.08**
	CHLORIDE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 117 : 1988) (AS Cl)	**0.01**
	ORGANIC IMPURITIES TEST (ASTM C 40 - 04)	**NIL**

SIEVE SIZE (mm)	% PASSING
0.600	**100**
0.300	**100**
0.150	**66**
0.075	**4.9**

SAMPLE BROUGHT IN BY : C.M. LAB. SECTION

CHECKED BY:

OFFICER INCHARGE:

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الإمارات العربية المتحدة - حكومة الشارقة
بلدية مدينة الشارقة
United Arab Emirates – Sharjah Government
SHARJAH CITY MUNICIPALITY

REPORT ON	: CHEMICAL ANALYSIS OF WATER FOR CONCRETING PURPOSES				
LABORATORY	: CHEMICAL	DATE OF SAMPLE RECEIVED			09/03/2015
DATES OF TEST SAMPLE ANALYZED		15-16/03/2015	DATE OF TEST REPORT ISSUED		17/03/2015
REPORT NO.	2015-130139	SAMPLE ID.	179478	SUB SAMPLE ID.	327013
PROJECT NAME	: QUALITY CONTROL				
MANUFACTURER	: CON MIX				
LOCATION	: INDUSTRIAL AREA#6				
SOURCE	: JUBAIL - DUBAI				
DESCRIPTION	: WATER FOR CONCRETING PURPOSES				
SAMPLE SIZE	: 1L				

ANALYSIS	RESULT	MAX. LIMITS S.Municipality	MAX. LIMITS B.S. STANDARD	TEST METHOD
SULPHATES (AS SO3), mg/L	73	500	1000	ASTM D516-90(95)
CHLORIDES (Cl), mg/L	369	600	500	ASTM D512-89(94) (TM-B)
TOTAL DISSOLVED SOLIDS ,mg/L	814	2000	2000	BS 1377:P3:90:CL.8(AMD9028)
CARBONATES , & BICARBONATES, mg/L	102	1000	1000	ASTM D1067-92(96) TEST METHOD B
pH VALUE	7.0	7 TO 9	NOT SPECIFIED	ASTM D1293-95:(TM-A)
TEMP. @ degrees Celsius	25.0			

SAMPLED BY : C.M.L SECTION
SAMPLE BROUGHT IN BY : C.M.L SECTION
SPECIFICATION FOR REQUIREMENTS : BS 3148:1980
SAMPLING METHOD : BS 3148:1980
TEST METHOD VARIATION : SULPHATE AS SO3 REPORTED.
REMARKS :

THIS REPORT RELATES TO THE SAMPLE TESTED ONLY.

TESTED BY:

OFFICER IN CHARGE:

هاتف ٥٦٢٣٣٣٣ ٦ ٩٧١+ فاكس ٥٦٢٦٤٥٥ ٦ ٩٧١+ ص.ب ٢٢ الشارقة - إ.ع.م.
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Elkem Microsilica®

CONCRETE

Guidance for the Specification of Silica Fume

C1-05
GENERAL INFORMATION

General

Silica Fume (also often termed condensed silica fume and microsilica) is a powerful pozzolanic material and has been used as an addition to concrete for some 30 years.

However, until more recently only a few international standards have been available for the specification of the material. This datasheet reviews the main standards and provides advice on how silica fume should be specified.

History

The first patent for a 'Silica Modified Cement' was granted in the USA in 1946. This was long before the first full-scale filtering came 'on-line'.

In 1986, Canada drew up a 'Standard for Supplementary Cementing Materials' – which included silica fume. This was revised in 1998.

In 1995, ASTM produced a Standard for the American market place and this undergoes almost annual review.

A new European Standard is under approval and will probably be issued in 2005.

These are the three main standards in global use, but many countries have now issued national standards for silica fume of which some are shown in Table 1.

Each should be checked for the date and only the latest edition used when specifying the silica fume.

Elkem Microsilica®

Elkem Materials produce Elkem Microsilica® which conforms to the mandatory requirements of the relevant standards from :

- **American Standards Institute**
- **Canadian Standards Association**
- **European Committee for Standardization**

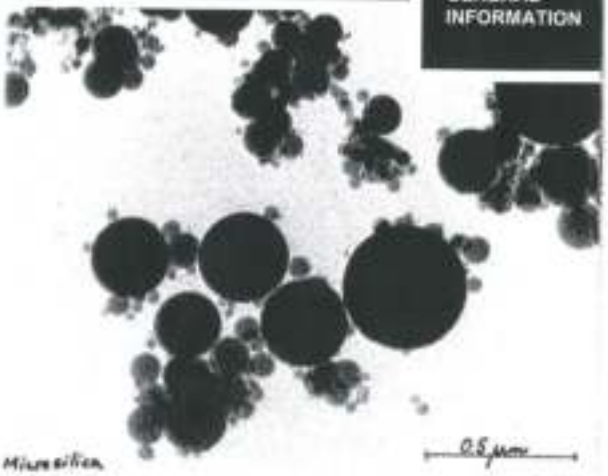
Standardisation Criteria

In order that the silica fume is of a suitable quality to use in concrete, a certain number of parameters have been set. While some of the values set may vary in 'National' Standards, the limits discussed here are considered the 'norm'.

Silicon Dioxide (SiO_2) – minimum 85%
While lower content fumes may be used under some National Standards, this is considered the lowest level for effective reaction in concrete use.

Specific Surface Area - 15 000 to 35 000 m²/kg
SSA defines the size of the particles. The higher the value, the smaller the sphere size. A 'normal' number is around 20 000. Out of range high values could have negative physical effects in the fresh concrete.

Loss on Ignition – maximum 4 to 6%
This is the amount of organic contaminant in the material. The lower this figure, the higher the quality. The 6% value is derived from the standard for fly ash.



SEM (Scanning Electron Micrograph) of silica fume

Retained on 45 micron sieve – up to 10%
The 'oversize' particles in the fume. These may be agglomerates or crystalline material. The lower this figure, the higher the quality. This is probably the most variable figure, with tolerance being up to 10%, depending on the standard used.

Pozzolanic Activity Index
The reactivity of the silica fume. This figure also varies from standard to standard depending on the design of the test mix and curing conditions. A good silica fume will always give a figure above 100% at 28 days.

Mix Proportioning

Due to the wide and varied nature of all the constituents of concrete – cements, aggregates, admixtures etc. – it is not feasible to give exact proportions for specific mixes – especially on a 'global' basis.

However, a review of past projects, and the mixes used, can give an insight into the level of silica fume dosage that may be advantageous for certain applications. These are quite simply, starting points for mix designs, until sufficient 'local' information has been determined. In almost all circumstances silica fume concrete is produced using a plasticiser or superplasticiser.

Table 2 sets out examples of the percentages that are suitable for the types of mixes given. Dosage levels will be relative to the environmental conditions and the performance requirements, hence the ranges given and the stress on trial mix work. The table shows areas of overlap. A low permeability concrete may also give a high strength, and a high strength shotcrete will also give a very

Elkem

CON MIX

MegaFlow 2000

Polycarboxylated High Range Superplasticiser

DESCRIPTION

MegaFlow 2000 is a high performance concrete superplasticiser based on modified polycarboxylate ether. Having unique carboxylic ether polymer with long lateral chains, it is an effective cement dispersant and high range water reducer as compared to conventional superplasticisers.

STANDARDS

ASTM C494, Type F and G, BSEN 934 - 2

USES

MegaFlow 2000 is used for ready-mix concrete, self compacting concrete, under water concrete, precast concrete, concrete containing silica fume, GGBS, PFA with extremely low w/c ratio, etc. It is specially designed to achieve improved concrete properties in plastic and hardened state. It is especially useful for ultra high strength concrete, high fines concrete, hot weather concrete, etc.

ADVANTAGES

- Produces high flowing concrete without segregation
- High early strength
- High workability with lower water content
- Increased durability
- Improved surface finish
- Improved adhesion to reinforcing and stressing steel
- Better resistance to carbonation
- Lower permeability
- Increased flexural strength

TYPICAL PROPERTIES at 25°C

PROPERTY	TEST METHOD	VALUE
Component	-	Single
Form	-	Liquid
Colour	-	Opaque
Specific Gravity	ASTM C494	1.10 +/- 0.02
Air Entrainment	ASTM C231	Up to 1% over Control mix
Chloride Content	BSEN 480-10	Nil to BSEN 934-2
pH	ASTM C494	5-7

COMPATIBILITY

MegaFlow 2000 can be used with all types of cements and cementitious materials like fly ash, GGBS, micro silica etc. **MegaFlow 2000** should not be premixed with other admixtures.

DOSAGE

Recommended dosage is 0.5 - 2% by weight of cementitious material. Higher dosage can be used after verification of performance by conducting lab and site trials. Optimum dosage of **MegaFlow 2000** and effect on concrete properties such as workability, strength, setting time, etc. are best assessed after preliminary tests on site using the actual materials of mixes under consideration. For self compacting concrete, a viscosity enhancer **MegaAdd VE**

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شركة الشارقة للاسمنت والتنمية الصناعية
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تليفون : ٥٣١١٥٨٣/٥٣١١٥٨٤/٥٣١١٧٨٣-٦-٠٠٩٧١
فاكس : ٥٣١١١٨١/٥٣١١٥٠٩-٦-٠٠٩٧١
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موقع الانترنت : www.sharjahcement.com

Our Ref: SEL

MANUFACTURER'S CERTIFICATE

Date : 17/06/2013

Ground Granulated Blastfurnace Slag

Despatched to the order of ____________________

to ____________________

is guaranteed to comply with BS 6699 : 1992

Test results relating to despatch samples for week ending **07/06/2013**

PHYSICAL TESTS

Test	Requirement	Result
Moisture	1.0 % max	**0.43**
Fineness Specific surface m^2/kg	275 minimum	**383**
Setting time* Minutes Initial	60 minimum	**280**
Final	Not specified	**340**
Soundness Le-chatelier* Expansion mm	10 maximum	**1.0**
Density gms/cc		**2.81**
Compressive Strength * Mortar Prism N/mm^2 2 day	Not specified	**6.9**
P C - 2 day	10 minimum	**27.7**
7 day	12 minimum	**26.9**
P C - 7 day	Not specified	**42.9**
W / E **17/05/2013** 28 day	32.5 minimum	**53.2**
P C - 28 day	42.5 minimum 62.5 maximum	**52.1**

CHEMICAL ANALYSIS

Test	Requirement	Result %
SiO_2	No Limit	**33.8**
IR	1.5 % max	**0.37**
Al_2O_3	No Limit	**13.6**
Fe_2O_3	No Limit	**0.7**
CaO	No Limit	**39.4**
MgO	14.0 % max	**6.2**
SO_3	2.5 % max	**0.09**
S	2.0 % max	**0.92**
$\equiv Na_2O$	No Limit	**0.46**
Mn_2O_3	2.0 % max	**0.27**
LOI**	3.0 % max	**2.0**
Cl^-	0.10 % max	**0.01**
CHEMICAL MODULAI SUM (CaO + MgO + SiO_2)	66.7 % min	79.4
Modulus (CaO+MgO) / (SiO_2)	1.0 min	1.3
Modulus (CaO) / (SiO_2)	1.4 max	1.2
Glass Content	67.0 % min	96.6

Test Temperature 22 ± 1 °C
+ 70 % GGBS + 30 % P C Class 42.5 N - LA
****Loss on ignition correction for sulfide**

FM 34670
ISO 9001

For and on behalf of
SHARJAH CEMENT FACTORY

Stephen E Leavy

pp WORKS MANAGER

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مصنـــع اسمنت الشـــارقـــة
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موقع الإنترنت : www.sharjahcement.com

Our Ref: SEL

MANUFACTURER'S CERTIFICATE

Date : 17/06/2013

Portland Cement

Despatched to the order of ________________

to ________________

is guaranteed to comply with BS EN 197 - 1 : 2011 CEM 1 42.5 N

Test results relating to despatch samples for week ending 07/06/2013

PHYSICAL TESTS

Test	Requirement	Result
Fineness Specific surface m^2/kg	Not Specified	325
Setting time Minutes Initial	60 minimum	140
Final	Not specified	190
Soundness Le-chatelier Expansion mm	10 maximum	1.0
Compressive Strength Mortar Prism MPa		
2 day	10 minimum	28.4
7 day	Not Specified	43.0
W / E 17/05/2013 28 day	42.5 minimum 62.5 maximum	55.0

CHEMICAL ANALYSIS

Test	Requirement	Result %
SiO_2	No Limit	20.5
IR	5.0 % max	0.34
Al_2O_3	No Limit	4.7
Fe_2O_3	No Limit	4.0
CaO	No Limit	64.1
MgO	5.0 % max (For clinker)	1.8
SO_3	3.5 % max	2.4
$\pm Na_2O$	No Limit	0.58
LOI	5.0 % max	1.5
Cl^-	0.10 % max	0.02
C_3A	No Limit	5.7

Test Temperature 22 ± 1 °C.

