DEVELOPMENT AND EVALUATION OF NANO-SILICA SUSTAINABLE CONCRETE

by

Habib Hassan Abdulla Alqamish

A Thesis presented to the Faculty of the
American University of Sharjah
College of Engineering
In Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in
Civil Engineering

Sharjah, United Arab Emirates

May 2017

Approval Signatures

We, the undersigned, approve the Master's Thesis of Habib Hassan Abdulla Alqamish.

Thesis Title: Development and Evaluation of Nano-silica Sustainable Concrete.

Signature	**Date of Signature** (dd/mm/yyyy)

___________________________ ______________

Dr. Adil Tamimi
Professor, Department of Civil Engineering

Thesis Advisor

___________________________ ______________

Dr. Kazi Parvez Fattah
Assistant Professor, Department of Civil Engineering
Thesis Committee Member

___________________________ ______________

Dr. Hussain Hameed Ahmed
Associate Professor, Department of Chemical Engineering
Thesis Committee Member

___________________________ ______________

Dr. Robert John Houghtalen
Head, Department of Civil Engineering

___________________________ ______________

Dr. Mohamed Guma El-Tarhuni
Associate Dean for Graduate Affairs and Research, College of Engineering

___________________________ ______________

Dr. Richard Schoephoerster
Dean, College of Engineering

___________________________ ______________

Dr. Khaled Assaleh
Interim Vice Provost for Research and Graduate Studies

Acknowledgment

First of all, I would like to thank Almighty Allah for blessing me with the resources, the health, the knowledge, and the ability to complete this thesis.

I would also like to extend my heartiest thanks with a deep sense of gratitude to Dr. Adil Tamimi who is not only an advisor but also a mentor and a father figure. His unlimited support, guidance, encouragement, patience, understanding, and insightful vision played a huge role in helping me writing my thesis.

I am also thankful for Conmix batching plant, especially Mr. Vishal Sharma, Mr. Manas Singh, and Mr. Mohammed Mobain for allowing me to use conmix's lab and helping me in the processes of mixing, casting, curing, and performing numerous tests.

My deepest thanks also go to the American University of Sharjah for providing the facilities that enable the students to conduct such a study. Also, my thanks go to Mr. Ansari and Mr. Thomas Job who helped me performing many tests in the university.

Last but not the least, I would like to mention that I am deeply grateful for each and every one who has been associated with my thesis at any stage but their names didn't find a place in this acknowledgment.

Dedication

To My Mother

I wouldn't be half the person I am today without your sacrifices, struggle, and love.

I owe you everything.

Abstract

The concrete industry is one of the main contributors in the emission of carbon dioxide. Yet, it is the most used man-made material. In the past few decades, different pozzolanic materials were used as a partial replacement of Portland cement. These materials played a major role in reducing the carbon footprint associated with the production of Portland concrete. Furthermore, they greatly improved the concrete's strength and durability. However, these materials are also responsible of causing significant shortcomings to the concrete such as the slow rate of strength development. In the last decade, the nanomaterials made a major breakthrough in the concrete industry in terms of reinforcing the concrete with unique properties. In this study, 1% and 2% dosages of nano-silica were added to concrete mixtures that contain 30% and 70% ground granulated blast-furnace slag (GGBS) dosages. Adding 1% of nano-silica to the 30% GGBS concrete mixture showed an increase in the compressive strength by 13.5%, 7.8%, 8.1%, and 2.2% at 1-day, 3-day, 7-day, and 28-day, respectively. The 2% of nano-silica increased the 30% GGBS concrete mixture's compressive strength less effectively by 4.3%, 7.6%, and 4.9% at 3-day, 7-day, and 28-day, respectively, when compared to the 1% dosage. On the other hand, adding 1% and 2% of nano-silica reduced the 70% GGBS concrete mixtures' compressive strength. Moreover, nano-silica reduced the deformability of the mixtures significantly which caused the increase in the Young's modulus. The flexural strength of the 30% GGBS concrete mixtures had similar behavior as the 28-day compressive strength. On the other hand, the flexural strength of the 70% GGBS concrete mixtures increased as the nano-silica's dosage increased. Nano-silica addition improved the microstructure and the interface structure of the mixtures due to its high pozzolanic activity and the nano-filler effect which is confirmed by the rapid chloride permeability test's (RCPT) results, and the scanning electron microscopy (SEM) images. Life-365 service life modeling showed that the 1% and 2% dosages of nano-silica extended the service life of the 30% GGBS concrete mixtures by 2.5 and 4.9 years and the 70% GGBS concrete mixtures by 11.2 and 24.7 years, respectively.

Key words: Sustainable concrete, Nano-silica, Durability, SEM, Embodied energy, Service life.

Table of Contents

List of Figures

List of Tables

List of Abbreviation

NS	Nano-silica
NP	Nano-particles
OPC	Ordinary Portland cement
GGBS	Ground granulated blast-furnace slag
RCPT	Rapid chloride permeability test
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
SF	Silica fume
BET	Brunauer–Emmett–Teller
UHPC	Ultra-high performance concrete
HPC	High performance concrete
LPR	Linear polarization resistance
SCC	Self consolidating concrete
CNAC	Commercial natural aggregate concrete
ORAC	Original recycled aggregate concrete
MRAC	Modified recycled aggregate concrete
CH	Calcium hydroxide
C-S-H	Calcium-Silicate-Hydrate
ITZ	Interfacial transition zone

Chapter 1: Introduction

1.1. Background

The rapid rate of growth of the world's population along with the enormous structural development movement, have led to high consumption of natural resources. Consequently, some of these natural resources or the non-renewable resources have depleted and the rest are being consumed extensively on daily basis. Moreover, the humankind's negative practices over the years has deteriorated the eco-system which caused a serious negative impact on the planet. For instance, climate change, ozone depletion, and loss of biodiversity. Therefore, a solution that meets the needs of this generation without compromising the ability of the future generations of meeting their needs, should take place. From this concept, the idea of sustainability or sustainable buildings came to life. The conventional construction methods and materials have undeniable issues that affect the planet in numerous ways, such as emitting carbon dioxide and consuming heavily two of the most important resources which are the water and the electricity. Sustainable construction methods and materials have various benefits such as consuming the natural resources efficiently, improving the delivery of public services, promoting health and well-being, creating a durable structure, organizing the building's waste, and promoting the concept of reduce, reuse and recycle.

Despite the fact that concrete industry is one of the largest contributor in emitting carbon dioxide, till this day, it is the most widely used construction material worldwide [1]. Ordinary Portland Cement (OPC) is the main ingredient in concrete [1]. However, the use of cement in concrete has raised concerns of its sustainability, given the fact that the production of one [ton] of OPC releases approximately one [ton] of carbon dioxide to the atmosphere [1]. In the past few decades, the scientists along with the engineers were able to partially replace the cement with supplementary cementitious materials, in order to reduce the extensive emission of CO_2 associated with the production of Portland cement, and create more sustainable concrete. The supplementary cementitious materials are byproducts of other industries, such as fly ash, ground granulated blast furnace slag, silica fume, and other natural pozzolans. Not only have these supplementary cementitious materials contributed in reducing the emission of CO_2, they also provided the concrete with high performance abilities in terms of strength and durability. However, different supplementary cementitious materials have some shortcomings. Therefore, there is continuous need to search for new supplementary cementitious materials to address these shortcomings.

The applications of nano-technology have been gaining popularity in different fields of science and technology, especially in concrete industries [2]. The development of new materials with new functions or improvements in the properties of existing materials using nano-technology are new areas of interest in civil engineering [2]. Nano-particles (NP) exhibits unique chemical and physical properties at the nano-scale. SiO_2, TiO_2, Al_2O_3, Fe_2O_3, ZnO_2, and carbon nano-tubes are considered the most commonly used nano-particles (NP) in the concrete production. The role of the NPs can be summarized as follows: (i) NPs not only act as fillers to improve the microstructure, but also as an activator to promote pozzolanic reactions, (ii) act as a nucleation site for C-S-H seeds which then accelerate the cement hydration, (iii) NPs (NS) accelerated the consumption of C_3S and the formation of portlandite (small sized CH) crystals and homogeneous clusters of CSH composition, and (iv) NPs improve the microstructure of the interfacial transition zone between aggregates and cement pastes [3].

Therefore, this research is mainly focused on evaluating the fresh and mechanical properties of concrete incorporating silica nanoparticles. Furthermore, it is also focused on studying the morphological characteristics of nano-silica concrete. The service life of the nano-silica concrete will be determined using Life-365 service life prediction model. Finally, the embodied energy associated with the production of nano-silica concrete will be reduced.

1.2. Research Significance

Partially replacing the Portland cement with eco-friendly cementitious materials has become mandatory by law in many countries around the world. For example, Dubai municipality has enforced the use of green concrete in the city of Dubai on the 1st of April 2015. The enforcement of this law contribute in protecting the environment and reducing the emission of the toxic gasses associated with the production of Portland cement. Therefore, researching and investigating for cementitious materials that have great market potential, economic impact, and capable of producing sustainable concrete, with unique properties in terms of durability and strength, has become a necessity.

Nano-silica is a pozzolanic material that can also be considered as a property enhancer due to its ability in providing very unique properties at the nano-scale to the concrete. Compared to other nano-particles, nano-silica has a unique advantage in the potential pozzolanic reaction with cement hydration products [4]. Due to its ultra-fine particles size, nano-silica can possess a distinct pozzolanic reaction at a very early age [4]. Hence, it promotes the hydration of cement with other cementitious materials such as fly ash, GGBS and silica-fume. Moreover, incorporating nano-silica improves the mechanical properties of concrete due to the pozzolanic reaction and the nano-filler effect.

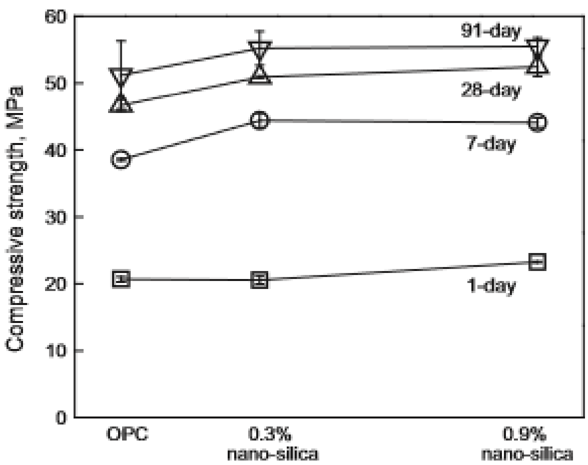


Figure 1. Compressive strength of concrete with nano-silica [4].

Figure 1 illustrates that the compressive strength of the mixtures that incorporate 0.3% nano-silica and 0.9% nano-silica is greater than OPC at 1, 7, 28, and 91 days. Thus, the increase in the compressive strength allows reduction in the structural members' sizes which in consequence reduces the required amounts of concrete's ingredients and therefore reduces the carbon footprint. Also due to the pozzolanic and the nano-filler effect, the nano-silica concrete's microstructure is more homogeneous and less porous. Consequently, this reduces the ingress rate of water and chloride ions. Furthermore, a small dosage of nano-silica is capable of controlling the slow rate of strength development that occurs due to incorporating some cementitious material such as fly ash class F. Therefore, it allows the construction companies to use green concrete without slowing down the construction process which might cause a late submission of the projects and consequently losing money. Avoiding this major issue facilities enforcing the use of green concrete which will have great reflects on the environment and the quality of construction. Moreover, A.M. Said [5] highlighted that nano-silica reduces the total porosity and the threshold pore diameter of the concrete as illustrated by numbers in Table 1.

Table 1. Mercury intrusion porosimetry (MIP) test results [5].

Mixture	Apparent total porosity (%)	Threshold pore diameter (µm)	Percentage of small pores (<0.1 µm) (%)
A-0	10.13	0.10	69.31
A-1	6.91	0.075	75.39
A-2	6.44	0.060	72.16
B-0	12.56	0.144	73.41
B-1	9.30	0.092	79.69
B-2	8.21	0.075	77.34

The mixtures that contain dosages of nano-silica, showed a lower total porosity and threshold pore diameter than the control mixture.

In conclusion, using nano-silica in small dosages has a major influence on the strength and durability of the concrete. Consequently, it makes the concrete more sustainable. Moreover, it ensures that incorporating other cementitious materials will not delay the rate of strength development of the concrete which has a great impact on the construction industry. Finally, with the optimum dosage of nano-silica incorporated in the production of normal and green concrete, nano-silica can have great market and economical potential.

1.3. Research Objectives

It is anticipated that this research will lead to the following outcomes:

- Develop nano-silica sustainable concrete mixtures.
- Evaluate the fresh concrete properties of nano-silica concrete.
- Evaluate the mechanical properties of nano-silica concrete.
- Study the morphological characteristics of nano-silica concrete.
- Model the service life of nano-silica concrete using Life-365 software
- Evaluate the embodied energy associated with the production of nano-silica sustainable concrete.

1.4. Literature Review

An extensive research has been recently focused on the influence of the nano-silica on the properties of OPC concrete and high performance concrete. Hongjian Du et al. [4] studied the durability properties of OPC concrete that contains nano-silica at dosages of 0.3% and 0.9%. Three different mix designs were prepared to be tested in this experiment, which are OPC concrete, 0.3 nano-silica concrete, and 0.9 nano- silica concrete. Compressive strength of each mix design was determined at 7, 28, and 91 days by preparing three (100x200mm) cylinders for each day. While, the water penetration depth was obtained by testing two (100x200mm) cylinders at a water pressure of 0.75 MPa for 7 days. On the other hand, water sorptivity was determined by using (100x500) cylindrical slices. Along with the other tests used in this experiment, the researchers were able to come up with multiple conclusions. First, nano-silica showed a clear pozzolanic reaction with the Portland cement. This reaction along with the nano filler effect of nano-silica, made the microstructure of the concrete more homogenous and less porous. Consequently, the permeability was reduced which increased the compressive strength and the resistance of the concrete against water penetration and chemical attacks such as chloride ions.

Ye Qing et al. [6] studied the influence of nano-silica on the properties of hardened cement paste compared to the influence of silica fume. Eight different mix designs using nano-silica (NS) and silica-fume (SF) were prepared and tested. The tests used in this experiment were consistency, setting time of fresh pastes, compressive strength, bond strength of cement paste-aggregate interface, and microstructure analysis by using cement paste-aggregate interface specimen. Multiple results were obtained in this experiment. First, nano-silica thickened the cement paste accelerated the hydration process. Second, the compressive strength is directly proportional to the NS dosage, especially at early age. While at early age, the compressive strength decreases slightly with increasing the dosage of silica fume; it increases at later ages. The bond strength of cement paste- aggregate interface is directly proportional to the NS dosage more than SF dosage. In addition, nano-silica has a higher pozzolanic activity than silica fume by a large margin. It is concluded that NS is more effective in improving the interface structure compared to SF.

D. Adak et al. [7] conducted a study about the effect of nano-silica on strength and durability of fly ash based geopolymer mortar. Fly ash based geopolymer mortar has a shortcoming which is the need for heat activator in order to develop early strength. To overcome this shortcoming, the researchers developed an experiment of using low calcium fly ash geopolymer having different molar concentrations of activator liquid and different nano-silica percentage dosages. The addition of 6% of nano-silica to the fly ash based geopolymer mortar showed an obvious increase in compressive, flexural, and tensile strength at 28 days under ambient temperature curing. Furthermore, the same percentage of nano-silica reduced the water absorption. The modification that took place in the geopolymer with 6% of nano-silica is due to transformation of amorphous compound to crystalline compound.

A.M. Said et al. [5] carried out an investigation of the properties of concrete incorporating nano-silica. Two types of concrete were investigated in this experiment which are concrete with ordinary cement and concrete with ordinary cement plus class F fly ash. In order to link macro and micro scale trends and study the effect of using nano-silica, the research included tests of adiabatic temperature, rapid chloride ion permeability, mercury intrusion porosimetry, thermogravimetry and backscattered scanning electron microscopy. Based on the tests results, multiple conclusions were reached. Both types of concrete used in this experiment showed a remarkable improvement in performance due to the addition of nano-silica. The nano- silica was responsible for accelerating the kinetics of hydration reactions. The addition of nano-silica showed a modification to the inherently slower rate of gaining strength of concrete that contains class F fly ash. The physical penetration depth was decreased which consequently decreased the conductivity. The specimens showed a significant reduction in porosity and threshold pore diameter.

Morteza Bastami et al. [8] studied the performance of nano-silica modified high strength concrete at elevated temperatures. The main focus of this experiment is on the effect of elevated temperature on the compressive strength, tensile strength, spalling, and mass loss of high strength concrete modified with nano-silica. Six samples with different percentage dosages of nano-silica were considered in this experiment along with two samples without nano-silica. The performance of the nano-silica modified high strength concrete was measured by using (150x100mm) cylinders that were heated to 400,600, and 800^{o} C at a rate of 20^{o} C/min. In general, the results of this experiment demonstrate that the mass loss is decreased as the dosage of nano-silica is increased and that is due to the improvement in tensile strength which helped in preventing spalling.

Moreover, the nano-silica also increased the residual compressive strength of the heated specimens.

Kiachehr Behfarnia et al. [9] investigated the effect of nano-silica and nano-alumina on frost resistance and the mechanical properties of normal concrete. Seven different mixtures were used in this experiment. NSC3, NSC5 and NSC7 denote the concrete containing 3 wt%, 5 wt% and 7 wt% nanosilica, by the weight of cement, respectively [9]. NAC1, NAC2, NAC3 denote the concrete containing 1 wt%, 2 wt% and 3 wt% nano-alumina, by the weight of cement, respectively [9]. The specimens were subjected to numerous tests. The compressive strength was determined at 7, 28 and 120 days. The percentage of water absorption was obtained after 28 days of moisture curing. Furthermore, the seven mixtures were subjected to cycles of freezing and thawing. The loss of mass, change in length, increase in water absorption and reduction in compressive strength of specimens was measured after specified number of freeze and thaw cycles [9]. The experiment results demonstrate that the addition of nano-particles increased the compressive strength whether they were nano-silica or nano-alumina. However, the nano-silica addition showed a remarkable increase in the compressive strength compared to the addition of nano-alumina. For example, at 28 days, NSC5 mixture showed an increase of (31.13%) in the compressive strength, while, NAC3 mixture showed an increase of (8.00%) in the compressive strength. Moreover, the mixtures that incorporates nano-particles showed a remarkable decrease in the water absorption compared to the control specimen due to the nano-filler effect which improved the pore structure of the concrete. The experimental results also showed that the addition of nano-particles improved the frost resistance considerably. However, the frost resistance of concrete that incorporates nano-alumina was better than the concrete that incorporates the same amount of nano-silica.

Min-Hong Zhang et al. [10] conducted a study about the effect of nano-silica in increasing the early strength and reducing the setting time of concrete with high volume of slag. Two types of nano-silica were used in this experiment. Type 1 nano-silica consists of (>99.8%) silicon dioxide, (200.1m^2/g) surface area, (12nm) average primary particle size, and (2.2) specific gravity. Type 2 nano-silica consists of (>99.8%) silicon dioxide, (321.6m^2/g) BET surface area, (7nm) average primary particle size, and (2.2) specific gravity. Eight different mortar mixtures were tested in this study. All the mixtures had a constant water to binder ratio of 0.45 and a constant sand to binder ratio of 2.75. Dosages of the Type 1 NS varied from 0 to 0.5%, 1.0% and 2.0% by mass of the cementitious materials [10]. Mortars with 1% Type 1 or Type 2 NS were compared with that with the same amount of silica fume to evaluate the effect of specific surface area and particle size of silica [10]. Furthermore, the influence of nano-silica on the concrete properties were compared to the influence of silica fume. Multiple conclusions were obtained from this study. The addition of nano-silica accelerated the rate of cement and slag hydration and shortened the length of dormant period. The compressive strength of the slag mortars was directly proportional to the nano-silica dosage at various ages up to 91 days. Moreover, the strength of the slag mortars was inversely proportional to the particle size of nano-silica inclusions at early age. The incorporation of 2% NS by mass of cementitious materials reduced initial and final setting time by 95 and 105 min, and increased 3- and 7-day compressive strengths of high-volume slag concrete by 22% and 18%, respectively, in comparison to the reference concrete with 50% slag [10]. Furthermore, as the dosage of nano-silica increased, the large capillary porosity was decreased. However, the medium capillary porosity was increased in the slag cement pastes at 28 days with the increase of nano-silica dosage. The 2% nano-silica dosage by mass of cementitious materials densified the paste-aggregate interface. Finally, both types of nano-silica were more effective in accelerating the hydration process compared to silica fume. The NS reduced the setting times and increased early strengths of the high-volume slag concrete [10]. In comparison, the silica fume almost had no influence on the setting time and early strength of the high-volume slag concrete.

S. Abd.El.Aleem et al. [3] carried out an experiment studying the hydration characteristic, thermal expansion, and microstructure of cement containing nano-silica. Seven different mixtures were used in this experiment that incorporate nano-silica at different dosages up to 6% partial replacement of OPC. The presence of nano-silica has remarkably increased the water demand which in consequence retarded the setting time. This seems to be controlled by the particle size distribution and the high specific surface area of NS in the presence of polycarboxylate superplasticizer [3]. Furthermore, the values of pH and free portlandite decrease as the dosage of nano-silica increases. Due to the pozzolanic reaction of nano-silica, the chemically combined water contents increased with increasing nano-silica percentage dosage. The microstructure and consequently the mechanical properties of the investigated cement mortars are improved sharply with NS up to 3.0% and then slightly up to 5% [3]. Also, using nano-silica as a partial replacement of Portland cement lowered the coefficient of thermal expansion of the hardened cement paste. Moreover, due to the continuous hydration of cement phases and the pozzolanic reaction of nano-silica, the thermal expansion of hydrated cement pastes incorporating 3% nano-silica dosage increased with curing time. The nano-sized SiO_2 up to 5% proved to be an effective mineral addition for blending with OPC to improve its chemical, physico-mechanical and thermal properties [3]. Finally, incorporating nano-silica increased the compressive strength because of the nano-filler effect which improves the microstructure and promoting the highly pozzolanic reaction.

Al-Rifaie et al. [11] investigated the mechanical properties of nano-cement mortar. The mixtures tested in this study are as follows: group (A) which consists of 0.4 w/c ratio, group (B) which consists of 10% nano-silica, 1.4% naphthalene sulphonate and 0.34 w/c ratio, group (C) which consists of 18% nano-clay, 1.4% naphthalene sulphonate and 0.34 w/c ratio, and group (D) which consists of 18% nano-clay, 10% nano-silica, 1.4% naphthalene sulphonate and 0.34 w/c ratio. The compressive strength values after 28 curing days of each group are shown in Table 2.

Table 2. The compressive strength of the developed nano cement mortar at age of 28 curing days [11].

Sand: cement ratio	Compressive strength, MPa (Each value is the average of six cubes)			
	Group A	Group B	Group C	Group D
1	50.47	65.688	84.325	99.33
1.5	57.43	72.598	92.5983	106.535
2	48.84	63.453	86.471	104.39
2.5	39.86	59.408	79.392	93.42
3	33.04	53.5283	75.415	89.39

The highest compressive strength results are achieved by the specimens that have 1.5 sand/cement ratio. It is seen that the developed nano cement mortar of group (D) can achieve more than 15% of its final compressive strength in one day and more than 60% in fourteen days of the final strength considered to be achieved in 120 days [11]. It seen that the developed nano mortar of group D can achieve more than 40% of compressive strength in one day in comparison with nano cement mortar with mortar matrix group A and the compressive strength in 3 days is more than 60% of the compressive strength of group A with 28 curing days and the compressive strength in 7 days is greater than the compressive strength of group A with 28 curing days [11]. Furthermore, three point bending test was performed on sixty prisms in order to obtain the flexural strength of the specimens of group (A, B, C, and D) after 28 days of curing. The highest flexural strength results are achieved by the specimens that have 1.5 sand/cement ratio as shown in Table 3. All in all, the cement mortars incorporating nano-particles showed a better mechanical performance compared to the plain cement mortar [11].

Table 3. The flexural strength of each group after 28 curing days [11].

Sand: cement ratio	Flexural strength, MPa			
	Group A	Group B	Group C	Group D
1	14.18	11.21	10.5	5.2
1.5	20.11	18.74	13.62	11.44
2	15.39	15.68	11.93	8.96
2.5	15	13.84	9.53	8.36
3	14.91	13.03	9.33	8.55

M. Berra et al. [12] conducted a study about the effects of nano-silica addition on workability of Portland cement pastes. The nano-silica slurry used in this experiment consists of 10.2 PH, 30 silica content (wt. %), 0.56 titrable alkalis (wt. % as Na_2O), 1.22 Density (g/cm^3), 5.5 viscosity (mPa s), 10 mean particle size (nm), 345 specific surface area (m^2/g). The workability of fourteen mixtures with different water/binder ratio and nano-silica concentrations in the liquid phase were evaluated using mini-slump tests. The addition of nanosilica to cementitious mixes produces a remarkable reduction of the mix workability, due to instantaneous interactions between the nanosilica sol and the liquid phase of the cementitious mixes (mainly dissolved alkalis), with formation of gels characterized by high water retention capacities [12]. The delayed addition of mixing water aliquots proves to be an effective way of reducing the adverse effect of nanosilica on mix workability, without changing the water/binder ratio and/or adding superplasticizer [12]. However, the delayed water addition didn't improve the workability of the Portland cement mixes. Moreover, due to the reduction of the nanosilica reactivity caused by the instantaneous interaction between superplasticizer and nanosilica, the immediate superplasticizer addition is considered to be useless in improving the workability of the mixtures. On the contrary, a delayed addition of the superplasticizer, coupled with the use of an appropriate mixer for the break down of the gels formed from nanosilica sol destabilization, proves to be the best procedure to uniformly disperse the mix ingredients, without significantly penalizing the nanosilica reactivity [12].

L.P. Singh et al. [13] investigated the beneficial role of nanosilica in cement based materials as illustrated in Figure 2.

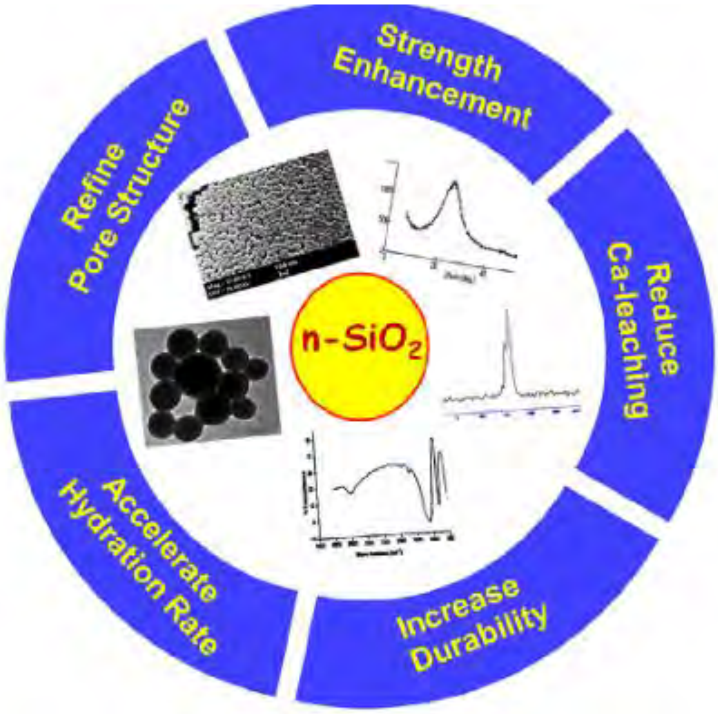


Figure 2. Role of nano-silica in cementitious system [13].

Nanosilica in concrete acts as nucleation site to accelerate the hydration of cement and also filling the pores to give higher packing density which leads to higher strength with lesser porosity [13].The development of nano-silica based high performance concrete will help in decreasing the consumption of cement for specific grade which will help in protecting the environment to a great extent. Furthermore, due to the high compressive strength, the nano-silica based high performance concrete will produce smaller structural members which will reduce the total amount of materials placed and consequently reduce the overall cost of the structure. Moreover, the high early strength development of nano-silica based high performance concrete will accelerate the construction process which will save time, money and materials. Finally, the long service life of the nano-silica based high performance concrete will reduce the maintenance costs to a great extent.

Sattawat Haruehansapong et al. [14] studied the effect of the particle size of nano-silica on the compressive strength and the optimum replacement content of cement mortar containing nano-silica. Three different particle sizes of nano-silica (12, 20, and 40nm) were used in this experiment. Two groups of mixtures were tested in which the first group incorporates different dosages of silica-fume and it consists of four mixtures, and the second group incorporates different dosages of nano-silica and it consists of four mixtures. Compared to the silica-fume mixtures, the compressive strength of the nano-silica mixtures was greater due to the pozzolanic activity and the packing ability. The mixture that incorporated 40nm nano-silica showed the highest compressive strength compared to the mixtures with 12nm and 20nm nano-silica. One possible reason is poor dispersion and agglomeration of very small particle of 12 and 20 nm-SiO_2 [14]. The optimum replacement content of cement mortars with NS particle size of 12, 20 and 40 nm, as well as cement mortar with SF, is obtained with NS 9% by weight of cement, independent of NS particle size [14]. SEM photographs showed that the microstructure of the cement pastes were improved by the incorporation of nano-silica making the paste more compact, homogenous and denser.

Bibhuti Bhusan Mukharjee et al. [15] investigated the influence of nano-silica on the properties of recycled aggregate concrete. The properties of colloidal nano-silica used in this study are 1.12 specific gravity, 39% solid content, 8-20nm particle size, 99.1% SiO_2 content, and 10.11 pH value. Eight different mixtures were casted in which four of them contain natural coarse aggregate (NCA) and the other four contain recycled coarse aggregate (RCA). Multiple conclusion were obtained. As the percentage of nano-silica increases, the slump values decreases due to the high surface area of colloidal nano-silica which causes absorption of mixing water by the nano-particles. Furthermore, replacement of natural coarse aggregates with recycled coarse aggregates reduced the workability of concrete mixture due to the high water absorption capacity of RCA and further decreased in workability was observed due to the addition of NS to RAC mixes [15]. Moreover, the addition of nano-silica enhanced the compressive strength results at early days because of the nano-silica's high pozzolanic activity at initial periods. A decrease of 14% of compressive strength was observed when replacement of NCA was done with 100% RCA [15]. However, addition of NS enhanced the compressive strength of RAC and with incorporation of 3% NS the 28 days compressive strength equalized with control concrete [15]. Compared to the natural coarse aggregate mixes, the recycled coarse aggregate mixes had weaker tensile strength. However, the decrease in tensile strength caused by using recycled coarse aggregate can be compensated by incorporating nano-silica.

Ehsan Ghafari et al. [16] studied the influence of nano-silica addition on the durability of ultra-high performance concrete (UHPC). The properties of nano-silica (NS) used in this experiment are (160±20m^2/g) specific surface area, (<99.9%) purity, amorphous crystal phase, (15±5nm) diameter, (<0.15g/cm^3) density, and spherical morphology. Three different sets of mixtures were considered for this test, consisting of UHPC containing NS, UHPC without NS, and high performance concrete (HPC) [16]. Based on the obtained results, multiple conclusions were drawn. First, UHPC-NS presented the best corrosion resistance performance, being time to cracking effectively increased with the NS addition [16]. Second, incorporating nano-silica contributes in extending the service life of concrete structures by delaying corrosion in steel rebars. Corrosion rate measurements, based on LPR and Tafel techniques, point out that the UHPC specimens containing NS addition has the lowest corrosion rate (when compared with HPC and UHPC specimens) [16].

G. Quercia et al. [17] conducted a study about the self-consolidating concrete (SCC) modification by use of amorphous nano-silica. Three different SCC mixes were studied in the experiment in which the first mix doesn't contain nano-silica, the second mix contain colloidal nano-silica, and the third mix contain powder nano-silica. Under the laboratory conditions, the compressive and tensile splitting strength of the reference SCC was improved by the addition of both types of nano-silica [17]. The colloidal nano-silica SCC mix had higher compressive strength and lower splitting tensile strength compared to powder nano-silica SCC mix. All durability indicators of the SCC studied (conductivity, chloride migration and diffusion coefficients, and freeze-thaw resistance) were significantly improved with the addition of 3.8% of both types of the nano-silica [17]. Compared to the poweder nano-silica SCC mix, the colloidal nano-silica SCC mix showed slightly better performance in terms of durability properties.

Ramesh. N and Eramma. H [18] studied the behavior of ground granulated blast-furnace slag (GGBS) and nano-silica on strength properties of concrete. The properties of of nano-silica used in this experiment are 23.6 pH, (1.08-1.11) Specific gravity, and 219nm particle size. Eight different mixes were tested in which mixes (1, 2, 3, and 4) contain zero nano-silica and (0%, 10%, 20%, 30%) GGBS respectively, and mixes (5, 6, 7, and 8) contain (1%, 2%, 3%, 2%) nano-silica and (0%, 0%, 0%, 30%) GGBS respectively. Based on the test results, multiple conclusions were obtained. First, mix#8 (30%GGBS and 2% nano-silica) achieved the highest 7-day and 28-day compressive and split tensile strength results. Similarly, mix#8 had the highest flexural strength compared to the other mixes. Second, The SEM test shows that microstructure of nano SiO_2 concrete is more uniform and compact than the normal concrete [18]. Third, the silica nano-particles addition improved the pore structure of concrete.