1 MPa = 1 N / mm^2

BSI
FM 34670
ISO 9001

KM35068

For and on behalf of
SHARJAH CEMENT FACTORY

Stephen E Lesurf

pp WORKS MANAGER

Appendix C: Scanning Electron Microscope model description

American University Of Sharjah
Central Instrumentation Facility

***Tescan VEGA III LMU* – Scanning Electron Microscope with *Oxford Instruments* EDS**

SEM 	***Model* : Tescan VEGA III LMU**
Resolution	3nm in High vacuum Mode (30kV)
Low Vac and BEI Resolution	5nm
Magnification	4x - 1,000,000x
Electron Gun	Tungsten heated cathode
Accelerating Voltage	0.2kV to 30 kV
EDS/EDX	***Model* : Oxford Instruments X-ACT**
EDS Detector Resolution	127 EV
EDS Detector Size	10 mm
EDS Detection range	Be4 to U92

Appendix D: MOE Test Readings

Stress = Load/Area

Strain = Average Gauge reading / 160mm (gauge length)

Readings for mix C250-S50-G250:

Cross section area of the specimen for mix C250-S50-G250 = 17671.46 mm^2

Load (KN)	Gauge.1 (mm)	Gauge.2 (mm)	Avg Gauge reading
4.94680	0.00000	0.00000	0.000
5.15490	0.33400	0.33400	0.334
5.15490	0.66600	0.66600	0.666
5.20410	0.99800	0.99800	0.998
5.29410	1.33200	1.33200	1.332
5.51210	1.66600	1.66600	1.666
5.88890	2.00000	2.00000	2.000
6.58210	2.33400	2.33400	2.334
7.49470	2.66600	2.66600	2.666
8.67450	2.99900	2.99900	2.999
10.30000	3.33200	3.33200	3.332
11.92690	3.66700	3.66700	3.667
15.87250	3.99900	3.99900	3.999
19.19380	4.33200	4.33200	4.332
21.42540	4.66700	4.66700	4.667
22.66420	4.99800	4.99800	4.998
24.02250	5.33200	5.33200	5.332
25.47930	5.66500	5.66500	5.665
26.94730	5.99900	5.99900	5.999
28.40400	6.33400	6.33400	6.334
29.83270	6.66500	6.66500	6.665
31.27960	6.99900	6.99900	6.999
32.72790	7.33200	7.33200	7.332
34.17480	7.66500	7.66500	7.665
35.59220	7.99900	7.99900	7.999
37.03070	8.33200	8.33200	8.332
38.45790	8.66600	8.66600	8.666
39.88520	9.00000	9.00000	9.000

Stress (MPa)	Strain
0.2799	0
0.2917	0.002088
0.2917	0.004163
0.2945	0.006238
0.2996	0.008325
0.3119	0.010413
0.3332	0.0125
0.3725	0.014588
0.4241	0.016663
0.4909	0.018744
0.5829	0.020825
0.6749	0.022919
0.8982	0.024994
1.0861	0.027075
1.2124	0.029169
1.2825	0.031238
1.3594	0.033325
1.4418	0.035406
1.5249	0.037494
1.6073	0.039588
1.6882	0.041656
1.7701	0.043744
1.8520	0.045825
1.9339	0.047906
2.0141	0.049994
2.0955	0.052075
2.1763	0.054163
2.2570	0.05625

41.31400	9.33200	9.33200	9.332
42.79200	9.66600	9.66600	9.666
44.27150	10.00000	10.00000	10.000
45.72000	10.33400	10.33400	10.334
47.16990	10.66700	10.66700	10.667
48.59860	11.00000	11.00000	11.000
50.04710	11.33200	11.33200	11.332
51.50690	11.66600	11.66600	11.666
52.92580	11.99900	11.99900	11.999
54.37570	12.33300	12.33300	12.333
55.80440	12.66600	12.66600	12.666
57.22330	12.99900	12.99900	12.999
58.66340	13.33300	13.33300	13.333
60.07240	13.66600	13.66600	13.666
61.48190	14.00000	14.00000	14.000
62.93200	14.33300	14.33300	14.333
64.38350	14.66700	14.66700	14.667
65.78430	14.99900	14.99900	14.999
67.22460	15.33200	15.33200	15.332
68.65640	15.66600	15.66600	15.666
70.07690	15.99900	15.99900	15.999
71.47770	16.33200	16.33200	16.332
72.91930	16.66600	16.66600	16.666
74.33990	17.00100	17.00100	17.001
75.77020	17.33300	17.33300	17.333
77.20200	17.66500	17.66500	17.665
78.63240	18.00000	18.00000	18.000
80.04310	18.33400	18.33400	18.334
81.48470	18.66700	18.66700	18.667
82.90520	19.00100	19.00100	19.001
84.33560	19.33300	19.33300	19.333
85.76600	19.66600	19.66600	19.666
87.21750	19.99900	19.99900	19.999
88.63810	20.33300	20.33300	20.333
90.04870	20.66600	20.66600	20.666
91.47060	20.99900	20.99900	20.999
92.90100	21.33200	21.33200	21.332
94.33140	21.66500	21.66500	21.665
95.77310	22.00100	22.00100	22.001
97.22320	22.33400	22.33400	22.334
98.62400	22.66600	22.66600	22.666
100.07550	23.00100	23.00100	23.001
101.50590	23.33300	23.33300	23.333
102.93620	23.66600	23.66600	23.666

2.3379	0.058325
2.4215	0.060413
2.5053	0.0625
2.5872	0.064588
2.6693	0.066669
2.7501	0.06875
2.8321	0.070825
2.9147	0.072913
2.9950	0.074994
3.0770	0.077081
3.1579	0.079163
3.2382	0.081244
3.3197	0.083331
3.3994	0.085413
3.4792	0.0875
3.5612	0.089581
3.6434	0.091669
3.7226	0.093744
3.8041	0.095825
3.8852	0.097913
3.9655	0.099994
4.0448	0.102075
4.1264	0.104163
4.2068	0.106256
4.2877	0.108331
4.3687	0.110406
4.4497	0.1125
4.5295	0.114588
4.6111	0.116669
4.6915	0.118756
4.7724	0.120831
4.8534	0.122913
4.9355	0.124994
5.0159	0.127081
5.0957	0.129163
5.1762	0.131244
5.2571	0.133325
5.3381	0.135406
5.4196	0.137506
5.5017	0.139588
5.5810	0.141663
5.6631	0.143756
5.7441	0.145831
5.8250	0.147913

104.33840	23.99900	23.99900	23.999	5.9043	0.149994
105.77870	24.33200	24.33200	24.332	5.9858	0.152075
107.21890	24.66600	24.66600	24.666	6.0673	0.154163
108.64090	24.99900	24.99900	24.999	6.1478	0.156244
110.07130	25.33300	25.33300	25.333	6.2288	0.158331
111.48170	25.66600	25.66600	25.666	6.3086	0.160413
112.90140	25.99900	25.99900	25.999	6.3889	0.162494
114.31260	26.33300	26.33300	26.333	6.4688	0.164581
115.78150	26.66600	26.66600	26.666	6.5519	0.166663
117.24200	27.00000	27.00000	27.000	6.6345	0.16875
118.64200	27.33400	27.33400	27.334	6.7138	0.170838
120.06160	27.66700	27.66700	27.667	6.7941	0.172919
121.48130	27.99900	27.99900	27.999	6.8744	0.174994
122.91220	28.33400	28.33400	28.334	6.9554	0.177088
124.31210	28.66600	28.66600	28.666	7.0346	0.179163
125.75150	29.00000	29.00000	29.000	7.1161	0.18125
127.17260	29.33300	29.33300	29.333	7.1965	0.183331
128.62180	29.66600	29.66600	29.666	7.2785	0.185413
130.04150	29.99900	29.99900	29.999	7.3588	0.187494
131.45270	30.33400	30.33400	30.334	7.4387	0.189588
132.87230	30.66600	30.66600	30.666	7.5190	0.191663
134.31170	31.00100	31.00100	31.001	7.6005	0.193756
135.72150	31.33400	31.33400	31.334	7.6803	0.195838
137.16230	31.66600	31.66600	31.666	7.7618	0.197913
138.58200	31.99900	31.99900	31.999	7.8421	0.199994
140.01150	32.33500	32.33500	32.335	7.9230	0.202094
141.40300	32.66600	32.66600	32.666	8.0018	0.204163
142.86200	32.99900	32.99900	32.999	8.0843	0.206244
144.27190	33.33200	33.33200	33.332	8.1641	0.208325
145.70280	33.66600	33.66600	33.666	8.2451	0.210413
147.15200	34.00100	34.00100	34.001	8.3271	0.212506
148.57170	34.33300	34.33300	34.333	8.4074	0.214581
149.99270	34.66800	34.66800	34.668	8.4878	0.216675
151.39270	34.99900	34.99900	34.999	8.5671	0.218744
152.83210	35.33400	35.33400	35.334	8.6485	0.220838
154.27280	35.66800	35.66800	35.668	8.7301	0.222925
155.68260	36.00000	36.00000	36.000	8.8098	0.225
157.11220	36.33300	36.33300	36.333	8.8907	0.227081
158.50220	36.66600	36.66600	36.666	8.9694	0.229163
159.94300	36.99900	36.99900	36.999	9.0509	0.231244
161.37250	37.33400	37.33400	37.334	9.1318	0.233338
162.79220	37.66800	37.66800	37.668	9.2122	0.235425
164.23300	37.99900	37.99900	37.999	9.2937	0.237494
165.66250	38.33500	38.33500	38.335	9.3746	0.239594

167.07230	38.66800	38.66800	38.668
168.47220	39.00000	39.00000	39.000
169.89330	39.33200	39.33200	39.332
171.34250	39.66800	39.66800	39.668
172.78190	39.99900	39.99900	39.999
174.18330	40.33300	40.33300	40.333
175.61280	40.66800	40.66800	40.668
177.02260	40.99900	40.99900	40.999
178.42250	41.33400	41.33400	41.334
179.86330	41.66700	41.66700	41.667
181.28300	42.00000	42.00000	42.000
182.71250	42.33300	42.33300	42.333
184.13350	42.66600	42.66600	42.666
185.57290	43.00100	43.00100	43.001
186.98270	43.33200	43.33200	43.332
188.42350	43.66600	43.66600	43.666
189.86290	44.00000	44.00000	44.000
191.29240	44.33400	44.33400	44.334
192.71350	44.66800	44.66800	44.668
194.11340	45.00000	45.00000	45.000
195.54290	45.33400	45.33400	45.334
196.95270	45.66700	45.66700	45.667
198.39350	46.00000	46.00000	46.000
199.82300	46.33400	46.33400	46.334
201.24270	46.66600	46.66600	46.666
202.65390	47.00000	47.00000	47.000
204.07350	47.33400	47.33400	47.334
205.52280	47.66700	47.66700	47.667
206.93400	48.00100	48.00100	48.001
208.35370	48.33300	48.33300	48.333
209.77330	48.66600	48.66600	48.666
211.17330	49.00100	49.00100	49.001
212.60440	49.33300	49.33300	49.333
214.03410	49.66600	49.66600	49.666
215.43420	49.99900	49.99900	49.999
216.89490	50.33300	50.33300	50.333
218.29500	50.66600	50.66600	50.666
219.71490	51.00000	51.00000	51.000
221.15440	51.33400	51.33400	51.334
222.56590	51.66600	51.66600	51.666
223.99560	52.00100	52.00100	52.001
225.43510	52.33200	52.33200	52.332
226.88600	52.66800	52.66800	52.668
228.27620	53.00000	53.00000	53.000

9.4544	0.241675
9.5336	0.24375
9.6140	0.245825
9.6960	0.247925
9.7775	0.249994
9.8568	0.252081
9.9377	0.254175
10.0174	0.256244
10.0966	0.258338
10.1782	0.260419
10.2585	0.2625
10.3394	0.264581
10.4198	0.266663
10.5013	0.268756
10.5811	0.270825
10.6626	0.272913
10.7440	0.275
10.8249	0.277088
10.9054	0.279175
10.9846	0.28125
11.0655	0.283338
11.1452	0.285419
11.2268	0.2875
11.3077	0.289588
11.3880	0.291663
11.4679	0.29375
11.5482	0.295838
11.6302	0.297919
11.7101	0.300006
11.7904	0.302081
11.8707	0.304163
11.9500	0.306256
12.0309	0.308331
12.1119	0.310413
12.1911	0.312494
12.2737	0.314581
12.3530	0.316663
12.4333	0.31875
12.5148	0.320838
12.5947	0.322913
12.6756	0.325006
12.7570	0.327075
12.8391	0.329175
12.9178	0.33125

229.69610	53.33500	53.33500	53.335
231.11590	53.66600	53.66600	53.666
232.53720	53.99900	53.99900	53.999
233.94720	54.33300	54.33300	54.333
235.38670	54.66800	54.66800	54.668
236.80800	55.00100	55.00100	55.001
238.23770	55.33400	55.33400	55.334
239.66740	55.66800	55.66800	55.668
241.08870	56.00000	56.00000	56.000
242.50850	56.33300	56.33300	56.333
243.91850	56.66600	56.66600	56.666
245.35810	57.00100	57.00100	57.001
246.75960	57.33500	57.33500	57.335
248.16960	57.66600	57.66600	57.666
249.60920	58.00100	58.00100	58.001
251.01920	58.33300	58.33300	58.333
252.43060	58.66600	58.66600	58.666
253.89970	58.99900	58.99900	58.999
255.28010	59.33300	59.33300	59.333
256.72110	59.66600	59.66600	59.666
258.15080	60.00100	60.00100	60.001
259.58050	60.33300	60.33300	60.333
261.02150	60.66600	60.66600	60.666
262.45120	61.00000	61.00000	61.000
263.85130	61.33300	61.33300	61.333
265.31200	61.66600	61.66600	61.666
266.74180	62.00000	62.00000	62.000
268.16160	62.33400	62.33400	62.334
269.55190	62.66600	62.66600	62.666
270.99290	63.00100	63.00100	63.001
272.42260	63.33500	63.33500	63.335
273.83250	63.66600	63.66600	63.666
275.28340	64.00200	64.00200	64.002
276.68350	64.33200	64.33200	64.332
278.11320	64.66700	64.66700	64.667
279.54430	65.00000	65.00000	65.000
280.96420	65.33300	65.33300	65.333
282.38400	65.66600	65.66600	65.666
283.81520	66.00000	66.00000	66.000
285.22520	66.33400	66.33400	66.334
286.63510	66.66700	66.66700	66.667
288.04510	67.00000	67.00000	67.000
289.44530	67.33500	67.33500	67.335
290.91580	67.66600	67.66600	67.666

12.9981	0.333344
13.0785	0.335413
13.1589	0.337494
13.2387	0.339581
13.3202	0.341675
13.4006	0.343756
13.4815	0.345838
13.5624	0.347925
13.6428	0.35
13.7232	0.352081
13.8030	0.354163
13.8844	0.356256
13.9637	0.358344
14.0435	0.360413
14.1250	0.362506
14.2048	0.364581
14.2846	0.366663
14.3678	0.368744
14.4459	0.370831
14.5274	0.372913
14.6083	0.375006
14.6893	0.377081
14.7708	0.379163
14.8517	0.38125
14.9309	0.383331
15.0136	0.385413
15.0945	0.3875
15.1748	0.389588
15.2535	0.391663
15.3351	0.393756
15.4160	0.395844
15.4957	0.397913
15.5779	0.400013
15.6571	0.402075
15.7380	0.404169
15.8190	0.40625
15.8993	0.408331
15.9797	0.410413
16.0607	0.4125
16.1404	0.414588
16.2202	0.416669
16.3000	0.41875
16.3793	0.420844
16.4625	0.422913

292.34550	68.00100	68.00100	68.001
293.74570	68.33300	68.33300	68.333
295.17680	68.66700	68.66700	68.667
296.59660	69.00000	69.00000	69.000
298.00660	69.33300	69.33300	69.333
299.44760	69.66600	69.66600	69.666
300.60960	70.00000	70.00000	70.000
299.48700	70.33300	70.33300	70.333
297.67000	70.66700	70.66700	70.667
296.17970	71.00100	71.00100	71.001
294.68940	71.33300	71.33300	71.333
293.28920	71.66700	71.66700	71.667
291.90880	72.00000	72.00000	72.000
290.47920	72.33300	72.33300	72.333
289.09880	72.66600	72.66600	72.666
287.68730	73.00100	73.00100	73.001
286.30690	73.33300	73.33300	73.333
284.89690	73.66800	73.66800	73.668
283.50670	74.00200	74.00200	74.002
282.10650	74.33300	74.33300	74.333
280.70640	74.66700	74.66700	74.667
279.27530	75.00100	75.00100	75.001
277.90480	75.33300	75.33300	75.333
276.49480	75.66800	75.66800	75.668
275.07490	76.00000	76.00000	76.000
273.68470	76.33300	76.33300	76.333
272.29440	76.66600	76.66600	76.666
270.88300	77.00000	77.00000	77.000
269.48280	77.33400	77.33400	77.334
268.10240	77.66700	77.66700	77.667
266.69240	78.00000	78.00000	78.000
265.29230	78.33400	78.33400	78.334
263.88100	78.66600	78.66600	78.666
262.49070	79.00000	79.00000	79.000
261.07080	79.33300	79.33300	79.333
259.69040	79.66700	79.66700	79.667
258.29030	80.00200	80.00200	80.002
256.86900	80.33300	80.33300	80.333
255.46890	80.66800	80.66800	80.668
254.09830	81.00200	81.00200	81.002
252.69820	81.33300	81.33300	81.333
251.29810	81.66700	81.66700	81.667
249.89790	82.00000	82.00000	82.000
248.49780	82.33500	82.33500	82.335

16.5434	0.425006
16.6226	0.427081
16.7036	0.429169
16.7839	0.43125
16.8637	0.433331
16.9453	0.435413
17.0110	0.4375
16.9475	0.439581
16.8447	0.441669
16.7603	0.443756
16.6760	0.445831
16.5968	0.447919
16.5187	0.45
16.4378	0.452081
16.3596	0.454163
16.2798	0.456256
16.2017	0.458331
16.1219	0.460425
16.0432	0.462513
15.9640	0.464581
15.8847	0.466669
15.8037	0.468756
15.7262	0.470831
15.6464	0.472925
15.5661	0.475
15.4874	0.477081
15.4087	0.479163
15.3288	0.48125
15.2496	0.483338
15.1715	0.485419
15.0917	0.4875
15.0125	0.489588
14.9326	0.491663
14.8539	0.49375
14.7736	0.495831
14.6955	0.497919
14.6162	0.500013
14.5358	0.502081
14.4566	0.504175
14.3790	0.506263
14.2998	0.508331
14.2206	0.510419
14.1413	0.5125
14.0621	0.514594

247.09630	82.66800	82.66800	82.668
245.69620	83.00000	83.00000	83.000
244.26640	83.33400	83.33400	83.334
242.86630	83.66600	83.66600	83.666
241.46620	84.00200	84.00200	84.002
240.06460	84.33300	84.33300	84.333
238.68420	84.66700	84.66700	84.667
237.27420	85.00200	85.00200	85.002
235.86430	85.33400	85.33400	85.334
234.46410	85.66700	85.66700	85.667
233.08370	86.00000	86.00000	86.000
231.66250	86.33500	86.33500	86.335
230.26230	86.66600	86.66600	86.666
228.86220	87.00000	87.00000	87.000
227.44240	87.33400	87.33400	87.334
226.05070	87.66700	87.66700	87.667
224.65050	88.00000	88.00000	88.000
223.26030	88.33500	88.33500	88.335
221.85030	88.66800	88.66800	88.668
220.43050	89.00100	89.00100	89.001
219.04020	89.33300	89.33300	89.333
217.63860	89.66600	89.66600	89.666
216.22870	90.00000	90.00000	90.000
214.83840	90.33300	90.33300	90.333
213.45800	90.66800	90.66800	90.668
212.00850	91.00000	91.00000	91.000
210.61690	91.33400	91.33400	91.334
209.20710	91.66700	91.66700	91.667
207.81710	92.00000	92.00000	92.000
206.41710	92.33400	92.33400	92.334
205.01720	92.66900	92.66900	92.669
203.60600	93.00000	93.00000	93.000
202.21590	93.33400	93.33400	93.334
200.79620	93.66700	93.66700	93.667
199.41600	94.00000	94.00000	94.000
198.03580	94.33400	94.33400	94.334
196.61610	94.66700	94.66700	94.667
195.22460	95.00000	95.00000	95.000
193.82470	95.33400	95.33400	95.334
192.43460	95.66800	95.66800	95.668
191.01500	96.00000	96.00000	96.000
189.65440	96.33400	96.33400	96.334
188.23480	96.66700	96.66700	96.667
186.83340	97.00100	97.00100	97.001

13.9828	0.516675
13.9036	0.51875
13.8226	0.520838
13.7434	0.522913
13.6642	0.525013
13.5849	0.527081
13.5068	0.529169
13.4270	0.531263
13.3472	0.533338
13.2680	0.535419
13.1898	0.5375
13.1094	0.539594
13.0302	0.541663
12.9510	0.54375
12.8706	0.545838
12.7919	0.547919
12.7126	0.55
12.6339	0.552094
12.5542	0.554175
12.4738	0.556256
12.3951	0.558331
12.3158	0.560413
12.2360	0.5625
12.1574	0.564581
12.0793	0.566675
11.9972	0.56875
11.9185	0.570838
11.8387	0.572919
11.7600	0.575
11.6808	0.577088
11.6016	0.579181
11.5217	0.58125
11.4431	0.583338
11.3627	0.585419
11.2846	0.5875
11.2065	0.589588
11.1262	0.591669
11.0475	0.59375
10.9682	0.595838
10.8896	0.597925
10.8092	0.6
10.7322	0.602088
10.6519	0.604169
10.5726	0.606256

185.43350	97.33500	97.33500	97.335
184.05330	97.66700	97.66700	97.667
182.65330	98.00100	98.00100	98.001
181.25340	98.33400	98.33400	98.334
179.86330	98.66900	98.66900	98.669
178.45350	99.00100	99.00100	99.001
177.05220	99.33500	99.33500	99.335
175.66210	99.66700	99.66700	99.667
174.26210	100.00000	100.00000	100.000
172.87200	100.33300	100.33300	100.333
171.48200	100.66900	100.66900	100.669
170.10170	101.00000	101.00000	101.000
168.70180	101.33600	101.33600	101.336
167.31030	101.66700	101.66700	101.667
165.90050	102.00200	102.00200	102.002
164.53020	102.33400	102.33400	102.334
163.13020	102.66700	102.66700	102.667
161.73030	103.00000	103.00000	103.000
160.35010	103.33300	103.33300	103.333
158.96000	103.66800	103.66800	103.668
157.57970	104.00000	104.00000	104.000
156.17840	104.33400	104.33400	104.334
154.78830	104.66800	104.66800	104.668
153.40810	105.00100	105.00100	105.001
152.01800	105.33600	105.33600	105.336
150.63780	105.66800	105.66800	105.668
149.24770	106.00100	106.00100	106.001
147.85760	106.33300	106.33300	106.333
146.45630	106.66700	106.66700	106.667
145.07600	107.00000	107.00000	107.000
143.69580	107.33400	107.33400	107.334
142.31560	107.66700	107.66700	107.667
140.94520	108.00000	108.00000	108.000
139.58470	108.33500	108.33500	108.335
138.18480	108.66800	108.66800	108.668
136.77500	109.00000	109.00000	109.000
135.41450	109.33400	109.33400	109.334
134.02440	109.66900	109.66900	109.669
132.65400	110.00100	110.00100	110.001
131.27380	110.33400	110.33400	110.334
129.87250	110.66700	110.66700	110.667
128.51340	111.00000	111.00000	111.000
127.15290	111.33400	111.33400	111.334
125.77120	111.66700	111.66700	111.667

10.4934	0.608344
10.4153	0.610419
10.3361	0.612506
10.2568	0.614588
10.1782	0.616681
10.0984	0.618756
10.0191	0.620844
9.9404	0.622919
9.8612	0.625
9.7826	0.627081
9.7039	0.629181
9.6258	0.63125
9.5466	0.63335
9.4678	0.635419
9.3880	0.637513
9.3105	0.639588
9.2313	0.641669
9.1521	0.64375
9.0740	0.645831
8.9953	0.647925
8.9172	0.65
8.8379	0.652088
8.7592	0.654175
8.6811	0.656256
8.6025	0.65835
8.5244	0.660425
8.4457	0.662506
8.3670	0.664581
8.2877	0.666669
8.2096	0.66875
8.1315	0.670838
8.0534	0.672919
7.9759	0.675
7.8989	0.677094
7.8197	0.679175
7.7399	0.68125
7.6629	0.683338
7.5842	0.685431
7.5067	0.687506
7.4286	0.689588
7.3493	0.691669
7.2724	0.69375
7.1954	0.695838
7.1172	0.697919

124.37130	112.00100	112.00100	112.001
123.03050	112.33400	112.33400	112.334
121.65030	112.66700	112.66700	112.667
120.27990	113.00000	113.00000	113.000
118.90950	113.33400	113.33400	113.334
117.52930	113.66700	113.66700	113.667
116.16880	114.00200	114.00200	114.002
114.79850	114.33500	114.33500	114.335
113.44780	114.66900	114.66900	114.669
112.04790	115.00100	115.00100	115.001
110.70680	115.33500	115.33500	115.335
109.33560	115.66700	115.66700	115.667
107.96440	116.00200	116.00200	116.002
106.63270	116.33400	116.33400	116.334
105.26150	116.66900	116.66900	116.669
103.90020	117.00100	117.00100	117.001
102.55860	117.33500	117.33500	117.335
101.18740	117.66700	117.66700	117.667
99.82600	118.00100	118.00100	118.001
98.49570	118.33400	118.33400	118.334
97.11470	118.66700	118.66700	118.667
95.78290	119.00000	119.00000	119.000
94.42160	119.33400	119.33400	119.334
93.08000	119.66700	119.66700	119.667
91.73840	120.00000	120.00000	120.000
90.40670	120.33400	120.33400	120.334
89.04530	120.66800	120.66800	120.668
87.71360	121.00000	121.00000	121.000
86.38330	121.33400	121.33400	121.334
85.05150	121.66900	121.66900	121.669
83.70990	122.00100	122.00100	122.001
82.40780	122.33400	122.33400	122.334
81.07600	122.66900	122.66900	122.669
79.74570	123.00000	123.00000	123.000
78.41400	123.33400	123.33400	123.334
77.09210	123.66700	123.66700	123.667
75.79980	124.00000	124.00000	124.000
74.48920	124.33400	124.33400	124.334
73.15750	124.66700	124.66700	124.667
71.82580	125.00100	125.00100	125.001
70.53350	125.33500	125.33500	125.335
69.22290	125.66800	125.66800	125.668
67.93060	126.00200	126.00200	126.002
66.60870	126.33300	126.33300	126.333