D. V. Prasada Rao and U. Anil Kumar [19] conducted an experimental investigation on strength properties of concrete containing micro-silica and nano-silica. The properties of nano-silica used in this experiment are (39.5-41%) nano solids, (9-10) pH, (1.29-1.31) specific gravity, and milky white liquid texture. Seven different mixtures were tested in which the mixes contain (0, 19, 38, 19, 38, 19, 38) kg micro-silica and (0, 0, 0, 14.25, 14.25, 28.5, 28.5) Liter colloidal nano-silica, respectively. The addition of 1.5% nano-silica to the 5% and 10% micro-silica mixes had better mechanical properties compared to the addition of 3% nano-silica to the 5% and 10% micro-silica mixes. Overall, in terms of strength performance, the addition of 1.5% nano-silica and 10% micro-silica achieved the highest results compared to the other mixes.

Maitri Mapa et al. [20] investigated the mechanical properties of silica and GGBS incorporated cement mortar. The properties of nano-silica used in this experiment are 2.4 specific gravity, 2200kg/m^3 bulk density, 640m^2/g fineness, and white color. Eleven different mixes were tested consisting of different dosages of GGBS, densified silica fume and nano-silica. Numerous conclusions were obtained from this experiment. First, the initial and final setting times are directly proportional to the GGBS content. The increase in initial setting time of GGBS incorporated cement paste is higher than the increase of final setting time with respect to cement paste [20]. Therefore, the incorporation of GGBS retards the initial hydration of cement. Second, the compressive strength of silica added mortar mixes [have] shown good improvement in early [age's] compressive strength as compared with the GGBS cement mix [20].

Hongru Zhang et al. [21] studied the modification effects of a nano-silica slurry on microstructure strength, and strain development of recycled aggregate concrete applied in an enlarged structural test. Three concrete groups were prepared in this study, i.e., the commercial natural aggregate concrete (CNAC), the original recycled aggregate concrete (ORAC), and the modified recycled aggregate concrete (MRAC) [21]. For both ORAC and MRAC, the percentage replacement of recycled aggregate is 50%. The strengthening slurry prepared for this experiment contains 100kg cement, 50kg water, 1kg superplasticizer, and 1kg nano-silica dispersant. Multiple conclusions were obtained during this experiment. First, Mechanical properties of ORAC and MRAC, i.e., the compressive strength and the splitting strength, are inferior to those of CNAC, given the mixture proportions employed in this study, i.e., the dosage of water, cement, and aggregates are kept the same among the three concrete groups [21]. Second, at an early age (before 28 days), the resistance of CNAC to shrinkage caused by deformation in the target beam is found to be inferior to ORAC and MRAC. However, after 90 days, CNAC has shown long-term superiority to ORAC and MRAC, in its deformability against loads, given the loads applied to the target beams similar [21]. Third, the employed nano-slurry has verified beneficial role on the deformability against shrinkage and loads of MRAC which were applied in RC beams in a real project.

Jing Xu et al. [22] studied the modification effects of nano-silica on the interfacial zone in concrete. At macro-scale level, compressive and flexural strength tests showed that the addition of nano-silica is beneficial for the improvement of interfacial transition zone (ITZ) performance in particular [22]. On the other hand, at micro-scale level, the addition of nano-silica accelerated the hydration process which played a major role in improving the interfacial transition zone (ITZ) in an early age.

A. Ghazy et al. [23] studied the nano-modified fly ash concrete as a repair option for concrete pavements. Numerous outcomes were obtained from this research. The incorporation of 6% nano-silica in concrete with up to 30% fly ash significantly shortened the dormant period and accelerated the rate of hydration reactions, which discounted some of the retarding effect of class F fly ash on the rate of hardening concrete [23]. Furthermore, the addition of nano-silica improved the early-age and the long-term compressive and tensile strength. Moreover, it refined the pore structure of the fly ash concrete. Hence, the nano-modified fly ash concrete presents a viable option for a suite of repair applications in concrete pavements [23].

1.4.1. Nano-silica VS. Micro-silica

1.4.1.1. Nano-silica. Nano-silica is used as a partial replacement of Portland cement in the concrete which makes it categorized as a supplementary cementitious material. Nano-silica is in amorphous state due to the fact that it is not crystalline material. Therefore, it doesn't dissolve in concrete. Moreover, it contains silicon dioxide which causes the reaction of nano-silica with the Portland cement. Table 4 shows the chemical properties of nano-silica.

Table 4. Chemical properties of nano-silica [24].

Chemical properties	Nano-silica
State	Amorphous
Silicon dioxide	99.988

According to Elkem's safety data sheet of Nano-silica powder grade 999 [24] the average Nano-silica particle is 40 nm. Furthermore, the approximate bulk density of Nano-silica ranges between 90 and 110 (kg/m^3). The safety data sheet also states that the specific gravity of Nano-silica is (2.2). Nano-silica particles are very small which makes the surface area very large. Consequently, that decreases the amount of Portland cement required. Furthermore, the large surface area has a positive impact on the reactivity, strength development, and the refinement of the pore structure of the concrete. As mentioned in Elkem's safety data sheet of Nano-silica powder grade 999 [24] the specific surface of Nano-silica ranges between 45,000 to 60,000 (m^2/kg). Table 5 shows the physical properties of nano-silica.

Table 5. Physical properties of nano-silica [24].

Physical properties	Nano-silica
Particle size	40 nm
Bulk density	90 to 110 kg/m^3
Specific gravity	2.2
Specific Surface	45,000 to 60,000 m^2 /kg

The physical contribution of Nano-silica in the concrete lies in reducing the capillary pores size by packing or nano-filling between the cement grains and that due to the very fine particle size of nano-silica. On the other hand, its chemical contribution in concrete lies in its high pozzolonic activity. Nano-SiO2 consumes CH crystals, deceases the orientation of CH crystals, reduces the size of CH crystals at the interface and improves the interface structure more effectively than silica fume [6].

1.4.1.2. Micro-silica

- **Pozzolanic:** Micro-silica will not gain strength when mixed with water [25].
- **Amorphous:** Micro-silica is in amorphous state due to the fact that it is not crystalline material. Therefore, it does not dissolve in concrete.
- **Silicon dioxide (SiO_2):** Micro-silica contains a high content of silicon dioxide as shown in Table 6. Consequently, this makes it very reactive.

Table 6. Chemical properties of micro-silica [25].

Chemical Properties	Micro-silica
State	Amorphous
Silicon Dioxide	> 85%

- **Particle size:** Silica fume particles are extremely small, with more than 95% of the particles being less than 1 µm (one micrometer) [25].
- **Bulk density:** The bulk density of the as-produced micro-silica is very low. Consequently, transporting it to long distances is not considered economical. Therefore, it gets densified in order to transport it to long distances which increases its bulk density.
- **Specific gravity:** Silica fume has a specific gravity of about 2.2, which is somewhat lighter than Portland cement, which has a specific gravity of 3.15 [25]. Thus, adding silica fume to a concrete mixture will not ‘densify’ the concrete in terms of increasing the density of the concrete [25].
- **Specific surface:** The specific surface of silica fume particle is very large, as shown in Table 7, due to its very small size.

Table 7. Physical properties of micro-silica [25].

Physical properties	Micro-silica
Particle size	< 1 µm
Bulk density	130 to 430 kg/m^3 (as produced) 480 to 720 kg/m^3 (Densified)
Specific gravity	2.2
Specific surface	15,000 to 30,000 m^2/kg

- **Physical contribution:** Silica fume fills in the spaces between cement grains [25]. This phenomenon is frequently referred to as particles packing or micro-filling [25].
- **Chemical contribution:** Because of its very high amorphous silicon dioxide content, silica fume is very reactive pozzolanic material in concrete [25]. As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide [25]. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from the Portland cement [25]. It is largely this additional binder that gives silica-fume concrete its improved hardened properties [25].

1.4.1.3. Comparison between nano-silica and micro-silica. Nano-silica's and micro-silica's properties were chosen from the same producer (Elkem) in order to ensure that both materials were produced with the same quality which will guarantee the fairness of the comparison as shown in Table 8.

Table 8. Nano-silica vs. micro-silica

	Nano-silica	Micro-silica	Comparison
State	Amorphous	Amorphous	Both of them are not crystalline materials, therefore they will not dissolve in concrete
Silicon dioxide	99.988 [24]	> 85% [25]	Nano-silica is more reactive than micro-silica, because it contains more silicon dioxide content
Particle size	40 nm [24]	< 1 µm [25]	Nano-silica has a smaller particle size than micro-silica. Consequently, it has a larger surface area. Therefore, nano-silica has a larger impact on the reactivity, strength development, and the refinement of the pore structure of the concrete.
Bulk density	90 to 110 kg/m^3 [24]	130 to 430 kg/m^3 (as produced) [25] 480 to 720 kg/m^3 (Densified) [25]	The weight per unit volume of nano-silica is lighter than both of as produced and densified micro-silica due to its lighter mass.
Specific gravity	2.2 [24]	2.2 [25]	Both of them have a specific gravity (2.2) which is lighter than Portland cement. Thus, adding nano-silica or micro-silica will not increase the density of the concrete
Specific surface	45,000 to 60,000 m^2/kg [24]	15,000 to 30,000 m^2/kg [25]	Nano-silica has a larger specific surface than micro-silica due to its smaller particle size. However, due to its smaller particle size, it has a higher water demand. Thus, it is necessary to use a water-reducing admixture or a superplasticizer in the mixture

Chapter 2: Experimental Program

The experimental program of this study includes the properties of the materials used, the tests performed, the mix designs of the concrete mixtures, and the preparation of the specimens.

2.1. Material Properties

2.1.1. Nano-silica. Nano-silica was manufactured and supplied by Nanostructured & Amorphous Materials, Inc. The physical and chemical properties of nano-silica are shown in Table 9, which were provided by the manufacturer.

Table 9. The properties of nano-silica.

The properties	Nano-silica
Silicon dioxide	99+%
Average particle size	20 nm
Morphology of particles	Spherical
Specific surface area	≤120 m^2/g
Surface performance	Hydrophilic
Crystallographic structure	Amorphous
Bulk density	0.03-0.05 g/cm^3
Color	White
pH value	5.5-6.5
Loss on drying (110°C/2h)	≤6.0 wt%
Loss on calcination (850°C/2h)	≤10.0 wt%

2.1.2. Ground granulated blastfurnace slag. The ground granulated blastfurnace slag is manufactured by Sharjah Cement Factory to comply with the requirement of BS 6699: 1992, as well as EN 15167-1: 2006 and exceeds the minimum strength and fineness requirement by a considerable margin [26]. Table 10 shows the properties of GGBS used in this experiment which were provided by Sharjah Cement Factory.

Table 10. Chemical analysis of GGBS.

Chemical composition	**Results (%)**
SiO_2	33.0
IR	0.28
AL_2O_3	14.7
Fe_2O_3	0.4
CaO	39.7
MgO	7.7
SO_3	0.08
S	0.86
Na_2O	0.42
Mn_2O_3	0.29
LOI corrected for sulfide	1.9
Cl_-	0.01
CHEMICAL MODULAISUM ($CaO+MgO+SiO_2$)	80.4
Modulus (CaO) / (SiO_2)	1.4
Glass content	98.8

2.1.3. Portland cement. The Portland cement was manufactured by Sharjah Cement Factory to comply with BS EN 197-1:2000 CEM I, Class 42.5 N and ASTM C-150-2000 Type I and exceeds the minimum strength required by both standards by a considerable margin [26]. Table 11 shows the properties of the Portland cement used in this experiment which were provided by Sharjah Cement Factory.

Table 11. Chemical composition of Portland cement.

Chemical composition	Result (%)
SiO_2	20.5
IR	0.34
Al_2O_3	5.0
Fe_2O_3	3.9
CaO	64.2
MgO	1.5
SO_3	2.1
Na_2O	0.50
LOI	2.6
Cl^-	0.02
C_3A	6.6

2.1.4. Aggregate. All the aggregate types used in this experiment were manufactured by Conmix Limited and their properties were provided by Sharjah Municipality.

2.1.4.1. Uncrushed sand. The properties of the uncrushed sand (dune sand) are shown in Table 12.

Table 12. The properties of uncrushed sand.

<table>
<tr><td colspan="4">Uncrushed sand (Dune sand)</td></tr>
<tr><td colspan="2" rowspan="4">Relative density & water absorption BS 812: part 2: 1995 CLS. 5.5</td><td>Apparent relative density</td><td>2.68</td></tr>
<tr><td>Relative density on oven dry basis</td><td>2.63</td></tr>
<tr><td>Relative density on S.S.D basis</td><td>2.65</td></tr>
<tr><td>Water absorption (%)</td><td>0.65</td></tr>
<tr><td colspan="2">Sieve analysis</td><td rowspan="2">Fines (% passing 0.075 mm sieve) (BS 812-103.1: Method 7.2: 1985, Amended 1989)</td><td rowspan="2">2.7</td></tr>
<tr><td colspan="2">BS 812-103.1: Method 7.2: 1985, Amended 1989</td></tr>
<tr><td>Sieve size (mm)</td><td>% passing</td><td>Sulphate content (% by mass of dry sample) (BS 812-118:1988)</td><td>0.08</td></tr>
<tr><td>0.6</td><td>100</td><td>Chloride content (% by mass of dry sample (BS 812-117:1988) (AS CI)</td><td>0.01</td></tr>
<tr><td>0.3</td><td>100</td><td>Organic impurities test (ASTM C 40-04)</td><td>NIL</td></tr>
<tr><td>0.15</td><td>72</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>0.075</td><td>7.2</td></tr>
</table>

2.1.4.2. (0-5mm) Crushed rock sand. The properties of the (0-5mm) crushed rock sand are shown in Table 13.

Table 13. The properties of (0-5mm) crushed rock sand.

<table>
<tr><td colspan="4">(0-5mm) crushed rock sand</td></tr>
<tr><td colspan="2" rowspan="4">Relative density & water absorption BS 812: part 2: 1995 CLS. 5.5</td><td>Apparent relative density</td><td>2.67</td></tr>
<tr><td>Relative density on oven dry basis</td><td>2.57</td></tr>
<tr><td>Relative density on S.S.D basis</td><td>2.61</td></tr>
<tr><td>Water absorption (%)</td><td>1.41</td></tr>
<tr><td colspan="2">Sieve analysis</td><td rowspan="2">Fines (% passing 0.075 mm sieve) (BS 812-103.1: Method 7.2: 1985, Amended 1989)</td><td rowspan="2">3.2</td></tr>
<tr><td colspan="2">BS 812-103.1: Method 7.2: 1985, Amended 1989</td></tr>
<tr><td>Sieve size (mm)</td><td>% passing</td><td>Sulphate content (% by mass of dry sample) (BS 812-118:1988)</td><td>0.14</td></tr>
<tr><td>6.3</td><td>100</td><td>Chloride content (% by mass of dry sample (BS 812-117:1988) (AS CI)</td><td>0.03</td></tr>
<tr><td>5.0</td><td>98</td><td>Clay lumps and friable particles (% by mass of dry sample [ASTM C 142-78(Reapproved 1990)])</td><td>0.2</td></tr>
<tr><td>2.36</td><td>65</td><td>Magnesium sulphate soundness (% by mass of dry sample) (ASTM C 88-99a)</td><td>2.0</td></tr>
<tr><td>1.18</td><td>39</td><td>Organic impurities test (ASTM C 40-04)</td><td>NIL</td></tr>
<tr><td>0.6</td><td>23</td><td colspan="2" rowspan="4"></td></tr>
<tr><td>0.3</td><td>12</td></tr>
<tr><td>0.15</td><td>6</td></tr>
<tr><td>0.075</td><td>3.2</td></tr>
</table>

2.1.4.3. 10 mm Crushed rock aggregate. The properties of the 10 mm crushed rock aggregate are shown in Table 14.

Table 14. The properties of 10 mm crushed rock aggregate.

10 mm crushed rock aggregate			
Relative		Apparent relative density	2.95
Density & water		Relative density on oven dry basis	2.90
Absorption		Relative density on S.S.D basis	2.91
ASTM C 127-01		Water absorption (%)	0.62
Sieve analysis BS812-103.1: Method 7.2:1985, Amended 1989		Fines (% passing 0.075 mm sieve) (BS 812-103.1: Method 7.2: 1985, Amended 1989)	0.7
Sieve size (mm)	% Passing	Sulphate content (% by mass of dry sample) (BS 812-118:1988)	0.09
14.0	100	Chloride content (% by mass of dry sample (BS 812-117:1988) (AS CI)	0.02
10.0	98	Flakiness index (% by mass of dry sample) (BS 812-105.1:1989)	14
6.30	47	Elongation index (% by mass of dry sample) (BS 812-105.2:1990)	24
5.00	14	Resistance to degradation of small size coarse aggregate by abrasion & impact in the Los Angeles machine (% loss by mass) (ASTM C 131-03)	12
2.36	1	Clay lumps & friable particles (% by mass of dry sample) (ASTM C 142-97)	0.1
0.075	0.7	Magnesium sulphate soundness (% loss by mass of dry sample) (ASTM C 88-99A)	0.8

2.1.4.4. 20 mm Crushed rock aggregate. The properties of the 20 mm crushed rock aggregate are shown in Table 15.

Table 15. The properties of 20 mm crushed rock aggregate.

20 mm crushed rock aggregate			
Relative		Apparent relative density	2.99
Density & water		Relative density on oven dry basis	2.95
Absorption		Relative density on S.S.D basis	2.96
ASTM C 127-01		Water absorption (%)	0.42
Sieve analysis BS812-103.1: Method 7.2:1985, Amended 1989		Fines (% passing 0.075 mm sieve) (BS 812-103.1: Method 7.2: 1985, Amended 1989)	0.3
Sieve size (mm)	% Passing	Sulphate content (% by mass of dry sample) (BS 812-118:1988)	0.07
28.0	100	Chloride content (% by mass of dry sample (BS 812-117:1988) (AS CI)	0.01
20.0	99	Flakiness index (% by mass of dry sample) (BS 812-105.1:1989)	14
14.0	47	Elongation index (% by mass of dry sample) (BS 812-105.2:1990)	25
10.0	7	Resistance to degradation of small size coarse aggregate by abrasion & impact in the Los Angeles machine (% loss by mass) (ASTM C 131-03)	13
6.3	1	Clay lumps & friable particles (% by mass of dry sample) (ASTM C 142-97)	0.1
5.0	0.4	Magnesium sulphate soundness (% loss by mass of dry sample) (ASTM C 88-99A)	0.5
2.36	0.4	Dry shrinkage of aggregate in concrete (BS 812-120:1989) (% by mass of dry sample)	0.072
0.075	0.3		

2.1.5. Megaflow 1000 polycarboxylated superplasticizer

- **Description:** Megaflow 1000 [27] , shown in Figure 3, is a modified polycarboxlate ether based superplasticizer. Having unique carboxylic ether polymer with long lateral chains, it is an effective cement dispersant, fluidifier and high range water reducer as compared to conventional superplasticizer.

Figure 3. Megaflow 1000 polycarboxylated superplasticizer.

- **Uses:** Megaflow 1000 [27] is specially intended for use in self-compacting concrete, high strength concrete, durable concrete containing GGBS, micro silica, fly ash, etc. It is used in ready-mix concrete where extra ordinary slump retention is required in hot weather conditions. It is extremely useful in high fines concrete.
- **Advantages:**
  1. Produces free flowing concrete without segregation and bleeding.
  2. High strength concrete with low water content.
  3. Produces self-compacting concrete without segregation.
  4. Improved surface finish.
  5. Improved adhesion to reinforcing and stressing steel.
  6. Lower permeability, better resistance to carbonation.
  7. Increased flexural strength.
  8. Good slump retention for longer time.
  9. Remarkably superior performance than normal superplasticizer.

Table 16 shows the properties of Megaflow 1000 polycarboxylated superplasticizer at 25° C.

Table 16. The properties of Megaflow 1000 at 25°C [27].

Property	Test method	Value
Component	-	Single
Form	-	Liquid
Color	-	Brown
Specific gravity	ASTM C494	1.10 ± 0.02
Air entrainment	-	Up to 1% over control mix
Chloride content	BSEN 480-10	0.0
pH	ASTM C494	5-7

2.2. Methodology

- The fresh concrete tests were carried out according to the following standard tests:
  1. Determination of the slump of hydraulic-cement concrete according to ASTM C143-03.
  2. Determination of the flow of concrete according to BS 1881: Part 105: 1984.
  3. Determination of the unit weight of freshly mixed concrete according to ASTM C 138.
- The hardened concrete tests were carried out according to the following standard tests:
  1. Determination of the compressive strength of concrete cubes according to BS 1881: Part 116: 198.
  2. Determination of the modulus of elasticity of concrete cylinders according to ASTM C 469 – 02
  3. Determination of the modulus of rupture of concrete beams according to ASTM C293.
  - Durability evaluation using Rapid Chloride Permeability Test according to ASTM C1202
  - Microstructure analysis using scanning electron microscopy (SEM) according to ASTM C1723
  - Service life determination using ACI Life-365 service life prediction model
  - Embodied energy calculation.

The proportions of nano-silica, GGBS, and Portland cement in each concrete mixture in this study are shown in Table 17.

Table 17. Proportions of the concrete mixtures.

	Nano-silica (%)	GGBS (%)	Portland Cement (%)
M1	0	70	30
M2	1	70	29
M3	2	70	28
M4	0	30	70
M5	1	30	69
M6	2	30	68

Two different cases were studied in this experiment; the influence of nano-silica addition on the durability and strength of concrete mixtures that consist of 70% dosage of GGBS and 30% dosage of GGBS. M1 and M4 were used as control mixtures due to the fact that they contain zero nano-silica dosage. On the other hand, (M2 and M3) incorporated (1% and 2%) dosages of nano-silica, respectively, and their various test results were compared with their control mixture (M1). Similarly, (M5 and M6) incorporated (1% and 2%) dosages of nano-silica, respectively, and their various test results were compared with their control mixtures (M4).

2.2.1. Tests. Six different mixtures were tested in this study. Each mixture has twelve cubes (100x100x100mm), three cylinders (150x300mm), three small cylinders (100x200mm), and three beams (500x100x100mm). The total number of specimens was seventy-two cubes, eighteen cylinders, eighteen small cylinder, and eighteen beams. The specimens were tested at 1, 3, 7, and 28 days as shown in Table 18.

Table 18. Testing event and concrete specimens

Testing Event	Cubes	Cylinders	Small cylinders	Beams
Day 1	Compressive Strength	-	-	-
Day 3	Compressive Strength	-	-	-
Day 7	Compressive Strength	-	-	-
Day 28	Compressive Strength	Modulus of Elasticity	RCPT & SEM	Modulus of Rupture

2.2.2. Mix design. The standard practice for selecting proportions for normal, heavyweight, and mass concrete (ACI 211.1) was used in designing and proportioning the concrete mixtures.

2.2.2.1. Mixture #1. The mix design of (M1) is shown in Tables 19 and 20.

Table 19. Summary of mix design #1.

30% OPC + 70% GGBS + 0% Nano Silica	
Mix grade	C40
Specified CCS	40 N/mm²
Slump	150+/-30 mm
Free W/C	0.36
M.S.A	20 mm
Air content	1.50 %
Megaflow 1000	4.5 kg/m³
GGBS	280 kg/m³
Portland cement	120 kg/m³
Nano-silica	0.0 kg/m³
Cementitious material	120 Kg OPC + 280 Kg GGBS

Table 20. Mix design #1.

Weight Calculations								
	Volume (L)	Sp.Gr	Propr's Kg/m³	Abs %	Moistr %	Moistr Corr'n	Final weights	Cumulative weights
Cement	38.10	3.15	120	0	0	0	120	120
GGBS	96.55	2.9	280	0	0	0	280	400
Nano-silica	0.00	2.2	0	0	0	0	0	400
Water	144.00	1	144	0	0	12.5	156	156
20 mm aggregate	231.72	2.9	672	0.7	0.1	-4.0	668	668
10 mm aggregate	126.39	2.9	367	0.7	0.1	-2.2	364	1032
5 mm washed Sand	126.39	2.7	341	1.2	0.3	-3.1	338	1370
5 mm crushed Sand	119.37	2.6	310	1.5	0.1	-4.3	306	1677
Red dune sand	98.31	2.6	256	0.8	0.2	-1.5	254	1931
MegaFlow 1000	4.17	1.08	4.50	0	60	2.7	4.50	4.50
Air	15							
Total	**1000 L**						**2491 kg/m³**	

2.2.2.2. Mixture #2. The mix design of (M2) is shown in Tables 21 and 22.

Table 21. Summary of mix design #2.

29% OPC + 70% GGBS + 1% Nano Silica	
Mix grade	C40
Specified CCS	40 N/mm^2
Slump	150+/-30 mm
Free W/C	0.36
M.S.A	20 mm
Air content	1.50 %
Megaflow 1000	4.5 kg/m^3
GGBS	280 kg/m^3
Portland cement	116 kg/m^3
Nano-silica	4.0 kg/m^3
Cementitious material	116 Kg OPC + 280 Kg GGBS + 4 Kg Nano Silica

Table 22. Mix design #2.

Weight calculations								
	Volume (L)	Sp.Gr	Propr's Kg/m^3	Abs %	Moistr %	Moistr Corr'n	Final weights	Cumulative weights
Cement	36.83	3.15	116	0	0	0	116	116
GGBS	96.55	2.9	280	0	0	0	280	396
Nano-silica	1.54	2.2	4	0	0	0	4	400
Water	144.00	1	144	0	0	12.5	156	156
20 mm aggregate	231.63	2.9	672	0.7	0.1	-4.0	668	668
10 mm aggregate	126.35	2.9	366	0.7	0.1	-2.2	364	1032
5 mm washed sand	126.35	2.7	341	1.2	0.3	-3.1	338	1370
5 mm crushed sand	119.33	2.6	310	1.5	0.1	-4.3	306	1676
Red dune sand	98.27	2.6	255	0.8	0.2	-1.5	254	1930
MegaFlow 1000	4.17	1.08	4.50	0	60	2.7	4.50	4.50
Air	15							
Total	**1000 L**						**2491 kg/m^3**	

2.2.2.3. Mixture #3. The mix design of (M3) is shown in Tables 23 and 24.

Table 23. Summary of mix design #3.

28% OPC + 70% GGBS + 2% Nano Silica	
Mix grade	C40
Specified CCS	40 N/mm^2
Slump	150+/-30 mm
Free W/C	0.36
M.S.A	20 mm
Air content	1.50 %
Megaflow 1000	4.75 kg/m^3
GGBS	280 kg/m^3
Portland cement	112 kg/m^3
Nano-silica	8.0 kg/m^3
Cementitious material	112 Kg OPC + 280 Kg GGBS + 8 Kg Nano Silica

Table 24. Mix design #3.

Weight Calculations								
	Volume (L)	Sp.Gr	Propr's Kg/m^3	Abs %	Moistr %	Moistr Corr'n	Final weights	Cumulative weights
Cement	35.56	3.15	112	0	0	0	112	112
GGBS	96.55	2.9	280	0	0	0	280	392
Nano-silica	3.08	2.2	8	0	0	0	8	400
Water	144.00	1	144	0	0	12.2	156	156
20 mm aggregate	231.39	2.9	671	0.7	0.1	-4.0	667	667
10 mm aggregate	126.21	2.9	366	0.7	0.1	-2.2	364	1031
5 mm washed sand	126.21	2.7	341	1.2	0.3	-3.1	338	1369
5 mm crushed sand	119.20	2.6	310	1.5	0.1	-4.3	306	1674
Red dune sand	98.17	2.6	255	0.8	0.2	-1.5	254	1928
MegaFlow 1000	4.63	1.08	5.00	0	60	3.0	4.75	4.75
Air	15							
Total	**1000 L**						**2490 kg/m^3**	

2.2.2.4. Mixture #4. The mix design of (M4) is shown in Tables 25 and 26.

Table 25. Summary of mix design #4.

70% OPC + 30% GGBS + 0% Nano Silica	
Mix grade	C40
Specified CCS	40 N/mm²
Slump	150+/-30 mm
Free W/C	0.36
M.S.A	20 mm
Air content	1.50 %
Megaflow 1000	3.5 kg/m³
GGBS	120 kg/m³
Portland cement	280 kg/m³
Nano-silica	0.0 kg/m³
Cementitious material	280 Kg OPC + 120 Kg GGBS + 0 Kg Nano Silica

Table 26. Mix design #4.

Weight Calculations								
	Volume (L)	Sp.Gr	Propr's Kg/m³	Abs %	Moistr %	Moistr Corr'n	Final weights	Cumulative weights
Cement	88.89	3.15	280	0	0	0	280	280
GGBS	41.38	2.9	120	0	0	0	120	400
Nano-silica	0.00	2.2	0	0	0	0	0	400
Water	144.00	1	144	0	0	12.9	157	157
20 mm aggregate	233.32	2.9	677	0.7	0.1	-4.1	673	673
10 mm aggregate	127.27	2.9	369	0.7	0.1	-2.2	367	1039
5 mm washed sand	127.27	2.7	344	1.2	0.3	-3.1	341	1380
5 mm crushed sand	120.19	2.6	313	1.5	0.1	-4.4	308	1688
Red dune sand	98.98	2.6	257	0.8	0.2	-1.5	256	1944
MegaFlow 1000	3.70	1.08	3.5	0	60	2.4	3.50	3.50
Air	15							
Total	**1000 L**						**2506 kg/m³**	

2.2.2.5. Mixture #5. The mix design of (M5) is shown in Tables 27 and 28.

Table 27. Summary of mix design #5.

69% OPC + 30% GGBS + 1% Nano Silica	
Mix grade	C40
Specified CCS	40 N/mm²
Slump	150+/-30 mm
Free W/C	0.36
M.S.A	20 mm
Air content	1.50 %
Megaflow 1000	4.0 kg/m³
GGBS	120 kg/m³
Portland cement	280 kg/m³
Nano-silica	4.0 kg/m³
Cementitious material	276 Kg OPC + 120 Kg GGBS + 4 Kg Nano Silica

Table 28. Mix design #5.

Weight Calculations								
	Volume (L)	Sp.Gr	Propr's Kg/m³	Abs %	Moistr %	Moistr Corr'n	Final weights	Cumulative weights
Cement	87.62	3.15	276	0	0	0	276	276
GGBS	41.38	2.9	120	0	0	0	120	396
Nano-silica	1.54	2.2	4	0	0	0	4	400
Water	144.00	1	144	0	0	12.9	157	157
20 mm aggregate	233.23	2.9	676	0.7	0.1	-4.1	672	672
10 mm aggregate	127.22	2.9	369	0.7	0.1	-2.2	367	1039
5 mm washed sand	127.22	2.7	343	1.2	0.3	-3.1	340	1379
5 mm crushed sand	120.15	2.6	312	1.5	0.1	-4.4	308	1687
Red dune sand	98.95	2.6	257	0.8	0.2	-1.5	256	1943
MegaFlow 1000	3.70	1.08	4.00	0	60	2.4	4.00	4.00
Air	15							
Total	**1000 L**						**2504 kg/m³**	

2.2.2.6. Mixture #6. The mix design of (M6) is shown in Tables 29 and 30.

Table 29. Summary of mix design #6.

68% OPC + 30% GGBS + 2% Nano Silica	
Mix grade	C40
Specified CCS	40 N/mm²
Slump	150+/-30 mm
Free W/C	0.36
M.S.A	20 mm
Air content	1.50 %
Megaflow 1000	5.0 kg/m³
GGBS	120 kg/m³
Portland cement	280 kg/m³
Nano-silica	8.0 kg/m³
Cementitious material	272 Kg OPC + 120 Kg GGBS + 8 Kg Nano Silica

Table 30. Mix design #6.

Weight Calculations								
	Volume (L)	Sp.Gr	Propr's Kg/m³	Abs %	Moistr %	Moistr Corr'n	Final weights	Cumulative weights
Cement	86.35	3.15	272	0	0	0	272	272
GGBS	41.38	2.9	120	0	0	0	120	392
Nano Silica	3.08	2.2	8	0	0	0	8	400
Water	144.00	1	144	0	0	13.0	157	157
20 mm aggregate	233.14	2.9	676	0.7	0.1	-4.1	672	672
10 mm aggregate	127.17	2.9	369	0.7	0.1	-2.2	367	1039
5 mm washed sand	120.10	2.7	324	1.2	0.3	-2.9	321	1360
5 mm crushed sand	127.17	2.6	331	1.5	0.1	-4.6	326	1686
Red dune sand	98.91	2.6	257	0.8	0.2	-1.5	256	1942
MegaFlow 1000	3.70	1.08	5.00	0	60	2.4	5.00	5.00
Air	15							
Total	**1000 L**						**2504 kg/m³**	

2.2.2.7. Summary of all concrete mix designs. A tabular summary of the mix designs of all the mixtures is shown in Table 31.