7.0380	0.700006
6.9621	0.702088
6.8840	0.704169
6.8064	0.70625
6.7289	0.708338
6.6508	0.710419
6.5738	0.712513
6.4963	0.714594
6.4198	0.716681
6.3406	0.718756
6.2647	0.720844
6.1871	0.722919
6.1095	0.725013
6.0342	0.727088
5.9566	0.729181
5.8795	0.731256
5.8036	0.733344
5.7260	0.735419
5.6490	0.737506
5.5737	0.739588
5.4956	0.741669
5.4202	0.74375
5.3432	0.745838
5.2673	0.747919
5.1913	0.75
5.1160	0.752088
5.0389	0.754175
4.9636	0.75625
4.8883	0.758338
4.8129	0.760431
4.7370	0.762506
4.6633	0.764588
4.5880	0.766681
4.5127	0.76875
4.4373	0.770838
4.3625	0.772919
4.2894	0.775
4.2152	0.777088
4.1399	0.779169
4.0645	0.781256
3.9914	0.783344
3.9172	0.785425
3.8441	0.787513
3.7693	0.789581

65.30800	126.66700	126.66700	126.667
63.99600	127.00000	127.00000	127.000
62.68400	127.33400	127.33400	127.334
61.39310	127.66700	127.66700	127.667
60.13160	128.00100	128.00100	128.001
58.87170	128.33500	128.33500	128.335
57.60060	128.66800	128.66800	128.668
56.32100	129.00100	129.00100	129.001
55.02040	129.33400	129.33400	129.334
53.74920	129.66900	129.66900	129.669
52.47950	130.00100	130.00100	130.001
51.20840	130.33600	130.33600	130.336
49.95840	130.66800	130.66800	130.668
48.73800	131.00000	131.00000	131.000
47.51610	131.33400	131.33400	131.334
46.27600	131.66700	131.66700	131.667
45.09500	132.00200	132.00200	132.002
43.89420	132.33400	132.33400	132.334
42.73290	132.66800	132.66800	132.668
41.55190	133.00000	133.00000	133.000
40.40120	133.33600	133.33600	133.336
39.29040	133.66700	133.66700	133.667
38.16970	134.00100	134.00100	134.001
37.06020	134.33600	134.33600	134.336
35.93950	134.66800	134.66800	134.668
34.80900	135.00100	135.00100	135.001
33.67850	135.33400	135.33400	135.334
32.54930	135.66700	135.66700	135.667
31.42860	136.00000	136.00000	136.000
30.33750	136.33400	136.33400	136.334
29.23790	136.66800	136.66800	136.668
28.14670	137.00100	137.00100	137.001
27.06540	137.33400	137.33400	137.334
25.98550	137.66800	137.66800	137.668
24.93510	138.00100	138.00100	138.001
23.89310	138.33500	138.33500	138.335
22.85260	138.66800	138.66800	138.668
21.83170	139.00100	139.00100	139.001
20.86010	139.33400	139.33400	139.334
19.90810	139.66800	139.66800	139.668
19.00540	140.00100	140.00100	140.001
18.13360	140.33600	140.33600	140.336
17.26040	140.66800	140.66800	140.668
16.39840	141.00100	141.00100	141.001

3.6957	0.791669
3.6214	0.79375
3.5472	0.795838
3.4741	0.797919
3.4028	0.800006
3.3315	0.802094
3.2595	0.804175
3.1871	0.806256
3.1135	0.808338
3.0416	0.810431
2.9697	0.812506
2.8978	0.8146
2.8271	0.816675
2.7580	0.81875
2.6889	0.820838
2.6187	0.822919
2.5519	0.825013
2.4839	0.827088
2.4182	0.829175
2.3514	0.83125
2.2862	0.83335
2.2234	0.835419
2.1600	0.837506
2.0972	0.8396
2.0338	0.841675
1.9698	0.843756
1.9058	0.845838
1.8419	0.847919
1.7785	0.85
1.7168	0.852088
1.6545	0.854175
1.5928	0.856256
1.5316	0.858338
1.4705	0.860425
1.4110	0.862506
1.3521	0.864594
1.2932	0.866675
1.2354	0.868756
1.1804	0.870838
1.1266	0.872925
1.0755	0.875006
1.0262	0.8771
0.9767	0.879175
0.9280	0.881256

15.55470	141.33500	141.33500	141.335
14.73210	141.66900	141.66900	141.669
13.90950	142.00100	142.00100	142.001
13.13620	142.33600	142.33600	142.336
12.37260	142.66800	142.66800	142.668
11.62880	143.00200	143.00200	143.002
11.11410	143.33400	143.33400	143.334
10.79630	143.66700	143.66700	143.667
10.49820	144.00200	144.00200	144.002
10.17200	144.33400	144.33400	144.334
9.85420	144.66900	144.66900	144.669
9.50690	145.00100	145.00100	145.001
9.17080	145.33400	145.33400	145.334
8.79400	145.66900	145.66900	145.669
8.44670	146.00100	146.00100	146.001
8.10920	146.33400	146.33400	146.334
7.76190	146.66800	146.66800	146.668
7.45540	147.00100	147.00100	147.001
7.14740	147.33400	147.33400	147.334
6.80990	147.66900	147.66900	147.669
6.49360	148.00100	148.00100	148.001
6.18560	148.33400	148.33400	148.334
5.88890	148.67000	148.67000	148.670
5.59080	149.00100	149.00100	149.001
5.31380	149.33400	149.33400	149.334
5.05510	149.66800	149.66800	149.668
4.77810	150.00100	150.00100	150.001
4.52070	150.33500	150.33500	150.335
4.28170	150.66700	150.66700	150.667
4.06370	151.00300	151.00300	151.003
3.83600	151.33600	151.33600	151.336
3.60820	151.66900	151.66900	151.669
3.40000	152.00100	152.00100	152.001
3.19190	152.33500	152.33500	152.335
3.00350	152.66800	152.66800	152.668
2.83480	153.00100	153.00100	153.001
2.64640	153.33400	153.33400	153.334
2.48750	153.66800	153.66800	153.668
2.29900	154.00100	154.00100	154.001
2.15140	154.33600	154.33600	154.336
2.02200	154.66800	154.66800	154.668
1.86310	155.00200	155.00200	155.002
1.72390	155.33500	155.33500	155.335
1.60580	155.66800	155.66800	155.668

0.8802	0.883344
0.8337	0.885431
0.7871	0.887506
0.7434	0.8896
0.7001	0.891675
0.6581	0.893763
0.6289	0.895838
0.6109	0.897919
0.5941	0.900013
0.5756	0.902088
0.5576	0.904181
0.5380	0.906256
0.5190	0.908338
0.4976	0.910431
0.4780	0.912506
0.4589	0.914588
0.4392	0.916675
0.4219	0.918756
0.4045	0.920838
0.3854	0.922931
0.3675	0.925006
0.3500	0.927088
0.3332	0.929188
0.3164	0.931256
0.3007	0.933338
0.2861	0.935425
0.2704	0.937506
0.2558	0.939594
0.2423	0.941669
0.2300	0.943769
0.2171	0.94585
0.2042	0.947931
0.1924	0.950006
0.1806	0.952094
0.1700	0.954175
0.1604	0.956256
0.1498	0.958338
0.1408	0.960425
0.1301	0.962506
0.1217	0.9646
0.1144	0.966675
0.1054	0.968763
0.0976	0.970844
0.0909	0.972925

1.46660	156.00200	156.00200	156.002
1.36820	156.33400	156.33400	156.334
1.25850	156.67000	156.67000	156.670
1.13900	157.00200	157.00200	157.002
1.08980	157.33400	157.33400	157.334
1.03070	157.66800	157.66800	157.668
0.98150	158.00100	158.00100	158.001
0.93090	158.33500	158.33500	158.335
0.89150	158.66800	158.66800	158.668
0.88160	159.00300	159.00300	159.003
0.82260	159.33600	159.33600	159.336
0.82260	159.66800	159.66800	159.668
0.76210	160.00100	160.00100	160.001
0.77200	160.33400	160.33400	160.334
0.76210	160.66800	160.66800	160.668
0.72280	161.00100	161.00100	161.001
0.70310	161.33600	161.33600	161.336
0.69320	161.66800	161.66800	161.668
0.66370	162.00100	162.00100	162.001
0.68340	162.33400	162.33400	162.334
0.68340	162.66800	162.66800	162.668
0.66370	163.00100	163.00100	163.001
0.66370	163.33500	163.33500	163.335
0.65390	163.66800	163.66800	163.668
0.64400	164.00300	164.00300	164.003
0.64400	164.33600	164.33600	164.336
0.65390	164.66800	164.66800	164.668
0.64400	165.00100	165.00100	165.001
0.64400	165.33400	165.33400	165.334
0.63420	165.66800	165.66800	165.668
0.66370	166.00300	166.00300	166.003
0.65390	166.33500	166.33500	166.335
0.66370	166.66800	166.66800	166.668
0.67350	167.00100	167.00100	167.001
0.67350	167.33700	167.33700	167.337
0.68340	167.66900	167.66900	167.669
0.70310	168.00200	168.00200	168.002
0.71290	168.33500	168.33500	168.335
0.74240	168.66800	168.66800	168.668
0.74240	169.00100	169.00100	169.001
0.79310	169.33600	169.33600	169.336
0.80290	169.66800	169.66800	169.668
0.87180	170.00100	170.00100	170.001
0.94070	170.33400	170.33400	170.334

0.0830	0.975013
0.0774	0.977088
0.0712	0.979188
0.0645	0.981263
0.0617	0.983338
0.0583	0.985425
0.0555	0.987506
0.0527	0.989594
0.0504	0.991675
0.0499	0.993769
0.0465	0.99585
0.0465	0.997925
0.0431	1.000006
0.0437	1.002088
0.0431	1.004175
0.0409	1.006256
0.0398	1.00835
0.0392	1.010425
0.0376	1.012506
0.0387	1.014588
0.0387	1.016675
0.0376	1.018756
0.0376	1.020844
0.0370	1.022925
0.0364	1.025019
0.0364	1.0271
0.0370	1.029175
0.0364	1.031256
0.0364	1.033338
0.0359	1.035425
0.0376	1.037519
0.0370	1.039594
0.0376	1.041675
0.0381	1.043756
0.0381	1.045856
0.0387	1.047931
0.0398	1.050013
0.0403	1.052094
0.0420	1.054175
0.0420	1.056256
0.0449	1.05835
0.0454	1.060425
0.0493	1.062506
0.0532	1.064588

1.05040	170.66900	170.66900	170.669
1.17980	171.00300	171.00300	171.003
1.40750	171.33500	171.33500	171.335
1.69440	171.66800	171.66800	171.668
2.04170	172.00200	172.00200	172.002
2.44810	172.33500	172.33500	172.335
2.91350	172.66800	172.66800	172.668
3.44930	173.00100	173.00100	173.001
4.04410	173.33400	173.33400	173.334
4.68950	173.66800	173.66800	173.668
5.38270	174.00300	174.00300	174.003
6.13640	174.33600	174.33600	174.336
7.05880	174.66800	174.66800	174.668
8.12890	175.00100	175.00100	175.001
9.38880	175.33600	175.33600	175.336
10.81600	175.66800	175.66800	175.668
13.42300	176.00200	176.00200	176.002
17.67660	176.33500	176.33500	176.335
21.72210	176.66900	176.66900	176.669
25.47930	177.00100	177.00100	177.001
28.57280	177.33400	177.33400	177.334
31.17130	177.66800	177.66800	177.668
32.74760	178.00100	178.00100	178.001
34.06520	178.33500	178.33500	178.335
35.49380	178.67000	178.67000	178.670
36.91120	179.00100	179.00100	179.001
38.35810	179.33500	179.33500	179.335
39.79660	179.66900	179.66900	179.669
41.25350	180.00300	180.00300	180.003
42.72310	180.33600	180.33600	180.336
44.19130	180.66800	180.66800	180.668
45.65100	181.00200	181.00200	181.002
47.08960	181.33500	181.33500	181.335
48.54940	181.66900	181.66900	181.669
49.99780	182.00100	182.00100	182.001
51.46740	182.33700	182.33700	182.337
52.88640	182.66900	182.66900	182.669
54.33480	183.00200	183.00200	183.002
55.76500	183.33600	183.33600	183.336
57.18390	183.66800	183.66800	183.668
58.61270	184.00100	184.00100	184.001
60.02320	184.33500	184.33500	184.335
61.42270	184.67000	184.67000	184.670
62.86300	185.00100	185.00100	185.001