Table 31. Summary of all the mixes.

Final Weights of all the mixes (Kg/m^3)						
Mix No:	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
OPC	120	116	112	280	276	272
GGBS	280	280	280	120	120	120
Nano-silica	0	4	8	0	4	8
20 mm aggregate	668	668	667	673	672	672
10 mm aggregate	364	364	364	367	367	367
5 mm washed sand	338	338	338	341	340	321
5 mm crushed sand	306	306	306	308	308	326
Red dune sand	254	254	254	256	256	256
Water	156	156	156	157	157	157
MegaFlow 1000	4.5	4.5	4.75	3.5	4	5
Total	**2491**	**2491**	**2490**	**2506**	**2504**	**2504**

2.3. Specimen Preparation

2.3.1. Mixing. The mixing process started by adding 20 mm crushed rock aggregate, 10 mm crushed rock aggregate, 5 mm washed sand, 5 mm crushed rock sand, and uncrushed sand (dune sand), respectively. After that, water was added while the mixer is running for half a minute in order to allow the aggregate to absorb it. In a different bucket, nano-silica was mixed with Megaflow 1000 polycarboxlate superplasticizer and some water until it dissolved completely. Then, GGBS and Portland cement were added to the immobile concrete mixer as shown in Figure 4. Once they were added, water along with the mixed solution of dissolved nano-silica, water, and Megaflow 1000 polycarboxlate superplasticizer were added while the mixer was running for two minutes in order for the concrete to disperse in the mixer. Three batches of twenty liter were mixed to cast twelve cubes (100x100x100mm), three cylinders (150x300mm), three small cylinders (100x200mm), and three beams (500x100x100mm) for each mixture.

Figure 4. Concrete mixing process.

2.3.2. Slump/Flow test. The slump and flow tests are indicators of the concrete's workability. The slump and flow test were performed in the lab according to ASTM C143-03 and BS 1881: Part 105: 1984, respectively, as shown in Figure 5.

Figure 5. Slump and flow tests.

2.3.3. Density (Unit weight). The determination of the density (unit weight) of freshly mixed concrete was carried out according to ASTM C 138, as shown in Figure 6. This test is a great tool in controlling the quality of the newly mixed concrete. A very high or low unit weight gives different indications such as that the concrete suffered from high or low air content, high or low water content, or change of the ingredients' proportions has taken place.

Figure 6. Unit weight test.

2.3.4. Curing. The cement hydration is considered a long-run process which depends on proper room temperature and submersion of the specimens in water as shown in Figure 7. The specimens were cured for 1, 3, 7, and 28 days in curing pool in an air conditioned room with 25^{o} C temperature.

Figure 7. Curing tank.

2.3.5. Concrete compressive strength. Compressive strength is one of the main structural design requirements to ensure that the structure will be able to carry the intended load [28].The compressive strength test was performed according to BS 1881: Part 116: 198. The test was performed on cubical specimens by applying axial compressive load with specified loading rate until failure took place, as shown in Figure 8.

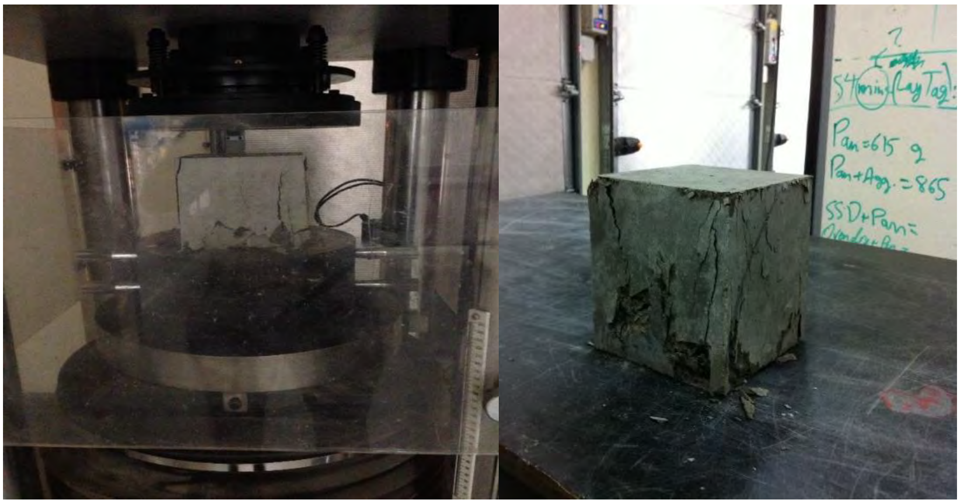


Figure 8. Compressive strength test.

2.3.6. Modulus of elasticity. For a homogeneous isotropic, and linear elastic material, the proportional constant between normal stress and normal strain of an axially loaded member is the modulus of elasticity or Young's modulus [28]. A slowly increasing longitudinal compressive strength was applied to a cylindrical specimen. Longitudinal strains are determined using either a bonded or unbonded sensing device that measures the average deformation of two diametrically opposite locations to the nearest 5 millionths of strain [29], as shown in Figure 9. The applied load and longitudinal strain are recorded when the longitudinal strain is 50 millionths and when the applied load is equal to 40% of the cylinder compressive strength [29].

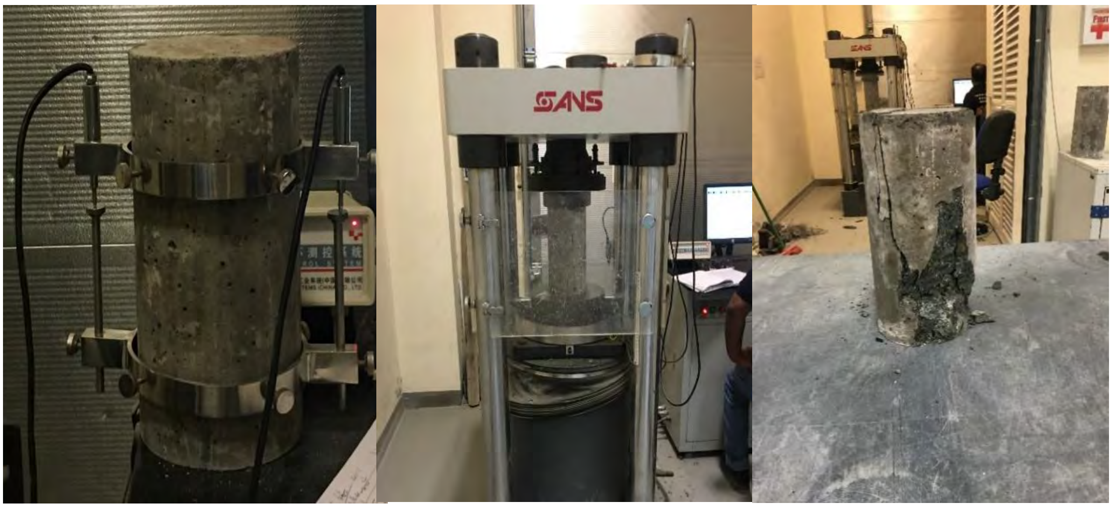


Figure 9. Modulus of elasticity test.

2.3.7. Modulus of rupture. The (500x100x100mm) beams were tested in the three-point loading apparatus as illustrated in Figure 10. The load is continuously applied at a specified rate until rupture [28]. The modulus of rupture was calculated when the fracture initiates in the tension surface within the middle third of the span length by using the following equation [28].

$$R = \frac{3PL}{2bd^2}$$

Where

R = Flexure strength, MPa

P = Maximum applied load, N

L = Span length, mm

b = Average width of specimen, mm

d = Average depth of specimen, mm

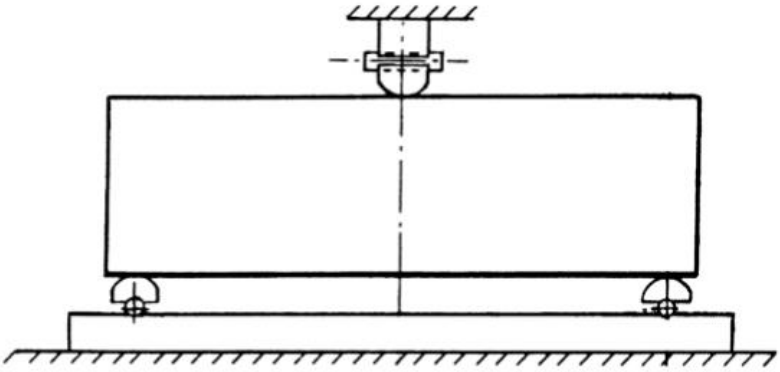


Figure 10. Three-point flexural test [30].

2.3.8. Rapid chloride permeability test (RCPT). Originally developed in the early 1980s, and standardized as ASTM in 1991, the rapid chloride permeability test is now being used extensively in specifications, quality control, and concrete durability research [31].The RCPT is performed by monitoring the amount of electrical current that passes through a sample 50 mm thick by 100 mm in diameter in 6 hours [32]. The specimens were prepared by casting (100x200mm) cylinders and slicing them to (100x50mm) samples. Throughout the test, a 60V DC voltage was maintained across the ends of the specimen. One lead is immersed in a 3.0% salt (NaCl) solution and the other in a 0.3 M sodium hydroxide (NaOH) solution [32], as demonstrated in Figure 11.

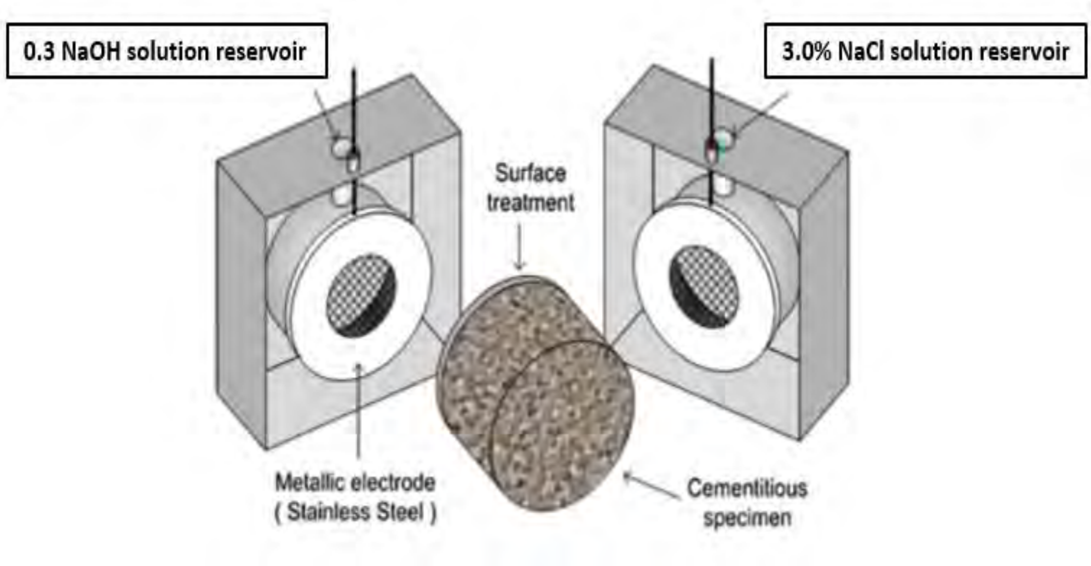


Figure 11. The RCP test setup [33].

A qualitative rating was concluded about the permeability of the concrete against chloride penetration based on the passing charge through the specimen, as illustrated in Table 32.

Table 32. Rating of chloride permeability of concrete according to RCPT [32].

Chloride permeability	Charge passing (Coulombs)	Typical concrete type
High	> 4000	High w/c ratio (>0.6) conventional PC concrete
Moderate	2000 to 4000	Moderate w/c ratio (0.4 to 0.50) conventional PC concrete
Low	1000 to 2000	Low w/c ratio (<0.4) conventional PC concrete
Very low	100 to 1000	Latex modified concrete, internally sealed concrete
Negligible	< 100	Polymer-impregnated concrete, polymer concrete

2.3.9. Scanning electron microscopy (SEM). The SEM provides images that can range in scale from a low magnification (for example, 15×) to a high magnification (for example, 50 000× or greater) of concrete specimens such as fragments, polished surfaces, or powders [34]. These images can provide information indicating compositional or topographical variations in the observed specimen [34]. The SEM functions by generating an electron beam over the surface of the concrete specimen. The beam impinges on the specimen and produces signals which can be detected as backscattered electrons (BE or BSE), secondary electrons (SE) and X-rays [35]. Figure 12 shows a general sketch of the scanning electron microscopy and its components.

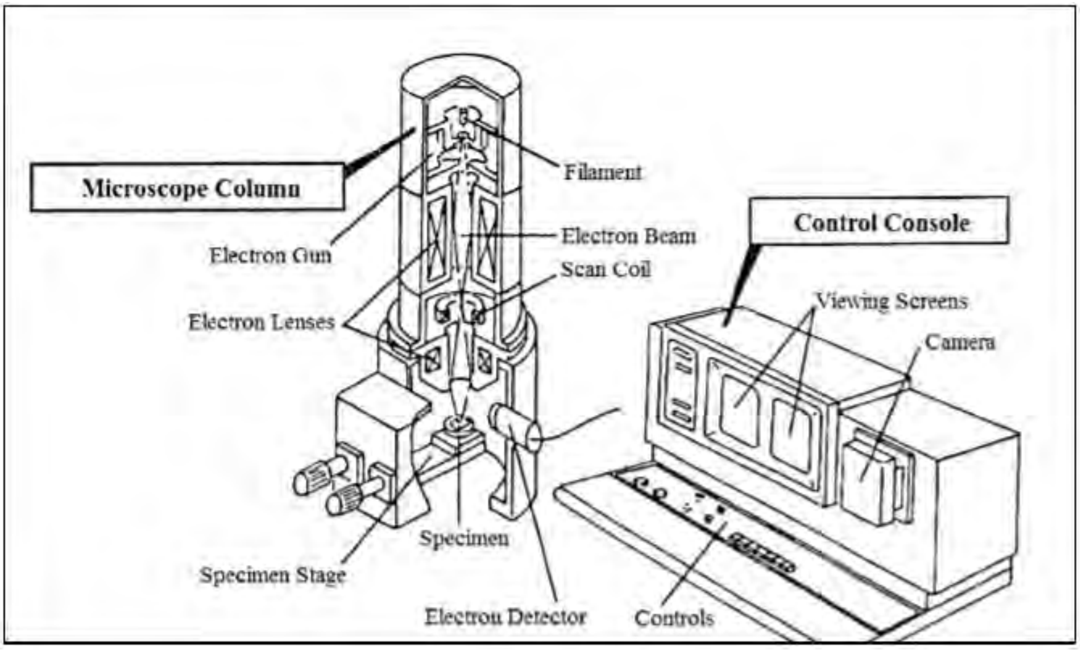


Figure 12. General Sketch of SEM and its components [33].

In order to ensure that the specimens are representatives and they contain different concrete components, they were taken from the center of the small cylinders by slicing a very thin disk using a saw-cut machine. After that, a small concrete piece was taken from the middle of the sliced disk as shown in Figure 13.

Figure 13. Small concrete pieces taken from different sliced disks.

Then, the small concrete piece was placed in the bottom of a mounting cup. In a separate mixing cup, a resin was prepared by mixing ClaroCit powder with ClaroCit liquid. Once the resin was prepared, it was poured in the mounting cup over the concrete piece. Next, the mounting cup was placed in an oven for half an hour in order for the resin to solidify. Afterwards, the solid resin which contains the concrete piece was taken out of the mounting cup and its surface was polished, as shown in Figure 14.