0.0594	1.066681
0.0668	1.068769
0.0796	1.070844
0.0959	1.072925
0.1155	1.075013
0.1385	1.077094
0.1649	1.079175
0.1952	1.081256
0.2288	1.083338
0.2654	1.085425
0.3046	1.087519
0.3472	1.0896
0.3994	1.091675
0.4600	1.093756
0.5313	1.09585
0.6121	1.097925
0.7596	1.100013
1.0003	1.102094
1.2292	1.104181
1.4418	1.106256
1.6169	1.108338
1.7639	1.110425
1.8531	1.112506
1.9277	1.114594
2.0085	1.116688
2.0887	1.118756
2.1706	1.120844
2.2520	1.122931
2.3345	1.125019
2.4176	1.1271
2.5007	1.129175
2.5833	1.131263
2.6647	1.133344
2.7473	1.135431
2.8293	1.137506
2.9125	1.139606
2.9928	1.141681
3.0747	1.143763
3.1557	1.14585
3.2359	1.147925
3.3168	1.150006
3.3966	1.152094
3.4758	1.154188
3.5573	1.156256

64.33420	185.33400	185.33400	185.334
65.75470	185.66800	185.66800	185.668
67.17530	186.00200	186.00200	186.002
68.59720	186.33500	186.33500	186.335
70.00780	186.66800	186.66800	186.668
71.43820	187.00200	187.00200	187.002
72.88830	187.33500	187.33500	187.335
74.33000	187.66800	187.66800	187.668
75.74060	188.00200	188.00200	188.002
77.16120	188.33500	188.33500	188.335
78.59300	188.66900	188.66900	188.669
80.00360	189.00300	189.00300	189.003
81.43400	189.33600	189.33600	189.336
82.86580	189.66900	189.66900	189.669
84.31590	190.00200	190.00200	190.002
85.75610	190.33500	190.33500	190.335
87.18790	190.66900	190.66900	190.669
88.59860	191.00300	191.00300	191.003
90.01910	191.33500	191.33500	191.335
91.45090	191.66800	191.66800	191.668
92.91090	192.00200	192.00200	192.002
94.35110	192.33500	192.33500	192.335
95.77310	192.66800	192.66800	192.668
97.18370	193.00100	193.00100	193.001
98.62400	193.33500	193.33500	193.335
100.05570	193.66900	193.66900	193.669
101.47630	194.00200	194.00200	194.002
102.91650	194.33600	194.33600	194.336
104.32860	194.67000	194.67000	194.670
105.75900	195.00300	195.00300	195.003
107.18930	195.33500	195.33500	195.335
108.63100	195.67000	195.67000	195.670
110.06140	196.00400	196.00400	196.004
111.48170	196.33500	196.33500	196.335
112.91260	196.66800	196.66800	196.668
114.35200	197.00200	197.00200	197.002
115.81110	197.33500	197.33500	197.335
117.19130	197.66800	197.66800	197.668
118.61240	198.00100	198.00100	198.001
120.05180	198.33500	198.33500	198.335
121.47140	198.66800	198.66800	198.668
122.89250	199.00200	199.00200	199.002
124.33180	199.33600	199.33600	199.336
125.76140	199.66900	199.66900	199.669

3.6406	1.158338
3.7210	1.160425
3.8013	1.162513
3.8818	1.164594
3.9616	1.166675
4.0426	1.168763
4.1246	1.170844
4.2062	1.172925
4.2860	1.175013
4.3664	1.177094
4.4475	1.179181
4.5273	1.181269
4.6082	1.18335
4.6892	1.185431
4.7713	1.187513
4.8528	1.189594
4.9338	1.191681
5.0137	1.193769
5.0940	1.195844
5.1751	1.197925
5.2577	1.200013
5.3392	1.202094
5.4196	1.204175
5.4995	1.206256
5.5810	1.208344
5.6620	1.210431
5.7424	1.212513
5.8239	1.2146
5.9038	1.216688
5.9847	1.218769
6.0657	1.220844
6.1473	1.222938
6.2282	1.225025
6.3086	1.227094
6.3895	1.229175
6.4710	1.231263
6.5536	1.233344
6.6317	1.235425
6.7121	1.237506
6.7935	1.239594
6.8739	1.241675
6.9543	1.243763
7.0357	1.24585
7.1166	1.247931

127.16270	200.00200	200.00200	200.002	7.1959	1.250013
128.60210	200.33500	200.33500	200.335	7.2774	1.252094
130.04150	200.66800	200.66800	200.668	7.3588	1.254175
131.46250	201.00200	201.00200	201.002	7.4393	1.256263
132.88220	201.33600	201.33600	201.336	7.5196	1.25835
134.29200	201.66800	201.66800	201.668	7.5994	1.260425
135.72150	202.00300	202.00300	202.003	7.6803	1.262519
137.16230	202.33500	202.33500	202.335	7.7618	1.264594
138.60170	202.67000	202.67000	202.670	7.8433	1.266688
140.01150	203.00200	203.00200	203.002	7.9230	1.268763
141.43250	203.33500	203.33500	203.335	8.0034	1.270844
142.86200	203.66900	203.66900	203.669	8.0843	1.272931
144.27190	204.00300	204.00300	204.003	8.1641	1.275019
145.70280	204.33500	204.33500	204.335	8.2451	1.277094
147.12240	204.66800	204.66800	204.668	8.3254	1.279175
148.54210	205.00200	205.00200	205.002	8.4058	1.281263
149.98290	205.33700	205.33700	205.337	8.4873	1.283356
151.41240	205.66900	205.66900	205.669	8.5682	1.285431
152.83210	206.00200	206.00200	206.002	8.6485	1.287513
154.25170	206.33600	206.33600	206.336	8.7289	1.2896
155.66290	206.66800	206.66800	206.668	8.8087	1.291675
157.09240	207.00300	207.00300	207.003	8.8896	1.293769
158.52200	207.33600	207.33600	207.336	8.9705	1.29585
159.95290	207.67000	207.67000	207.670	9.0515	1.297938
161.36270	208.00200	208.00200	208.002	9.1313	1.300013
162.79220	208.33500	208.33500	208.335	9.2122	1.302094
164.21330	208.67000	208.67000	208.670	9.2926	1.304188
165.64280	209.00400	209.00400	209.004	9.3735	1.306275
167.07230	209.33500	209.33500	209.335	9.4544	1.308344
168.51310	209.66900	209.66900	209.669	9.5359	1.310431
169.94260	210.00200	210.00200	210.002	9.6168	1.312513
171.33270	210.33500	210.33500	210.335	9.6954	1.314594
172.76220	210.66800	210.66800	210.668	9.7763	1.316675
174.18330	211.00200	211.00200	211.002	9.8568	1.318763
175.62260	211.33700	211.33700	211.337	9.9382	1.320856
177.03240	211.67000	211.67000	211.670	10.0180	1.322938
178.44220	212.00300	212.00300	212.003	10.0978	1.325019
179.87320	212.33500	212.33500	212.335	10.1787	1.327094
181.27310	212.67000	212.67000	212.670	10.2580	1.329188
182.71250	213.00300	213.00300	213.003	10.3394	1.331269
184.12370	213.33500	213.33500	213.335	10.4193	1.333344
185.57290	213.67000	213.67000	213.670	10.5013	1.335438
186.98270	214.00300	214.00300	214.003	10.5811	1.337519
188.40380	214.33500	214.33500	214.335	10.6615	1.339594

189.86290	214.66900	214.66900	214.669
191.30230	215.00300	215.00300	215.003
192.71350	215.33500	215.33500	215.335
194.13310	215.66900	215.66900	215.669
195.54290	216.00200	216.00200	216.002
196.98230	216.33600	216.33600	216.336
198.40340	216.66900	216.66900	216.669
199.80330	217.00200	217.00200	217.002
201.22300	217.33600	217.33600	217.336
202.64400	217.67000	217.67000	217.670
204.06370	218.00100	218.00100	218.001
205.50310	218.33700	218.33700	218.337
206.94390	218.66800	218.66800	218.668
208.36350	219.00200	219.00200	219.002
209.77330	219.33700	219.33700	219.337
211.17330	219.67000	219.67000	219.670
212.59450	220.00400	220.00400	220.004
214.02420	220.33500	220.33500	220.335
215.46380	220.66900	220.66900	220.669
216.88500	221.00200	221.00200	221.002
218.32460	221.33700	221.33700	221.337
219.73460	221.66800	221.66800	221.668
221.15440	222.00200	222.00200	222.002
222.56590	222.33500	222.33500	222.335
224.00540	222.66900	222.66900	222.669
225.41540	223.00200	223.00200	223.002
226.83670	223.33700	223.33700	223.337
228.25650	223.66800	223.66800	223.668
229.69610	224.00400	224.00400	224.004
231.11590	224.33600	224.33600	224.336
232.56680	224.66800	224.66800	224.668
233.99650	225.00200	225.00200	225.002
235.37690	225.33700	225.33700	225.337
236.79820	225.66900	225.66900	225.669
238.21800	226.00300	226.00300	226.003
239.64770	226.33500	226.33500	226.335
241.06760	226.66900	226.66900	226.669
242.49870	227.00300	227.00300	227.003
243.89880	227.33600	227.33600	227.336
245.33840	227.66900	227.66900	227.669
246.73990	228.00300	228.00300	228.003
248.16960	228.33600	228.33600	228.336
249.60920	228.66900	228.66900	228.669
251.01920	229.00300	229.00300	229.003

10.7440	1.341681
10.8255	1.343769
10.9054	1.345844
10.9857	1.347931
11.0655	1.350013
11.1469	1.3521
11.2273	1.354181
11.3066	1.356263
11.3869	1.35835
11.4673	1.360438
11.5476	1.362506
11.6291	1.364606
11.7106	1.366675
11.7910	1.368763
11.8707	1.370856
11.9500	1.372938
12.0304	1.375025
12.1113	1.377094
12.1928	1.379181
12.2732	1.381263
12.3546	1.383356
12.4344	1.385425
12.5148	1.387513
12.5947	1.389594
12.6761	1.391681
12.7559	1.393763
12.8363	1.395856
12.9167	1.397925
12.9981	1.400025
13.0785	1.4021
13.1606	1.404175
13.2415	1.406263
13.3196	1.408356
13.4000	1.410431
13.4804	1.412519
13.5613	1.414594
13.6416	1.416681
13.7226	1.418769
13.8018	1.42085
13.8833	1.422931
13.9626	1.425019
14.0435	1.4271
14.1250	1.429181
14.2048	1.431269

252.45030	229.33600	229.33600	229.336
253.88990	229.66900	229.66900	229.669
255.32100	230.00200	230.00200	230.002
256.76060	230.33700	230.33700	230.337
258.19030	230.66900	230.66900	230.669
259.62140	231.00300	231.00300	231.003
261.04120	231.33700	231.33700	231.337
262.45120	231.67000	231.67000	231.670
263.88100	232.00200	232.00200	232.002
265.28250	232.33700	232.33700	232.337
266.71220	232.67000	232.67000	232.670
268.15180	233.00300	233.00300	233.003
269.57300	233.33500	233.33500	233.335
271.01260	233.66900	233.66900	233.669
272.43240	234.00300	234.00300	234.003
273.85370	234.33700	234.33700	234.337
275.27350	234.67100	234.67100	234.671
276.69340	235.00300	235.00300	235.003
278.10340	235.33700	235.33700	235.337
279.51470	235.66900	235.66900	235.669
280.93460	236.00200	236.00200	236.002
282.32490	236.33600	236.33600	236.336
283.77430	236.66900	236.66900	236.669
285.17580	237.00400	237.00400	237.004
286.60560	237.33600	237.33600	237.336
288.02540	237.67100	237.67100	237.671
289.44530	238.00200	238.00200	238.002
290.86650	238.33600	238.33600	238.336
292.29620	238.66900	238.66900	238.669
293.73580	239.00300	239.00300	239.003
295.17680	239.33600	239.33600	239.336
296.57690	239.66900	239.66900	239.669
298.01650	240.00200	240.00200	240.002
299.45740	240.33700	240.33700	240.337
300.67870	240.67100	240.67100	240.671
299.68560	241.00300	241.00300	241.003
297.74880	241.33600	241.33600	241.336
296.22900	241.66900	241.66900	241.669
294.75000	242.00300	242.00300	242.003
293.31880	242.33600	242.33600	242.336
291.91870	242.67100	242.67100	242.671
290.52840	243.00400	243.00400	243.004
289.11850	243.33600	243.33600	243.336
287.74790	243.67100	243.67100	243.671

14.2858	1.43335
14.3672	1.435431
14.4482	1.437513
14.5297	1.439606
14.6106	1.441681
14.6916	1.443769
14.7719	1.445856
14.8517	1.447938
14.9326	1.450013
15.0119	1.452106
15.0928	1.454188
15.1743	1.456269
15.2547	1.458344
15.3362	1.460431
15.4165	1.462519
15.4969	1.464606
15.5773	1.466694
15.6576	1.468769
15.7374	1.470856
15.8173	1.472931
15.8976	1.475013
15.9763	1.4771
16.0583	1.479181
16.1376	1.481275
16.2186	1.48335
16.2989	1.485444
16.3793	1.487513
16.4597	1.4896
16.5406	1.491681
16.6220	1.493769
16.7036	1.49585
16.7828	1.497931
16.8643	1.500013
16.9458	1.502106
17.0149	1.504194
16.9587	1.506269
16.8491	1.50835
16.7631	1.510431
16.6794	1.512519
16.5984	1.5146
16.5192	1.516694
16.4405	1.518775
16.3608	1.52085
16.2832	1.522944