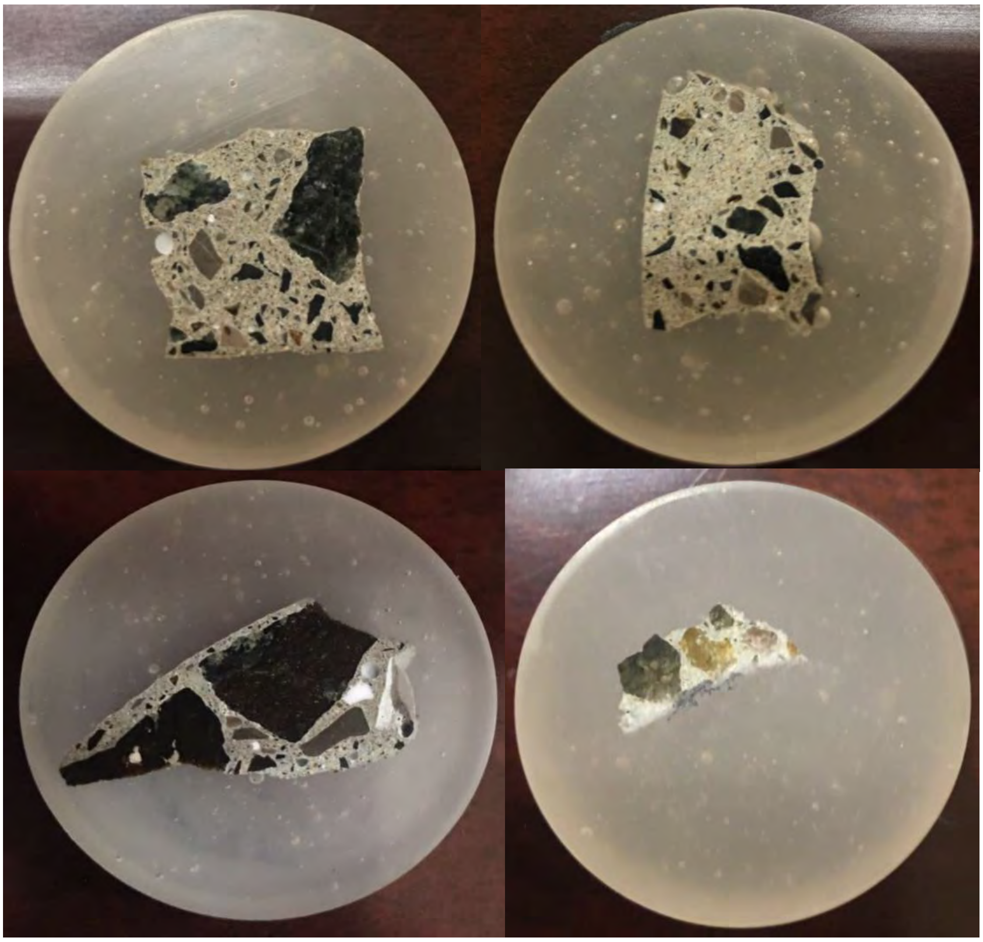


Figure 14. Concrete pieces inside the solid resins.

Chapter 3: Results and Discussion

3.1. Slump/Flow

The slump and flow tests were performed in the lab at three different times; immediately, thirty minutes, and sixty minutes after the concrete mixing process, as shown in Tables 33 and 34. The specific surface of nano-silica's particles is very large due to its very small size which increases the water demand of the concrete mixes. Therefore, as the nano-silica dosage increased from one mixture to another, the Megaflow 1000 polycarboxylated superplasticizer dosage was increased in order to maintain the same water/cement ratio in all the mixtures.

Table 33. Slump test results.

	M1	M2	M3	M4	M5	M6
Initial slump (mm)	240	230	220	240	230	230
Slump after 30 mins (mm)	240	220	220	240	220	160
Slump after 60 mins (mm)	240	220	130	240	200	110

Table 34. Flow test results.

	M1	M2	M3	M4	M5	M6
Initial flow (mm)	630	590	470	600	620	520
Flow after 30 mins (mm)	630	580	400	620	520	0
Flow after 60 mins (mm)	600	580	0	600	460	0

Comparing the initial slump and flow tests results of (M2 and M3) to (M1) and (M5 and M6) to (M4) showed that adding nano-silica reduced the slump and the flow spread of the mixtures which in consequence reduced the workability of the concrete. Furthermore, comparing the slump and flow tests results after (30 and 60 mins) to the initial slump and flow tests results showed that using nano-silica reduced the setting time due to the fact that nano-silica accelerated the hydration process. Moreover, the 30% GGBS concrete mixtures (M5 and M6) required higher Megaflow 1000 polycarboxylated superplasticizer dosages as the nano-silica dosage increased from one mixture to another, in order to maintain the water/cement ratio, compared to the 70% GGBS concrete mixtures (M2 and M3). Therefore, the 30% GGBS mixtures (M5 and M6) had higher water demand in comparison to the 70% GGBS mixtures (M2 and M3). Finally, the mixtures that contain 2% dosage of nano-silica (M3 and M6) had significant slump and flow reduction especially after sixty minutes compared to the mixtures that contain 1% dosage of nano-silica (M2 and M4). Thus, as the dosage of nano-silica increased, the workability of the concrete decreased.

3.2. Density (unit weight)

The unit weight test was conducted on the freshly mixed concrete in the lab. Results are shown in Figure 15.

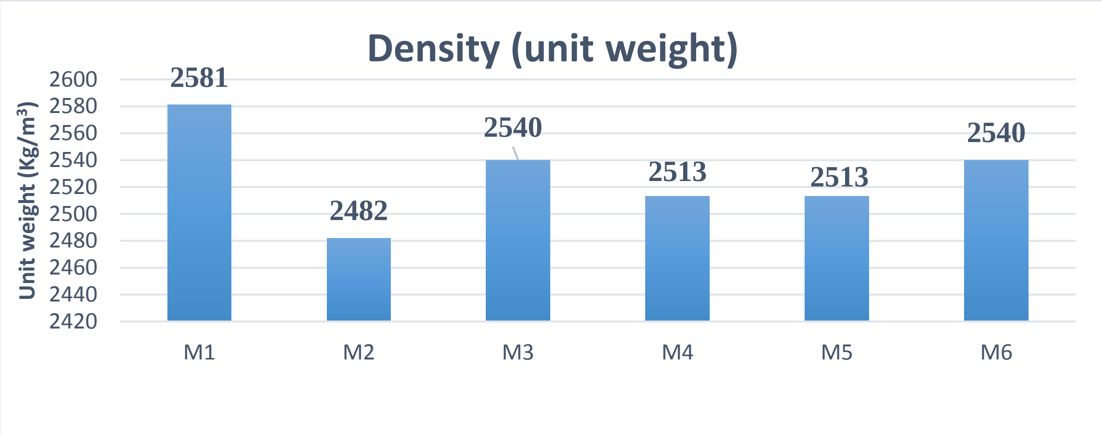


Figure 15. The unit weight of all the mixtures.

Figure 15 illustrates that incorporating 1% and 2% dosages of nano-silica reduced the unit weight of (M2) and (M3) by 3.8% and 1.6%, respectively, when compared to the control mixture (M1). On the other hand, adding 1% dosage of nano-silica didn't increase nor decrease the unit weight of (M5) compared to the control mixture (M4). While, adding 2% dosage of nano-silica increased the unit weigh of (M6) by 1.1% with respect to the control mixture (M4). In general, the percentage increase or decrease that took place for all the mixtures were very low when compared to their respective control mixtures which indicates that the addition of nano-silica doesn't densify nor shrink the unit weight of the concrete.

3.3. Compressive Strength

The compressive strength test was performed after 1-day, 3-days, 7-days, and 28-days of curing. The compressive strength (average of three specimens) and the standard deviation of all the mixtures are shown in Tables 35 and 36, respectively.

Table 35. The compressive strength results.

	M1	M2	M3	M4	M5	M6
1 Day – Compressive strength (MPa) (Average of 3 specimens)	25.5	25.6	21.1	20.8	23.6	25.5
3 Days – Compressive strength (MPa) (Average of 3 specimens)	48.7	44.9	43.3	39.9	43.0	41.3
7 Days – Compressive strength (MPa) (Average of 3 specimens)	61.7	52.8	54.2	55.6	60.1	55.9
28 Days – Compressive strength (MPa) (Average of 3 specimens)	71.8	57.9	59.1	63.1	64.5	61.4

Table 36. The standard deviation of the compressive strength results.

	M1	M2	M3	M4	M5	M6
1 Day – Standard deviation	1.0	1.0	0.8	0.9	0.3	0.1
3 Days – Standard deviation	0.4	0.7	1.3	1.1	0.7	0.7
7 Days – Standard deviation	1.1	2.5	1.6	1.9	1.6	2.1
28 Days – Standard deviation	1.7	1.0	1.2	1.3	0.7	1.3

3.3.1. 70% GGBS concrete mixtures. Figure 16 shows that the incorporation of 1% of nano-silica at 1 day almost had no effect on the compressive strength, while the incorporation of 2% of nano-silica at 1 day reduced the compressive strength by 17.3% with respect to the control mixture (M1). After 3 days, adding 1% and 2% dosages of nano-silica to the 70% GGBS concrete mixtures reduced the compressive strength by 7.8% and 11.1%, respectively, when compared to the compressive strength of (M1). Unlike the 1-day and the 3-day compressive strength results, the 7-day compressive strength of (M3) was higher than (M2) by 1.4 MPa. However, both 7-day compressive strength results of (M2 and M3) were lower than the control mixture (M1), as shown in Figure 16. At 28-days, the percentage decrease in compressive strengths of (M2 and M3) compared to the control mixture (M1) increased remarkably to 19.4% and 17.7%, respectively.

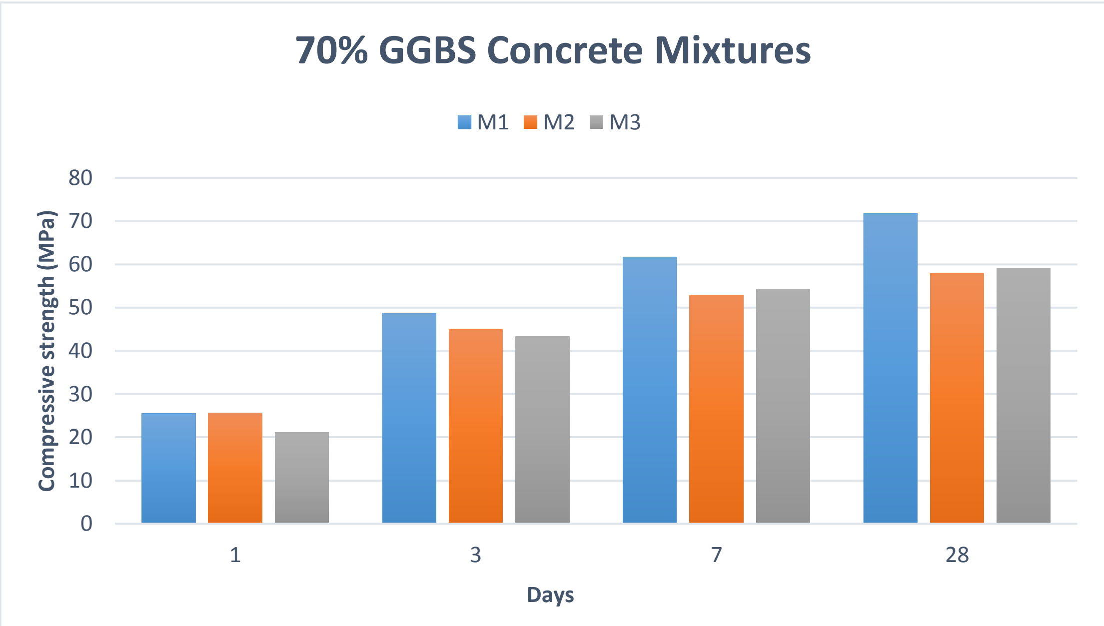


Figure 16. The compressive strength results of the 70% GGBS concrete mixtures.

The reduction in compressive strength that took place in the mixtures that incorporated nano-silica (M2 and M3) can be attributed to the consumption of calcium hydroxide, which was released by the Portland cement during the hydration process, by the high dosage of GGBS. Therefore, this would leave almost no chemical hydration between nano-silica and calcium hydroxide. In terms of compressive strength, it is not recommended to use nano-silica with the 70% GGBS concrete mixtures.

3.3.2. 30% GGBS concrete mixtures. The addition of 1% and 2% dosages of nano-silica increased the 1-day compressive strength by (2.8 MPa) and (4.7 MPa), respectively, compared to the control mixture (M4). Unlike the 1-day compressive strength, the combination of 30% GGBS and 1% nano-silica (M5) improved the 3-day compressive strength more than the combination of 30% GGBS and 2% nano-silica (M6), as demonstrated by Figure 17.

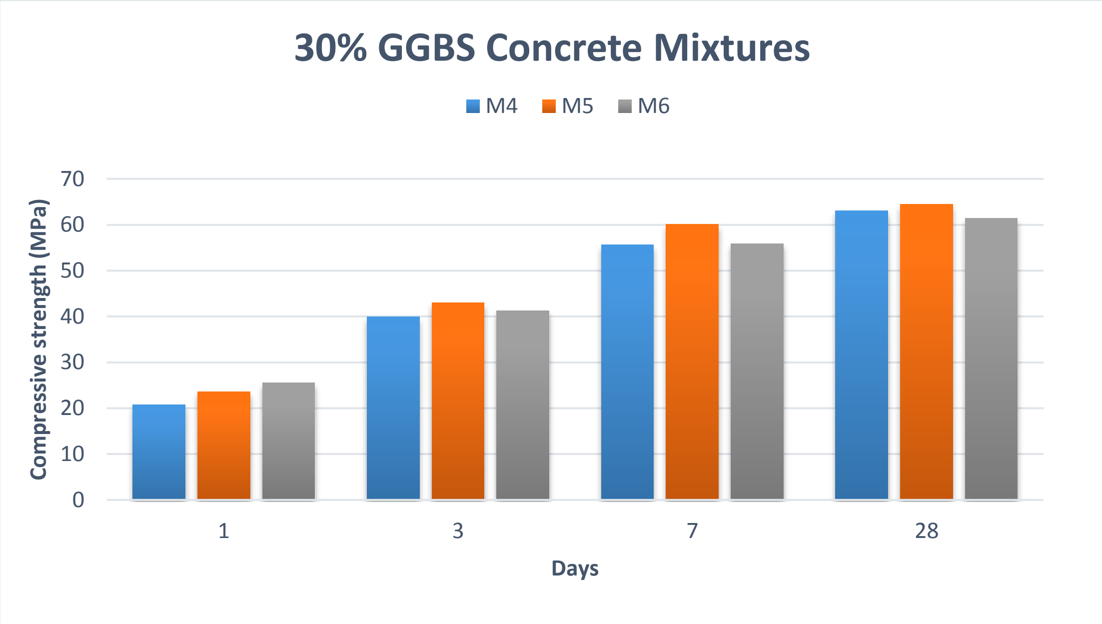


Figure 17. The compressive strength results of the 30% GGBS concrete mixtures.

At 7 days, the addition of 2% nano-silica to the 30% GGBS concrete mixture (M6) almost had an equal compressive strength to the control mixture (M4) with minor percentage increase of (0.5%). On the other hand, the addition of 1% nano-silica to the 30% GGBS mixture (M5) improved the 7-day compressive strength by (8.1%) in comparison to the control mixture (M4). At 28 days, (M5) had compressive strength of (64.5 MPa) which is 2.2% higher than the control mixture (M4), while (M6) had compressive strength of (61.4 MPa) which is 2.7% lower than the control mixture (M4). In general, the improvement in the compressive strength for the 30% GGBS concrete mixtures that incorporated nano-silica can be ascribed to the high pozzolanic activity and the nano-filler effect of nano-silica which makes the concrete's microstructure denser, compact, and homogenous. Most of the compressive strength's improvement took place within the first 7 days. Furthermore, the 1% dosage of nano-silica had greater impact on the compressive strength development of the 30% GGBS concrete mixtures compared to the 2% dosage of nano-silica. One possible reason is that the combination of 30% GGBS and 1% nano-silica reacted more efficiently with released calcium hydroxide from the Portland cement during the hydration process to form the additional calcium-silicate-hydrate gel. Another possible reason is the agglomeration effect. Nano-particles, due to their small size, have high inter-particle van der Waal's forces causing the nano-particles to agglomerate [1]. Therefore, the optimum dosage of nano-silica to be added to the 30% GGBs concrete mixture is 1%.

3.4. Modulus of Elasticity

The modulus of elasticity test was performed after 28-days of curing. Results are shown in Table 37.

Table 37. Modulus of elasticity of all the mixtures.

	M1	M2	M3	M4	M5	M6
Modulus of elasticity (E) (GPa) (Average of two specimens)	59.4	84.7	61.0	57.0	60.6	58.1
(%) increase with respect to the control mixture	-	42.6	2.7	-	6.3	1.9

For the 70% GGBS concrete mixtures, the incorporation of 1% nano-silica increased the young's modulus remarkably by 42.6% compared to the control mixture (M1), as shown in Figure 18. On the other hand, the incorporation of 2% nano-silica increased the young's modulus by 2.7% with respect to the control mixture (M1), which is less than (M2). Similarly, the addition of 1% of nano-silica to the 30% GGBS concrete mixtures had greater effect than the 2% dosage of nano-silica by 4.4% as illustrated in Figure 18. Nano-silica decreased the deformation of the concrete specimens by nano-filling the pores which caused the modulus of elasticity of the mixtures to increase.

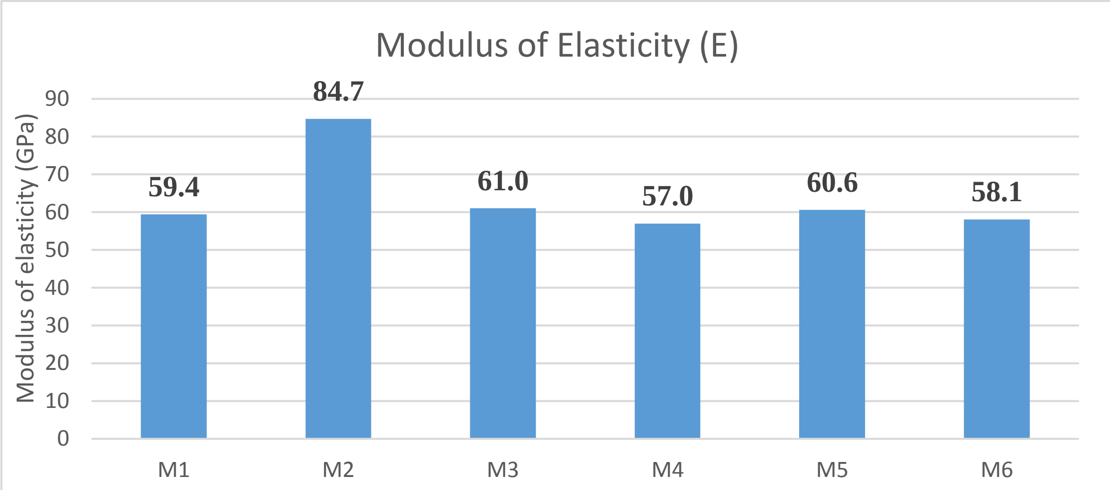


Figure 18. The modulus of elasticity results of all the mixtures.

3.5. Modulus of Rupture

The modulus of rupture test was performed after 28-days of curing. The maximum applied load and the calculated modulus of rupture are shown in Table 38.

Table 38. Modulus of rupture of all the mixtures.

	M1	M2	M3	M4	M5	M6
Maximum applied Load (KN) (Average of 3 specimens)	15.6	16.1	21.2	19.2	20.2	17.0
Modulus of rupture (MPa) (Average of 3 specimens)	11.7	12.1	15.9	14.4	15.0	12.7

The addition of 1% and 2% dosages of nano-silica increased the flexural strength of the 70% GGBS concrete mixtures (M2) and (M3) by 3.4% and 35.9%, respectively, compared to the control mixture (M1). Therefore, the flexural strength of the 70% GGBS concrete mixtures increased as the nano-silica's dosage increased as shown in Figure 19. Similarly, the addition of 1% dosage of nano-silica increased the flexural strength of the 30% GGBS concrete mixture (M5) by 4.2% compared to the control mixture (M4). However, the 2% dosage of nano-silica decreased the modulus of rupture of (M6) by 11.8% compared to the control mixture (M4). This possibly due the agglomeration effect, the mixing process, or the released calcium hydroxide from the Portland cement during the hydration process wasn't consumed efficiently by the 2% dosage of nano-silica.

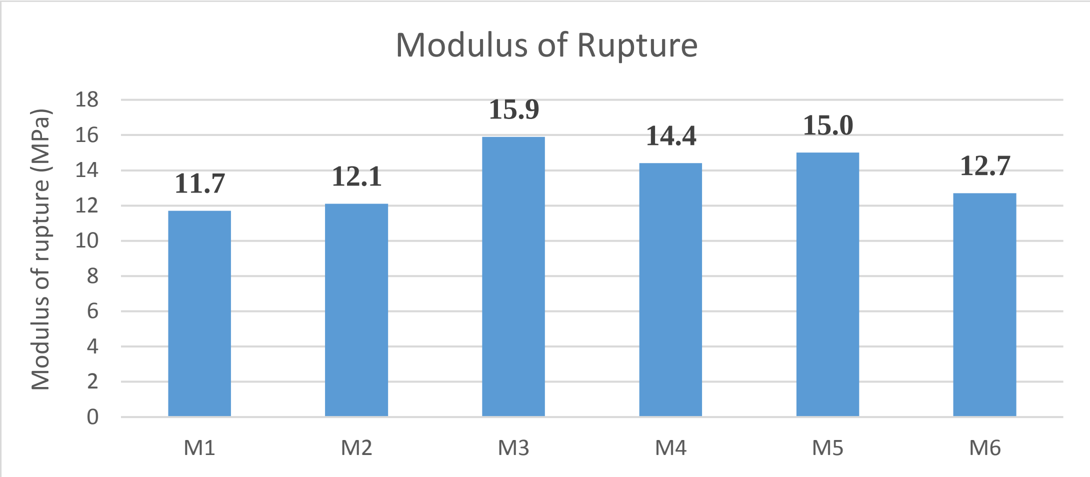


Figure 19. Modulus of rupture of all the mixtures.

3.6. Rapid Chloride Permeability Test

Table 39 shows the average passing charges of three specimens and the penetrability class as specified by ASTM C 1202 of each mixture.

Table 39. RCPT results of all the mixtures.

	M1	M2	M3	M4	M5	M6
Charge passing (Coulombs) (Average of 3 specimens)	775.5	505.5	367.0	1458.3	614.7	967.0
Penetrability class	Very low	Very low	Very low	Low	Very low	Very low

Partially replacing the Portland cement with 1% and 2% dosages of nano-silica improved the resistance of the 70% GGBS concrete mixtures (M2 and M3) to chloride penetration by 34.8% and 52.7%, respectively, when compared to the control mixture (M1). Therefore, the chloride ingress of the 70% GGBS concrete mixtures decreased as the nano-silica dosage increased. On the other hand, the partial replacement of cement with 1% dosage of nano-silica reduced the passing charges of the 30% GGBS concrete mixture (M5) by 57.8% with respect to the control mixture (M4), changing the penetrability class from low to very low . Similarly, the 2% nano-silica addition reduced the chloride ingress of the 30% GGBS concrete mixture (M6) by 33.7% and changed the penetrability class from low to very low when compared to the control mixture (M4). However, as shown in Figure 20, the addition of 2% dosage of nano-silica wasn't as effective compared to the 1% dosage of nano-silica in improving the resistance of the 30% GGBS concrete mixtures against chemical attacks.

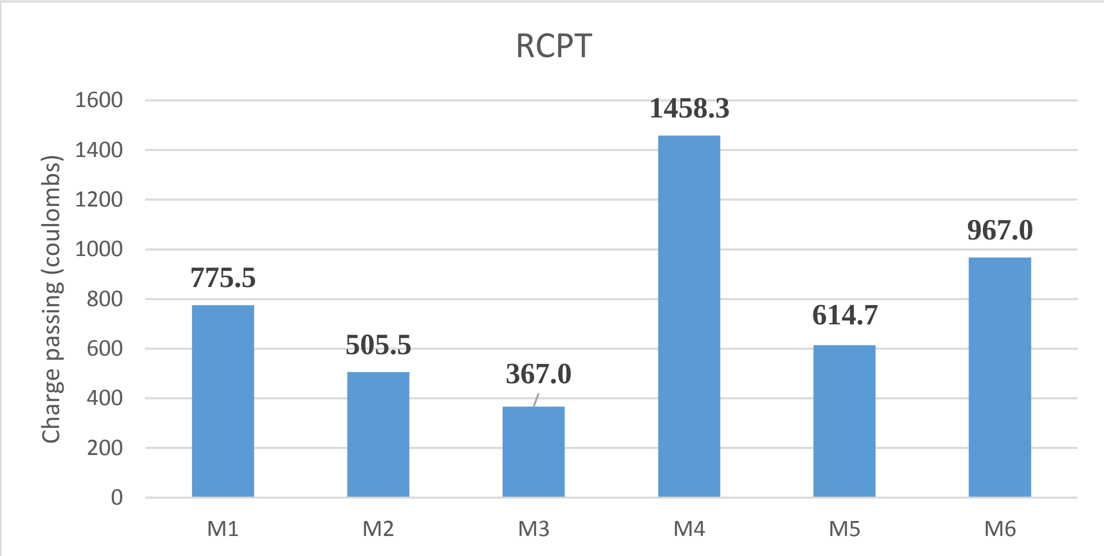


Figure 20. RCPT results of all the mixtures

In general, adding small dosages of nano-silica had noticeable effect on decreasing the conductivity of the concrete and refining the pore structure of all the mixtures due to the pozzolanic reaction and the nano-filler effect of nano-silica which made the microstructure of the concrete mixtures more homogenous and less porous. Consequently, this improved the resistance of the concrete mixtures against physical penetration of chloride ions. Thus, nano-silica addition improves the durability of the concrete making it more sustainable.

3.7. Scanning Electron Microscopy (SEM)

3.7.1. SEM images analysis. Figures 21, 22, and 23 show the scanning electron and backscattered electrons images of the 70% GGBS concrete mixtures (M1, M2, and M3).While, Figures 24, 25, and 26 show the scanning electron and backscattered electrons images of the 30% GGBS concrete mixtures (M4, M5, and M6) . The scanning electron images show the cementitious paste-aggregate interface and the microstructure of the concrete mixture. On the other hand, the backscattered electron images show the micro-cracks that took place in the cementitious paste-aggregate interface and other areas of the specimen.

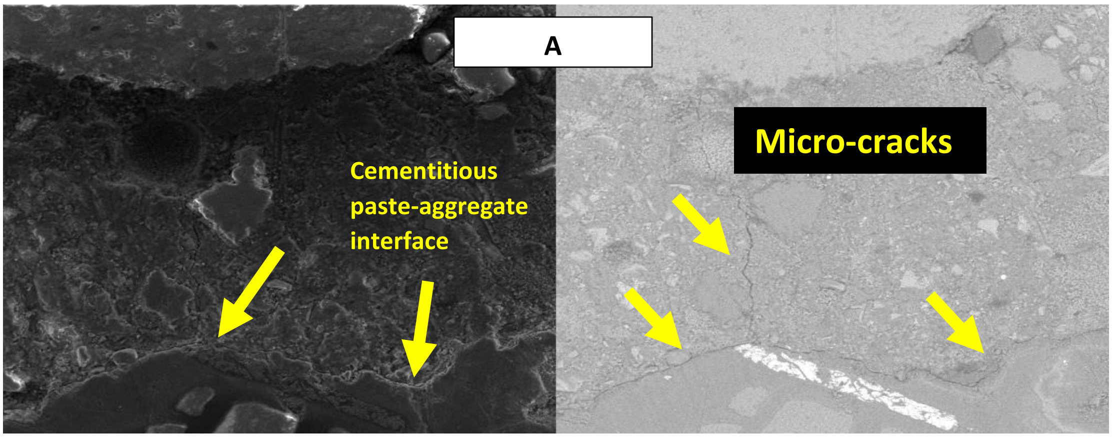


Figure 21. SE and BSE images of M1 at 500 X SEM magnification.

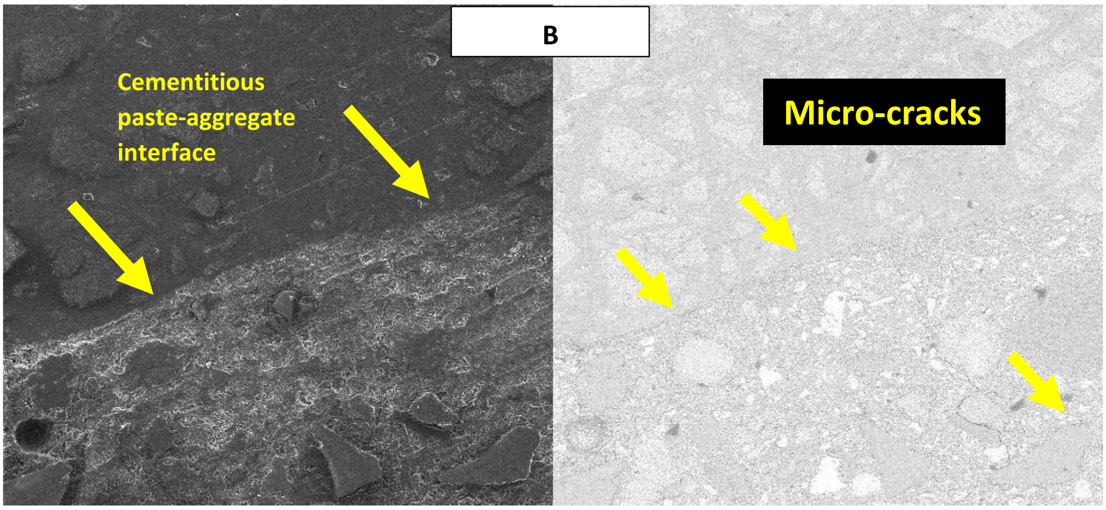


Figure 22. SE and BSE images of M2 at 200 X SEM magnification.

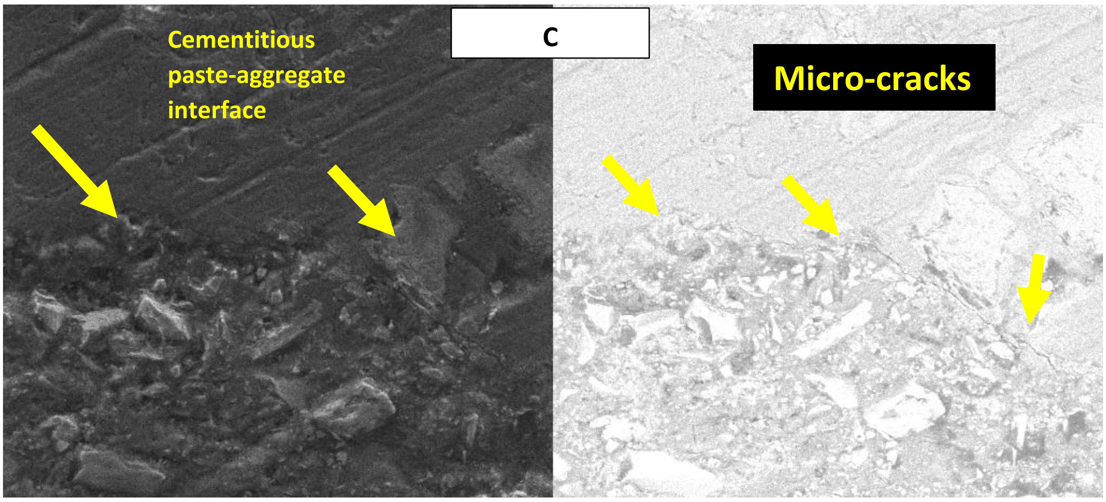


Figure 23. SE and BSE images of M3 at 1.00 KX SEM magnification.

Generally, the 70% GGBS mixtures, due to incorporating 70% dosage of GGBS, have homogenous microstructures and great interface structure which is shown clearly in the SE and BSE image of M1 (Figure 21). However, using 1% and 2% dosages of nano-silica further refined the microstructure and increased the bond strength of the cementitious paste-aggregate interface by nano-filling the micro-cracks and the pores, as shown in Figures 22 and 23. The 2% dosage of nano-silica had more pronounced effect compared to 1% dosage of nano-silica in refining the microstructure and the interface structure of the 70% GGBS mixtures. Therefore, as the nano-silica's dosage increased, the microstructure's homogeneity and bond strength of cementitious paste-aggregate interface increased. Furthermore, the SE and BSE images of the 70% GGBS concrete mixtures reinforced the drawn conclusion from the rapid chloride permeability test results that the incorporation of nano-silica improved the pore structure of the concrete which results in reducing the ingress rate of water and chloride ions due to the packing ability of nano-silica. Thus, nano-silica incorporation improved the durability of the concrete.

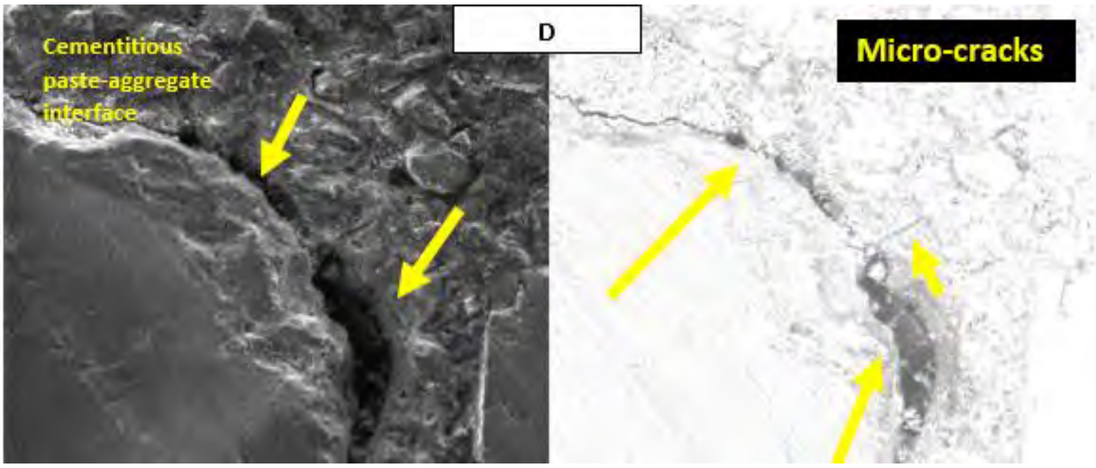


Figure 24. SE and BSE images of M4 at 1.00 KX SEM magnification.