286.31680	244.00400	244.00400	244.004
284.93640	244.33700	244.33700	244.337
283.52640	244.66900	244.66900	244.669
282.12630	245.00300	245.00300	245.003
280.72610	245.33600	245.33600	245.336
279.35560	245.66900	245.66900	245.669
277.94420	246.00200	246.00200	246.002
276.58350	246.33700	246.33700	246.337
275.16370	246.67100	246.67100	246.671
273.80300	247.00300	247.00300	247.003
272.38310	247.33500	247.33500	247.335
270.99290	247.66900	247.66900	247.669
269.58290	248.00200	248.00200	248.002
268.18130	248.33600	248.33600	248.336
266.82060	248.67100	248.67100	248.671
265.40080	249.00200	249.00200	249.002
264.03020	249.33700	249.33700	249.337
262.62020	249.66900	249.66900	249.669
261.23980	250.00200	250.00200	250.002
259.82980	250.33600	250.33600	250.336
258.43820	250.66900	250.66900	250.669
257.02820	251.00400	251.00400	251.004
255.65760	251.33700	251.33700	251.337
254.24760	251.67100	251.67100	251.671
252.86720	252.00500	252.00500	252.005
251.46710	252.33600	252.33600	252.336
250.06700	252.66900	252.66900	252.669
248.67530	253.00500	253.00500	253.005
247.29490	253.33600	253.33600	253.336
245.89480	253.67100	253.67100	253.671
244.48480	254.00400	254.00400	254.004
243.10440	254.33600	254.33600	254.336
241.69440	254.66900	254.66900	254.669
240.30410	255.00200	255.00200	255.002
238.89270	255.33600	255.33600	255.336
237.50240	255.67000	255.67000	255.670
235.11910	256.23800	256.23800	256.238
233.71900	256.57100	256.57100	256.571
232.33860	256.90300	256.90300	256.903
230.94830	257.23800	257.23800	257.238
229.53690	257.57100	257.57100	257.571
228.14670	257.90500	257.90500	257.905
226.73670	258.23600	258.23600	258.236
224.36320	258.80300	258.80300	258.803

16.2022	1.525025
16.1241	1.527106
16.0443	1.529181
15.9651	1.531269
15.8858	1.53335
15.8083	1.535431
15.7284	1.537513
15.6514	1.539606
15.5711	1.541694
15.4941	1.543769
15.4137	1.545844
15.3351	1.547931
15.2553	1.550013
15.1760	1.5521
15.0990	1.554194
15.0186	1.556263
14.9411	1.558356
14.8613	1.560431
14.7831	1.562513
14.7034	1.5646
14.6246	1.566681
14.5448	1.568775
14.4673	1.570856
14.3875	1.572944
14.3094	1.575031
14.2301	1.5771
14.1509	1.579181
14.0721	1.581281
13.9940	1.58335
13.9148	1.585444
13.8350	1.587525
13.7569	1.5896
13.6771	1.591681
13.5984	1.593763
13.5186	1.59585
13.4399	1.597938
13.3050	1.601488
13.2258	1.603569
13.1477	1.605644
13.0690	1.607738
12.9891	1.609819
12.9105	1.611906
12.8307	1.613975
12.6964	1.617519

222.97290	259.13800	259.13800	259.138		12.6177	1.619613
221.60240	259.46900	259.46900	259.469		12.5401	1.621681
220.17130	259.80300	259.80300	259.803		12.4591	1.623769
218.78100	260.13600	260.13600	260.136		12.3805	1.62585
217.38090	260.46900	260.46900	260.469		12.3012	1.627931
215.98070	260.80300	260.80300	260.803		12.2220	1.630019
214.59050	261.13600	261.13600	261.136		12.1433	1.6321
213.18050	261.47100	261.47100	261.471		12.0635	1.634194
211.78880	261.80400	261.80400	261.804		11.9848	1.636275
210.39860	262.13700	262.13700	262.137		11.9061	1.638356
208.99870	262.47100	262.47100	262.471		11.8269	1.640444
207.59880	262.80200	262.80200	262.802		11.7477	1.642513
205.23550	263.36900	263.36900	263.369		11.6140	1.646056
203.83550	263.70200	263.70200	263.702		11.5347	1.648138
202.43420	264.03700	264.03700	264.037		11.4554	1.650231
201.05400	264.37000	264.37000	264.370		11.3773	1.652313
199.65400	264.70300	264.70300	264.703		11.2981	1.654394
198.26390	265.03600	265.03600	265.036		11.2194	1.656475
196.87390	265.36900	265.36900	265.369		11.1408	1.658556
195.46410	265.70400	265.70400	265.704		11.0610	1.66065
194.08380	266.03600	266.03600	266.036		10.9829	1.662725
192.67260	266.36900	266.36900	266.369		10.9030	1.664806
191.29240	266.70300	266.70300	266.703		10.8249	1.666894
189.91220	267.03600	267.03600	267.036		10.7468	1.668975
188.53200	267.37000	267.37000	267.370		10.6687	1.671063
187.12220	267.70400	267.70400	267.704		10.5889	1.67315
185.73210	268.03600	268.03600	268.036		10.5103	1.675225
184.32230	268.36900	268.36900	268.369		10.4305	1.677306
182.95190	268.70500	268.70500	268.705		10.3530	1.679406
181.54070	269.03700	269.03700	269.037		10.2731	1.681481
180.19010	269.37000	269.37000	269.370		10.1967	1.683563
178.76050	269.70400	269.70400	269.704		10.1158	1.68565
176.41700	270.26900	270.26900	270.269		9.9832	1.689181
174.20300	270.80300	270.80300	270.803		9.8579	1.692519
172.79180	271.13800	271.13800	271.138		9.7780	1.694613
171.43270	271.46900	271.46900	271.469		9.7011	1.696681
170.02150	271.80500	271.80500	271.805		9.6212	1.698781
168.65110	272.13800	272.13800	272.138		9.5437	1.700863
167.25120	272.47000	272.47000	272.470		9.4645	1.702938
165.87090	272.80500	272.80500	272.805		9.3864	1.705031
164.49070	273.13800	273.13800	273.138		9.3083	1.707113
163.10060	273.47000	273.47000	273.470		9.2296	1.709188
161.70070	273.80400	273.80400	273.804		9.1504	1.711275
160.33030	274.13700	274.13700	274.137		9.0728	1.713356

158.93880	274.47000	274.47000	274.470
157.54880	274.80300	274.80300	274.803
156.18820	275.13600	275.13600	275.136
154.78830	275.47000	275.47000	275.470
153.40810	275.80500	275.80500	275.805
152.04760	276.13600	276.13600	276.136
150.63780	276.47200	276.47200	276.472
149.25760	276.80500	276.80500	276.805
147.89700	277.13800	277.13800	277.138
146.50700	277.47100	277.47100	277.471
145.14650	277.80300	277.80300	277.803
143.75640	278.13700	278.13700	278.137
142.39590	278.47000	278.47000	278.470
140.88610	278.83600	278.83600	278.836
139.49600	279.17100	279.17100	279.171
138.13550	279.50300	279.50300	279.503
136.65530	279.87200	279.87200	279.872
135.26520	280.20300	280.20300	280.203
133.88500	280.53600	280.53600	280.536
132.52450	280.87000	280.87000	280.870
131.15410	281.20500	281.20500	281.205
129.78370	281.53600	281.53600	281.536
128.43310	281.87200	281.87200	281.872
127.06270	282.20400	282.20400	282.204
125.72190	282.53800	282.53800	282.538
124.34170	282.87200	282.87200	282.872
122.97130	283.20300	283.20300	283.203
121.62070	283.53700	283.53700	283.537
120.25030	283.87000	283.87000	283.870
118.90950	284.20300	284.20300	284.203
117.52930	284.53700	284.53700	284.537
116.17870	284.86900	284.86900	284.869
114.82800	285.20500	285.20500	285.205
113.46750	285.53700	285.53700	285.537
112.09720	285.87000	285.87000	285.870
110.76740	286.20300	286.20300	286.203
109.41590	286.53700	286.53700	286.537
108.07430	286.87200	286.87200	286.872
106.72290	287.20500	287.20500	287.205
105.39120	287.53700	287.53700	287.537
104.01010	287.87100	287.87100	287.871
102.68820	288.20500	288.20500	288.205
101.34660	288.53700	288.53700	288.537
100.00500	288.87200	288.87200	288.872

8.9941	1.715438
8.9154	1.717519
8.8384	1.7196
8.7592	1.721688
8.6811	1.723781
8.6041	1.72585
8.5244	1.72795
8.4463	1.730031
8.3693	1.732113
8.2906	1.734194
8.2136	1.736269
8.1349	1.738356
8.0580	1.740438
7.9725	1.742725
7.8939	1.744819
7.8169	1.746894
7.7331	1.7492
7.6544	1.751269
7.5763	1.75335
7.4994	1.755438
7.4218	1.757531
7.3443	1.7596
7.2678	1.7617
7.1903	1.763775
7.1144	1.765863
7.0363	1.76795
6.9588	1.770019
6.8823	1.772106
6.8048	1.774188
6.7289	1.776269
6.6508	1.778356
6.5744	1.780431
6.4979	1.782531
6.4209	1.784606
6.3434	1.786688
6.2682	1.788769
6.1917	1.790856
6.1158	1.79295
6.0393	1.795031
5.9639	1.797106
5.8858	1.799194
5.8110	1.801281
5.7350	1.803356
5.6591	1.80545

98.66480	289.20300	289.20300	289.203
97.31340	289.53700	289.53700	289.537
95.98160	289.87200	289.87200	289.872
94.65980	290.20400	290.20400	290.204
93.33790	290.53800	290.53800	290.538
92.00610	290.87000	290.87000	290.870
90.68570	291.20300	291.20300	291.203
89.36380	291.53700	291.53700	291.537
88.03210	291.87200	291.87200	291.872
86.72990	292.20400	292.20400	292.204
85.40950	292.53800	292.53800	292.538
83.18290	293.10500	293.10500	293.105
80.96750	293.67200	293.67200	293.672
79.63580	294.00400	294.00400	294.004
77.56840	294.53600	294.53600	294.536
76.27760	294.87100	294.87100	294.871
74.98530	295.20500	295.20500	295.205
73.69440	295.53600	295.53600	295.536
72.41200	295.87000	295.87000	295.870
71.10990	296.20300	296.20300	296.203
68.91430	296.77000	296.77000	296.770
67.65300	297.10400	297.10400	297.104
66.33110	297.43700	297.43700	297.437
65.06840	297.77000	297.77000	297.770
63.76770	298.10300	298.10300	298.103
62.49520	298.43700	298.43700	298.437
61.24370	298.77100	298.77100	298.771
60.02320	299.10500	299.10500	299.105
58.76190	299.43800	299.43800	299.438
57.51190	299.77100	299.77100	299.771
56.25070	300.10400	300.10400	300.104
55.00070	300.43700	300.43700	300.437
53.73940	300.77000	300.77000	300.770
52.52880	301.10400	301.10400	301.104
51.29850	301.43700	301.43700	301.437
50.05700	301.77000	301.77000	301.770
48.14260	302.30500	302.30500	302.305
46.94040	302.63900	302.63900	302.639
45.79040	302.97100	302.97100	302.971
44.60930	303.30400	303.30400	303.304
43.45790	303.63700	303.63700	303.637
42.30640	303.97000	303.97000	303.970
41.17460	304.30500	304.30500	304.305
40.07360	304.63700	304.63700	304.637

5.5833	1.807519
5.5068	1.809606
5.4314	1.8117
5.3566	1.813775
5.2818	1.815863
5.2065	1.817938
5.1318	1.820019
5.0570	1.822106
4.9816	1.8242
4.9079	1.826275
4.8332	1.828363
4.7072	1.831906
4.5818	1.83545
4.5065	1.837525
4.3895	1.84085
4.3164	1.842944
4.2433	1.845031
4.1702	1.8471
4.0977	1.849188
4.0240	1.851269
3.8998	1.854813
3.8284	1.8569
3.7536	1.858981
3.6821	1.861063
3.6085	1.863144
3.5365	1.865231
3.4657	1.867319
3.3966	1.869406
3.3252	1.871488
3.2545	1.873569
3.1831	1.87565
3.1124	1.877731
3.0410	1.879813
2.9725	1.8819
2.9029	1.883981
2.8326	1.886063
2.7243	1.889406
2.6563	1.891494
2.5912	1.893569
2.5244	1.89565
2.4592	1.897731
2.3941	1.899813
2.3300	1.901906
2.2677	1.903981

39.00350	304.97000	304.97000	304.970
37.90250	305.30300	305.30300	305.303
36.84230	305.63600	305.63600	305.636
35.75110	305.97000	305.97000	305.970
34.68100	306.30300	306.30300	306.303
33.58990	306.63700	306.63700	306.637
32.52970	306.97100	306.97100	306.971
31.42860	307.30400	307.30400	307.304
30.36700	307.63700	307.63700	307.637
29.31660	307.97000	307.97000	307.970
28.27610	308.30500	308.30500	308.305
27.25380	308.63900	308.63900	308.639
26.23300	308.97200	308.97200	308.972
25.20230	309.30600	309.30600	309.306
24.21090	309.63700	309.63700	309.637
23.21960	309.97200	309.97200	309.972
22.24800	310.30500	310.30500	310.305
21.30580	310.63700	310.63700	310.637
20.39330	310.97200	310.97200	310.972
19.50180	311.30400	311.30400	311.304
18.65810	311.63700	311.63700	311.637
17.84530	311.97200	311.97200	311.972
17.04240	312.30600	312.30600	312.306
16.21980	312.63900	312.63900	312.639
15.43660	312.97100	312.97100	312.971
14.66320	313.30500	313.30500	313.305
13.89970	313.63600	313.63600	313.636
13.18540	313.97000	313.97000	313.970
12.46120	314.30300	314.30300	314.303
11.77780	314.63700	314.63700	314.637
11.18300	314.97100	314.97100	314.971
10.86520	315.30500	315.30500	315.305
10.59810	315.63700	315.63700	315.637
10.30000	315.97100	315.97100	315.971
10.01310	316.30400	316.30400	316.304
9.70520	316.63900	316.63900	316.639
9.38880	316.97200	316.97200	316.972
9.07100	317.30500	317.30500	317.305
8.74340	317.63800	317.63800	317.638
8.43680	317.97000	317.97000	317.970
8.13870	318.30300	318.30300	318.303
7.85190	318.63700	318.63700	318.637
7.54390	318.97000	318.97000	318.970
7.26690	319.30500	319.30500	319.305

2.2071	1.906063
2.1448	1.908144
2.0848	1.910225
2.0231	1.912313
1.9625	1.914394
1.9008	1.916481
1.8408	1.918569
1.7785	1.92065
1.7184	1.922731
1.6590	1.924813
1.6001	1.926906
1.5422	1.928994
1.4845	1.931075
1.4262	1.933163
1.3701	1.935231
1.3140	1.937325
1.2590	1.939406
1.2057	1.941481
1.1540	1.943575
1.1036	1.94565
1.0558	1.947731
1.0098	1.949825
0.9644	1.951913
0.9179	1.953994
0.8735	1.956069
0.8298	1.958156
0.7866	1.960225
0.7461	1.962313
0.7052	1.964394
0.6665	1.966481
0.6328	1.968569
0.6148	1.970656
0.5997	1.972731
0.5829	1.974819
0.5666	1.9769
0.5492	1.978994
0.5313	1.981075
0.5133	1.983156
0.4948	1.985238
0.4774	1.987313
0.4606	1.989394
0.4443	1.991481
0.4269	1.993563
0.4112	1.995656

6.96880	319.63700	319.63700	319.637
6.69180	319.97200	319.97200	319.972
6.40360	320.30400	320.30400	320.304
6.13640	320.63900	320.63900	320.639
5.85940	320.97000	320.97000	320.970
5.59080	321.30400	321.30400	321.304
5.34330	321.63700	321.63700	321.637
5.11550	321.97200	321.97200	321.972
4.87790	322.30300	322.30300	322.303
4.61920	322.63700	322.63700	322.637
4.38150	322.97100	322.97100	322.971
4.14390	323.30500	323.30500	323.305
3.90630	323.63900	323.63900	323.639
3.68690	323.97100	323.97100	323.971
3.47880	324.30600	324.30600	324.306
3.27070	324.63800	324.63800	324.638
3.07240	324.97200	324.97200	324.972
2.87420	325.30500	325.30500	325.305
2.67590	325.63900	325.63900	325.639
2.53810	325.97000	325.97000	325.970
2.34970	326.30400	326.30400	326.304
2.18090	326.63700	326.63700	326.637
2.02200	326.97100	326.97100	326.971
1.88280	327.30600	327.30600	327.306
1.72390	327.63900	327.63900	327.639
1.61570	327.97100	327.97100	327.971
1.45680	328.30500	328.30500	328.305
1.35690	328.63700	328.63700	328.637
1.23880	328.97100	328.97100	328.971
1.14880	329.30400	329.30400	329.304
1.07010	329.63700	329.63700	329.637

0.3944	1.997731
0.3787	1.999825
0.3624	2.0019
0.3472	2.003994
0.3316	2.006063
0.3164	2.00815
0.3024	2.010231
0.2895	2.012325
0.2760	2.014394
0.2614	2.016481
0.2479	2.018569
0.2345	2.020656
0.2211	2.022744
0.2086	2.024819
0.1969	2.026913
0.1851	2.028988
0.1739	2.031075
0.1626	2.033156
0.1514	2.035244
0.1436	2.037313
0.1330	2.0394
0.1234	2.041481
0.1144	2.043569
0.1065	2.045663
0.0976	2.047744
0.0914	2.049819
0.0824	2.051906
0.0768	2.053981
0.0701	2.056069
0.0650	2.05815
0.0606	2.060231

Appendix E: Particle Size Distribution from Cement and GGBS

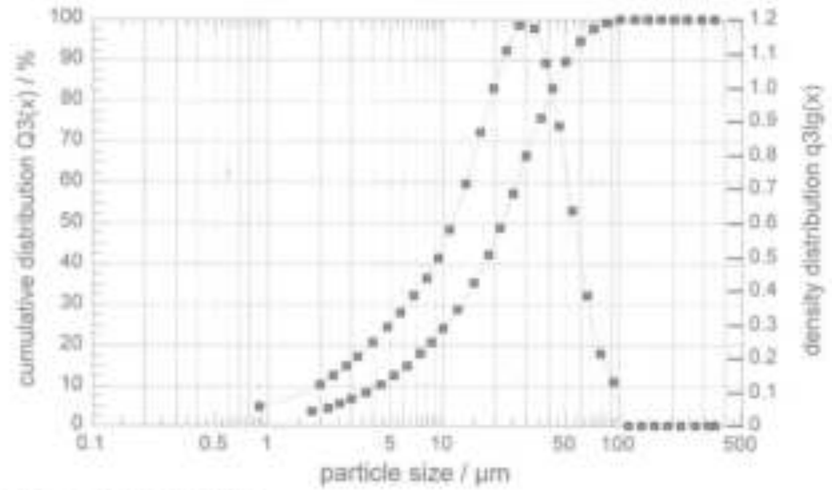
GULF CEMENT COMPANY
Particle Size Analysis

Sympatec HELOS (H0893) RODOS: cement 08/25/13 / 10:09:49

feeder:	VIBRI		Measuring conditions:	for all samples
pressure:	3.50	bar	measuring range:	R4: 0.5/1.8...350µm
vacuum:	100.00	mbar	measuring duration:	2.88 s
feed rate:	75.00	%	cycle time:	100 ms
funnel gap:	1.30	mm	start when:	2.00% at C.Opt
revolution:	0.00	%	reference measurement:	00:08:41 , 0.00 %
			evaluation:	HRLD (V 3.3 Rel.1)

operator : THANAPALAN
identifier : SHIPPING CEMENT TYPE I
Comments:

HELOS/DOS file name :



Volume Size Distribution

x0/µm	Q3/%	x0/µm	Q3/%	x0/µm	Q3/%	x0/µm	Q3/%
1.80	3.14	7.40	17.59	30.00	66.28	122.00	100.00
2.20	4.18	8.60	20.42	36.00	75.55	146.00	100.00
2.60	5.23	10.00	23.64	42.00	82.71	174.00	100.00
3.00	6.30	12.00	28.19	50.00	89.39	206.00	100.00
3.60	7.91	15.00	35.07	60.00	94.38	246.00	100.00
4.40	10.34	18.00	41.89	72.00	97.43	294.00	100.00
5.20	12.12	21.00	48.28	86.00	99.35	350.00	100.00
6.20	14.64	25.00	56.95	102.00	100.00		

x10 =	4.39 µm	x50 =	21.66 µm	x90 =	51.22 µm
x16 =	6.75 µm	x84 =	43.35 µm	x99 =	85.56 µm
VMD =	25.4 µm	Sv =	0.416 m2/cm3	c_opt =	14.23 %

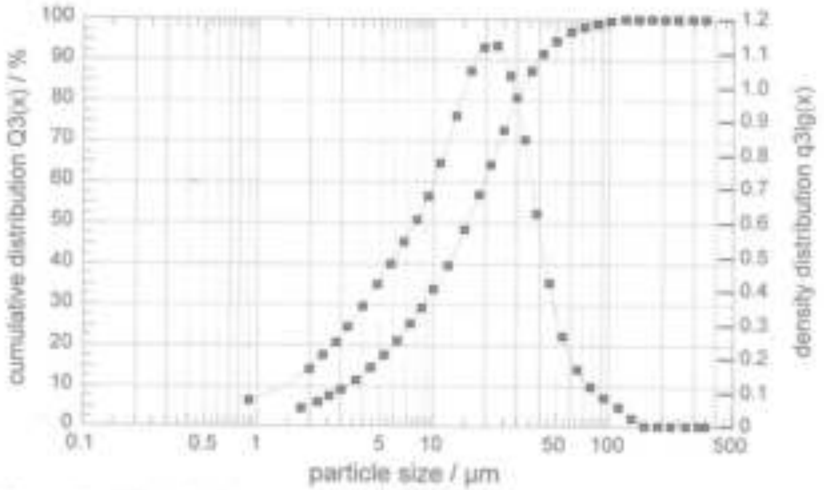
CHEMIST/CHIEF CHEMIST

GULF CEMENT COMPANY
Particle Size Analysis

Sympatec HELOS (H0893) RODOS: GGBS 09/25/13 / 09:46:04

feeder:	VIBRI		Measuring conditions:	for all samples
pressure:	3.00	bar	measuring range:	R4: 0.5/1.8...350µm
vacuum:	100.00	mbar	measuring duration:	4.67 s
feed rate:	75.00	%	cycle time:	100 ms
funnel gap:	1.50	mm	start when:	2.000 at C.opt
revolution:	0.00	%	reference measurement:	00:00:32 , 0.00 %
			evaluation:	HRLD (V 3.3 Rel.1)
			HELOS/VDE file name :	

operator : THANAPALAN
identifier : SHIPPING GGBS
Comments: W 37



Volume Size Distribution

x0/µm	Q3/%	x0/µm	Q3/%	x0/µm	Q3/%	x0/µm	Q3/%
1.80	4.22	7.40	24.85	30.00	80.57	122.00	99.83
2.20	5.66	8.60	28.81	36.00	87.23	146.00	100.00
2.60	7.17	10.00	33.24	42.00	91.39	174.00	100.00
3.00	8.69	12.00	39.34	50.00	94.56	206.00	100.00
3.60	11.00	15.00	48.18	60.00	96.62	246.00	100.00
4.40	14.06	18.00	56.47	72.00	97.80	294.00	100.00
5.20	17.06	21.00	63.94	86.00	98.90	350.00	100.00
6.20	21.70	25.00	72.42	102.00	99.41		

x10 =	3.31 µm	x50 =	15.86 µm	x90 =	40.33 µm
x16 =	4.92 µm	x84 =	33.09 µm	x99 =	91.34 µm
VMD =	18.8 µm	Sv =	0.783 m2/cm3	c_opt =	32.82 %

CHEMIST/CHIEF CHEMIST

Appendix F: Using EMMA for Packing Concrete Particles

I. EMMA mix analyzer application interface is shown in Figure 91.

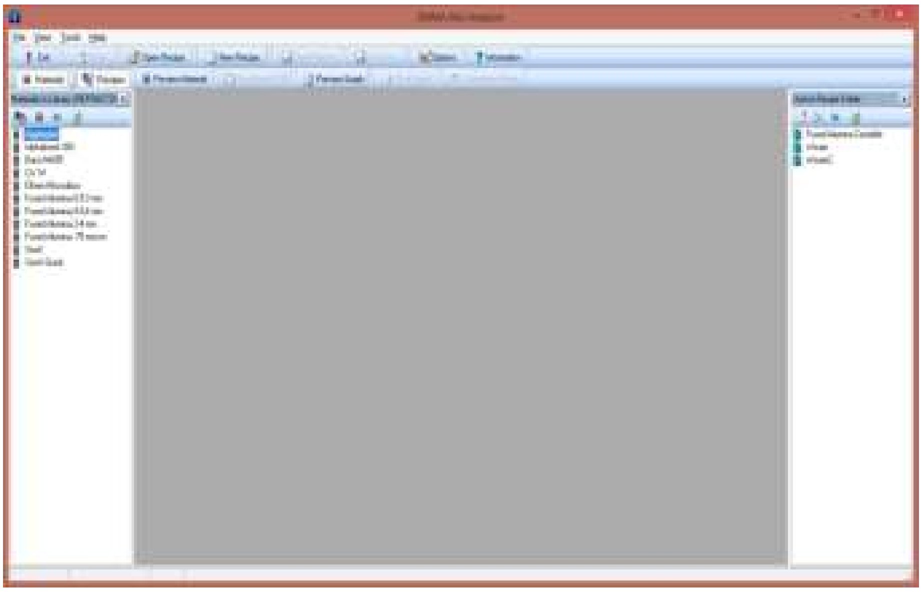


Figure 91: EMMA Mix Analyzer User Interface

II. Material library was created to save a database for all materials used. This database was used for different mixes as shown in Figure 92 to Figure 95.

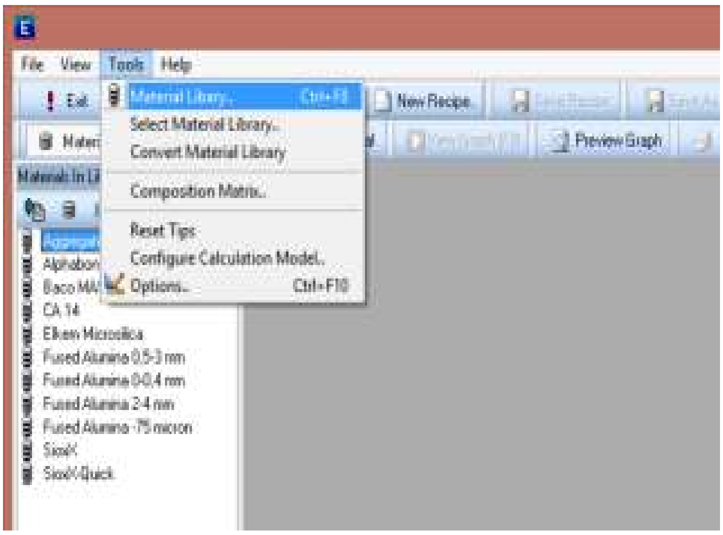


Figure 92: Reaching Material Library

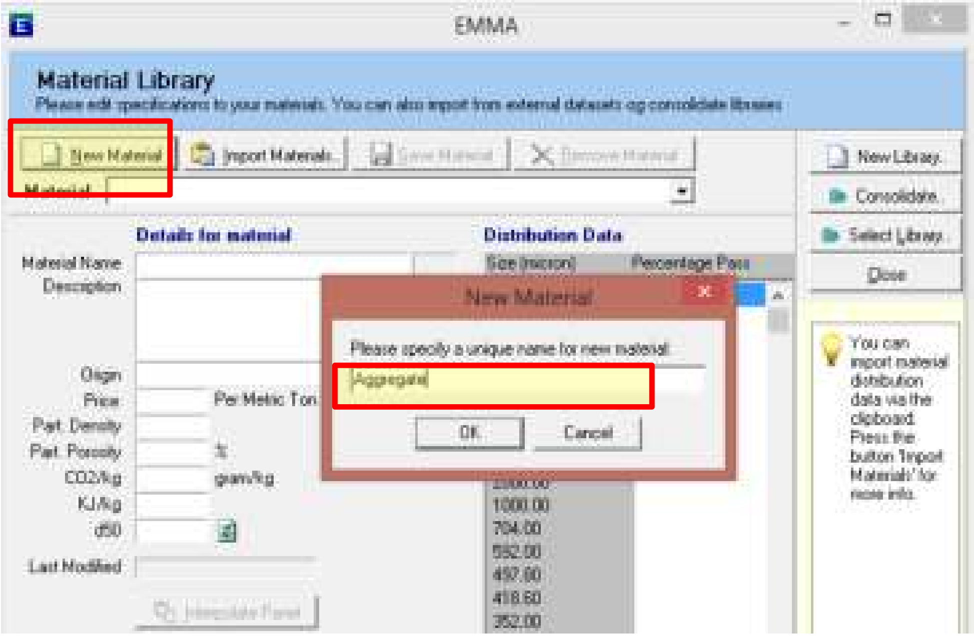


Figure 93: Material Library

III. The program was fed with particles size distribution, density and some description as highlighted in Figure 94.

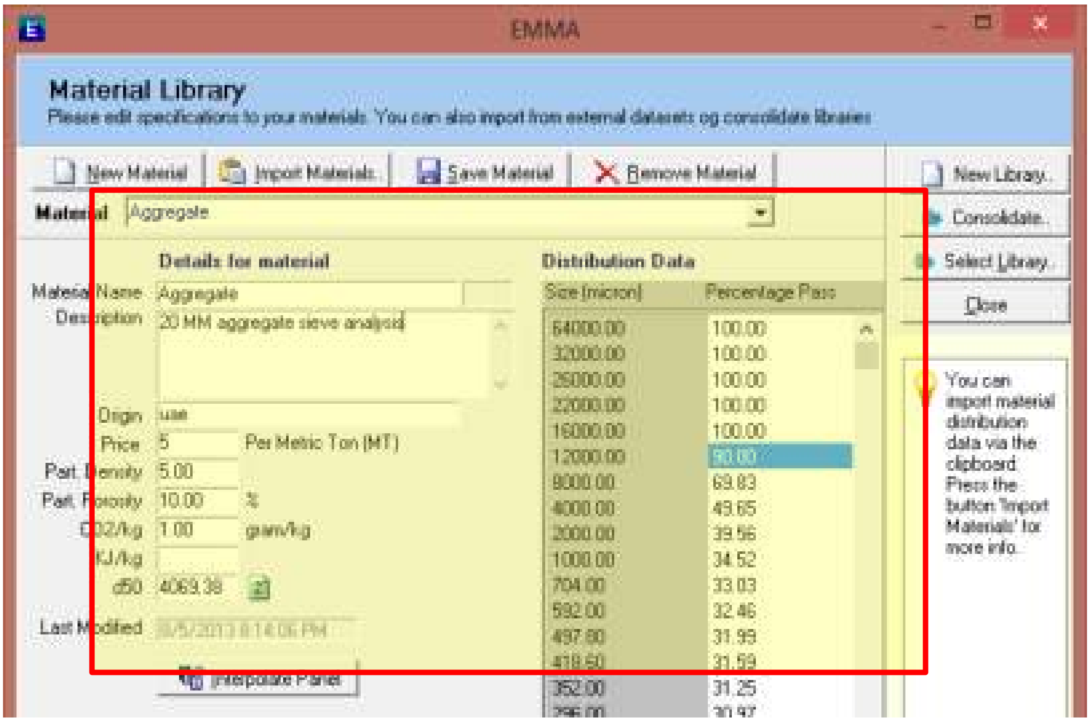


Figure 94: Input of New Material

IV. After entering the information for each material, a list of concrete ingredients was constructed in EMMA as shown in Figure 95. Materials were added by repeating steps I to III till all materials were added.

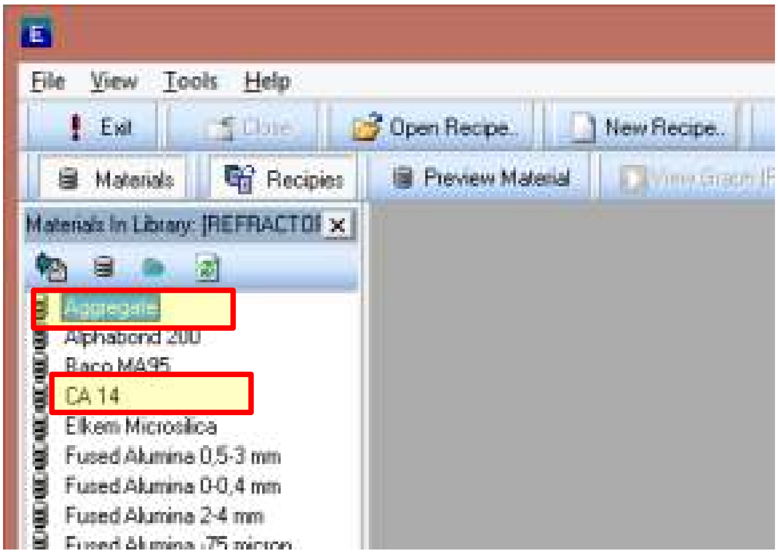


Figure 95: New Material Has Been Added to the Library

V. After adding all the required materials to the library, a recipe for the new mix was opened as shown in Figure 96.

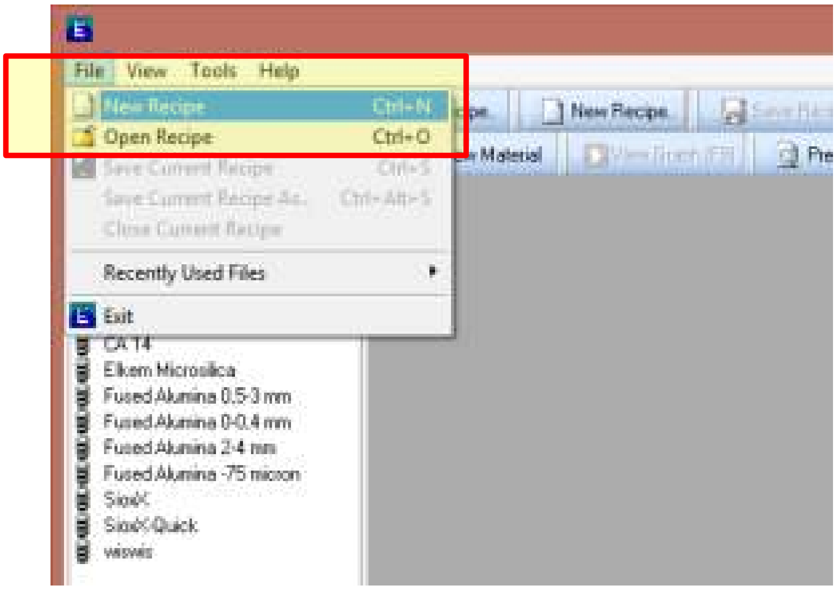


Figure 96: Adding New Recipe

VI. Creating recipes for new mix designs

A recipe of each new mix design was completed by adjusting the quantities of each material in the mix using trial and error method to reach the best match between materials PSD and Andreassen model, as shown in Figure 97.

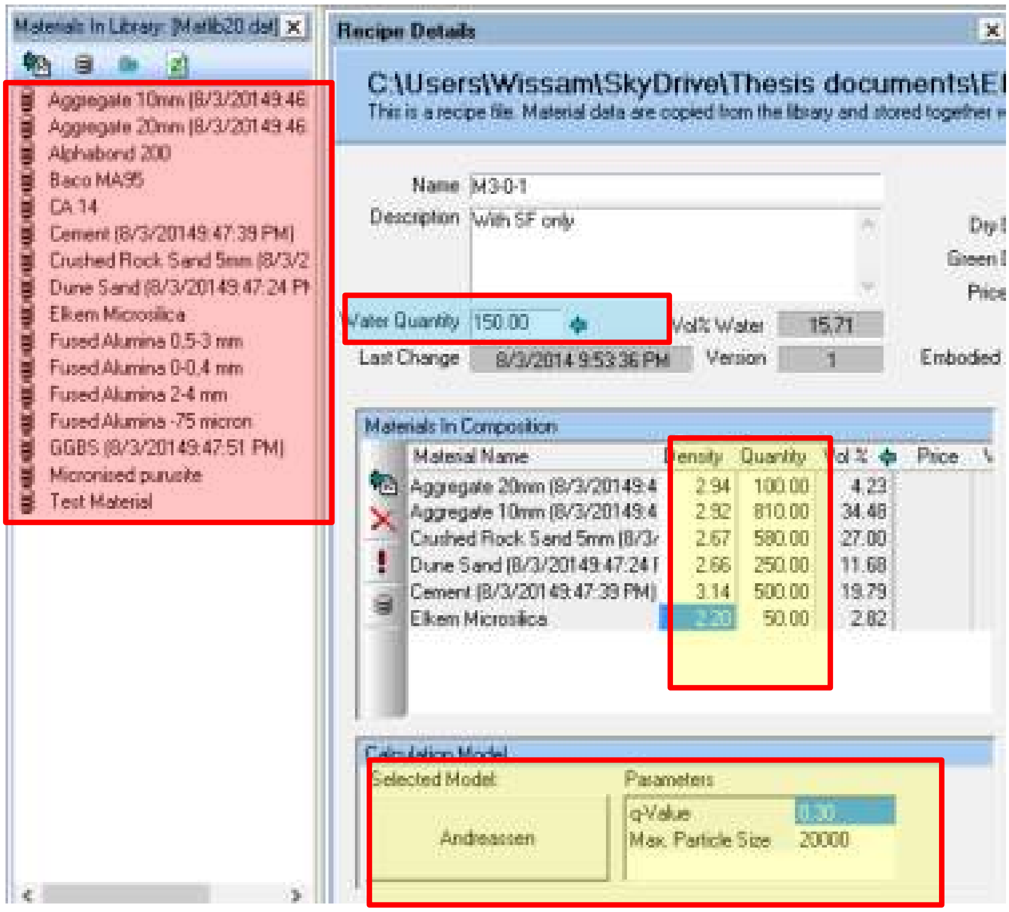


Figure 97: Green Mix Design Inputs in EMMA

The materials quantities were changed in loop until best match between recipe model and Andreassen model was obtained as shown in Figure 16 and Figure 17.

Vita

Wisam Abdulkatib was born on May 10, 1987, in Baghdad, Iraq. His family moved to the United Arab Emirates in 1997. He was educated in private school in Sharjah and graduated in 2005. After that, he studied civil engineering at University of Sharjah for 4 years and graduated with a Bachelor of Science degree in 2009.

Mr. Abdulkatib joined the construction industry in 2009 by working with a construction contractor of buildings and villas in Dubai for 2 years. In 2012, he moved to Petrofac Int Ltd, one of the biggest EPC companies for oil and gas projects. In the same year, he began a Master's program in Civil Engineering at the American University of Sharjah.

Since that time, Mr. Abdulkatib has published 2 papers in international conferences regarding sustainable concrete mix design.