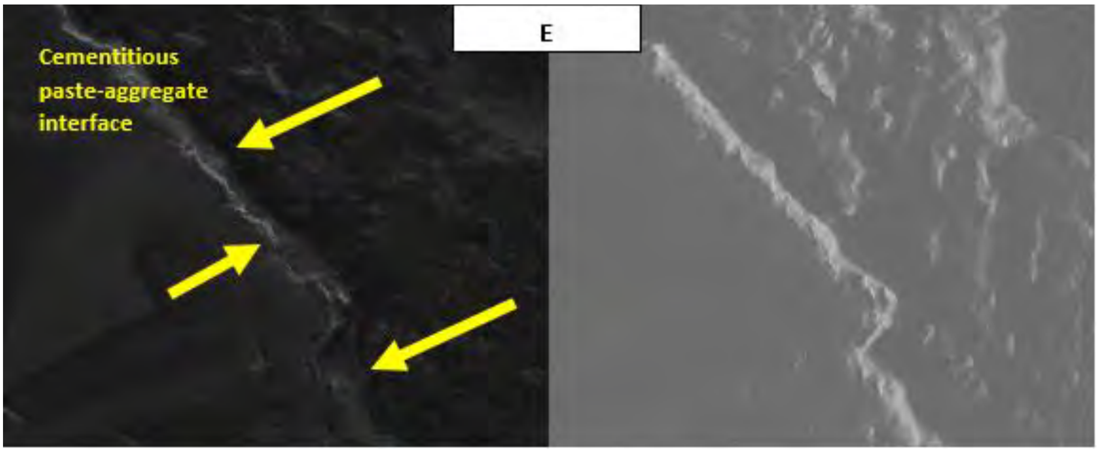


Figure 25. SE and BSE images of M5 at 1.00 KX SEM magnification.

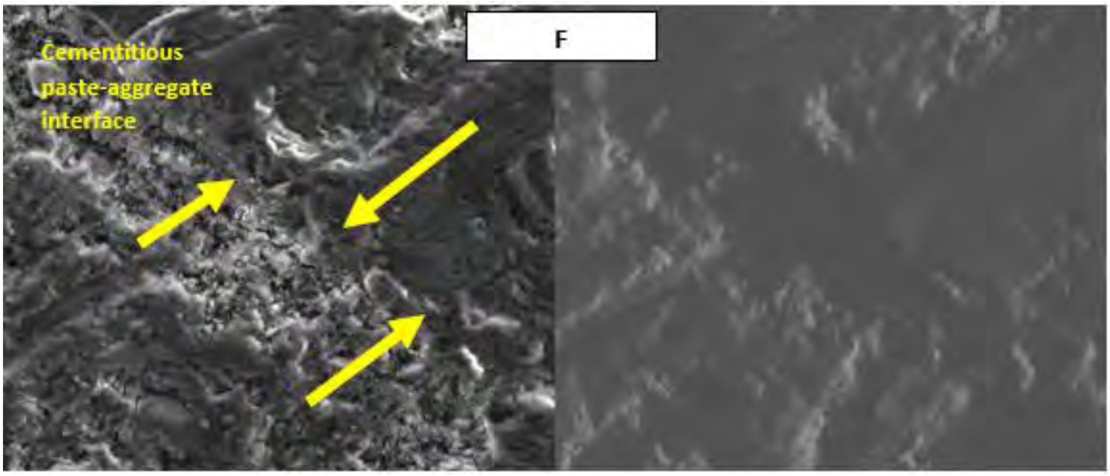


Figure 26. SE and BSE images of M6 at 2.00 KX SEM magnification.

The SE and BSE images of the control mixture of the 30% GGBS concrete mixtures (M4) illustrate that the cementitious paste-aggregate bond is weak as the micro-crack in the interface is very wide as shown in (Figure 24). Moreover, the microstructure contains micro-cracks and voids. The addition of 1% and 2% dosages of nano-silica improved the cementitious paste-aggregate interface's bond significantly as almost no visible micro-cracks shown at 1.00 KX and 2.00 KX SEM magnification in (Figure 25 and 26). Furthermore, the microstructure of (M5) and (M6) became more homogenous, dense, and compact due to the nano-filler effect of nano-silica which refined the pore structure of the 30% GGBS concrete mixtures. Also, the SE and BSE images of the 30% GGBS concrete mixtures show greater improvement in terms of cementitious paste-aggregate interface's bond due to the incorporation of nano-silica when compared to the 70% GGBS concrete mixtures. All in all, nano-silica addition increases the sustainability of the concrete by enhancing its durability.

3.7.2. X-ray analysis. The x-ray analysis were applied on three different locations (spectrums) of each mixture's specimen in which two locations were on the cementitious paste and one location was on the aggregate, as shown in Figure 27

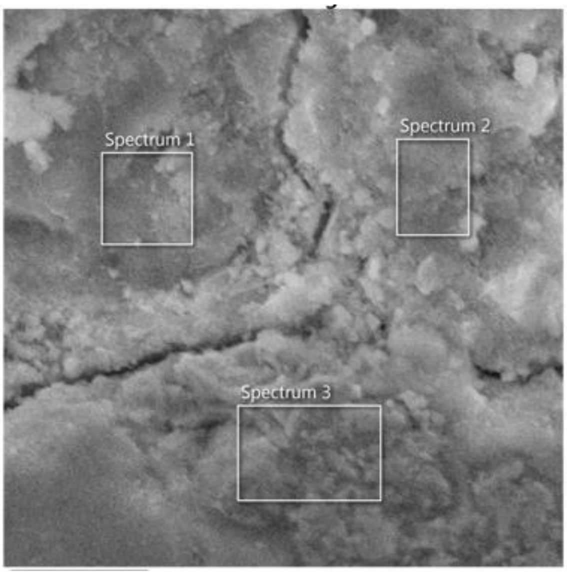


Figure 27. X-ray analysis of a concrete specimen.

Graphical chemical analyses for the concentrations of O, C, Ca, Si, Mg, Al, Mo, and Fe of each location (spectrum) were produced. For example, Figure 28 shows the chemical analysis of spectrum 1. The average concentrations of Ca and Si of the two locations (spectrums) that were on the cementitious paste of each mixture's specimen were calculated.

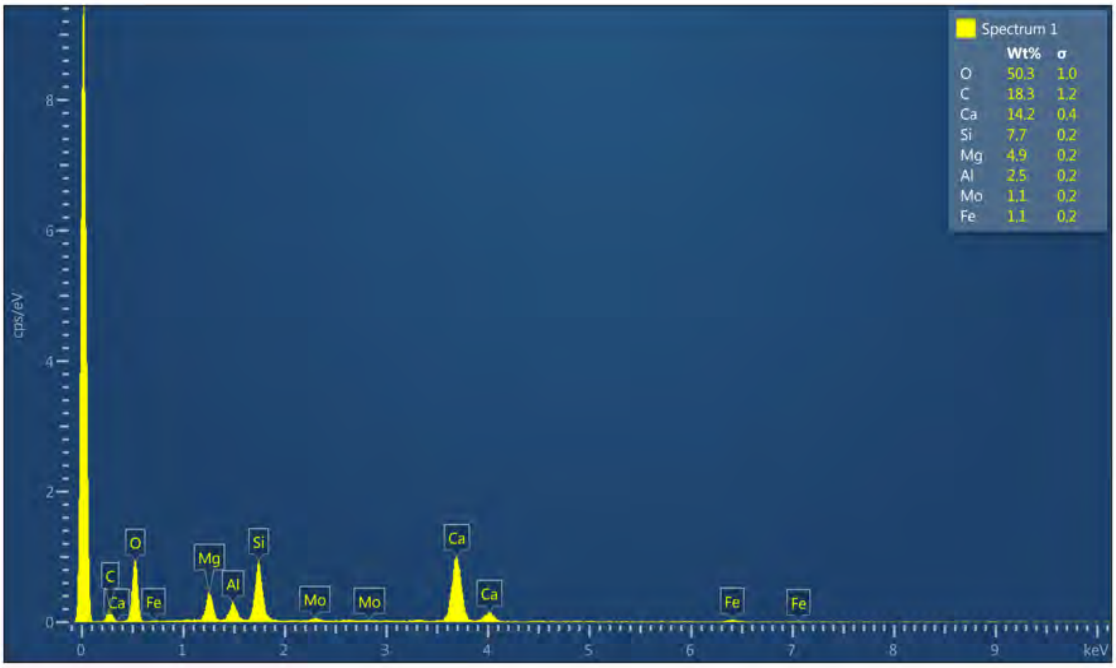


Figure 28. Chemical analysis of a concrete mixture.

The Ca/Si ratios were calculated based on the average of Ca and Si in order to evaluate the influence of nano-silica on the amount of C-S-H gel formed during the hydration process. Results are shown in Table 40.

Table 40. Ca/Si ratio of all the mixtures.

	M1	M2	M3	M4	M5	M6
Ca (wt %) (Average of 2 spectrums)	13.8	13.7	9.5	2.4	1.2	10.7
Si (wt %) (Average of 2 spectrums)	10.0	9.8	6.7	2.1	0.8	6.3
Ca/Si (Average of 2 spectrums)	1.4	1.4	1.4	1.2	1.4	1.7

Pozzolanic materials such as GGBS and nano-silica react with the calcium hydroxide which is released from the Portland cement during the hydration process to form additional C-S-H gel that enhances the strength and the durability properties of concrete. When the Ca/Si ratio decreases, it gives an indication that more C-S-H gel was formed during the hydration process. In general, the calculated Ca/Si ratios of the all mixtures were low due to the incorporation of pozzolanic materials. Despite the fact that nano-silica act as a nucleation site for C-S-H seeds, the addition of 1% and 2% dosages of nano-silica to the 70% GGBS concrete mixtures didn't decrease the Ca/Si ratios when compared to the control mixture (M1). This can be attributed to consumption of calcium hydroxide by the high GGBS dosage which left almost no chemical hydration between nano-silica and calcium hydroxide.

3.8. Service Life Modeling

The service life of the concrete mixtures was modeled using ACI Life-365 software. This software is a program used to predict the service life and life-cycle cost of reinforced concrete that is exposed to chlorides. The corrosion of embedded steel reinforcement in concrete due to the penetration of chlorides from deicing salts, groundwater, or seawater is the most prevalent form of premature concrete deterioration worldwide and costs billions of dollars a year in infrastructure repair and replacement [36]. Currently, the service life of the reinforced structures exposed to chloride is increased by using multiple strategies such as using high performance concrete. Each of these strategies has different technical merits and costs associated with their use [36]. Selecting the optimum strategy requires the means to weigh all associated costs against the potential extension to the life of the structure [36]. Therefore, for this purpose, the life cycle cost analysis is being used more frequently. Over the years, a number of models were designed to predict the service life of the concrete structures that is exposed to harsh environments and estimate the life cycle cost of different applied strategies for the purpose of extending the service life of concrete structures. The approaches adopted by the different models vary considerably and consequently there can be significant variances between the solutions produced by individual models [36]. Among the engineering communities, the development of different models which vary significantly caused some concerns. Thus, Life-365 model was developed by a consortium consisting of W. R. Grace construction products, Master builders, and the Silica fume association under the supervision of the American concrete institute (ACI).

3.8.1. Life-365 model analysis. The following steps should be followed to perform the life-365 model analysis:

- The unit (SI or US) should be selected, the structure should be defined, and the nature of the exposure condition (chloride and temperature) should be chosen.
- One or more corrosion protection scenarios should be defined.
- Once all the scenarios are defined, various analysis types can be carried out such as chloride concentration profile at any given age, a plot of chloride concentration versus depth, and a plot of cost versus time which shows the life cycle cost.
- Finally, a tabular summarization of the input data and the results of the service life and the life cycle cost analysis can be produced.

3.8.2. Life-365 model results. Life-365 service life predication model includes only data about GGBS, fly ash, and silica fume. Therefore, nano-silica was considered as silica fume. Furthermore, life-365 allows only 70% replacement of cement by supplementary cementitious materials. Consequently, the GGBS dosages of (M2) and (M3) was considered as 69% and 68%, respectively, instead of 70% to allow the 1% and 2% dosages of nano-silica to be considered in the analysis.

➢ The description of structure and the properties of the mixtures.

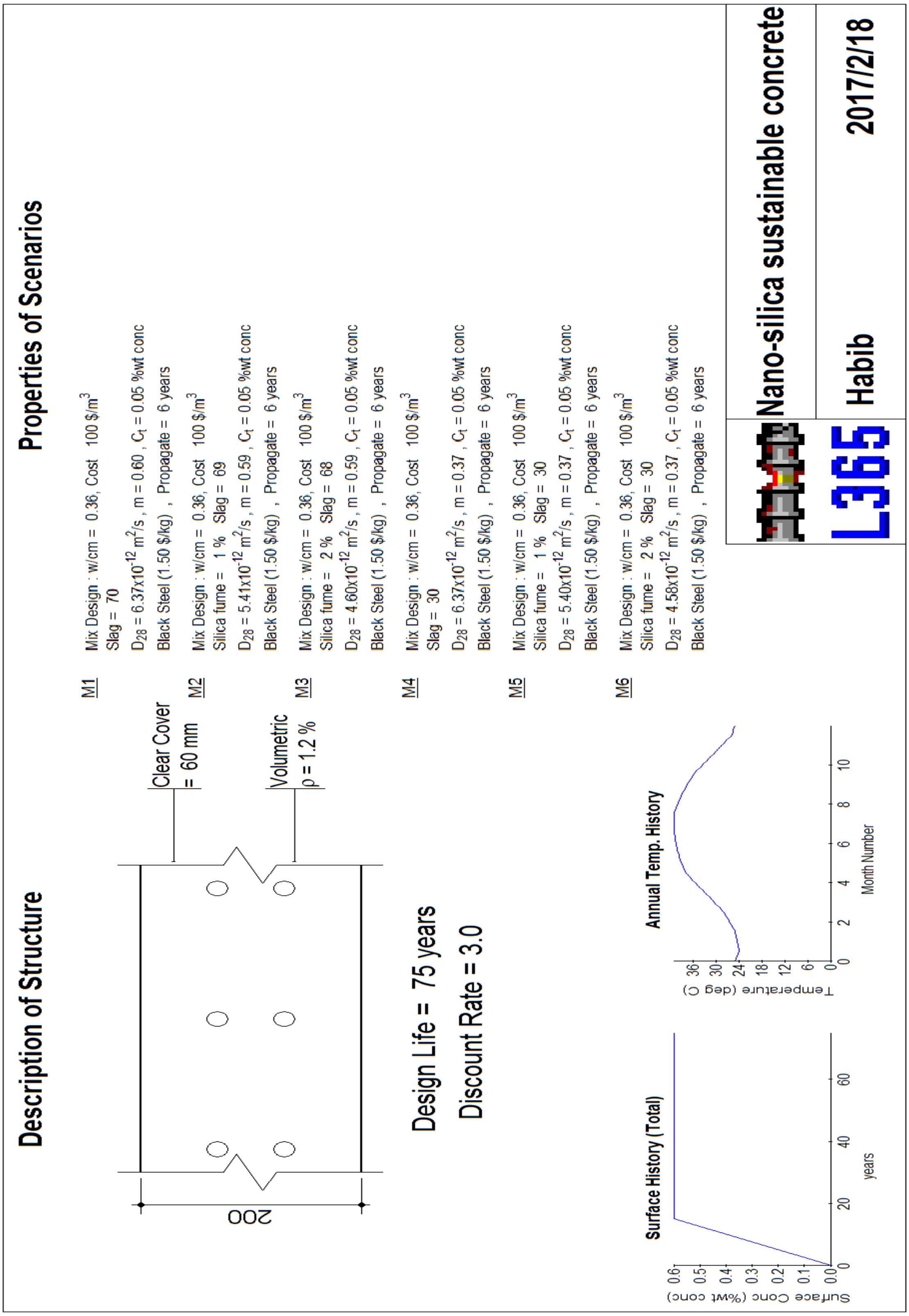


Figure 29. The description of structure and the considered scenarios.

➢ Chloride concentration versus depth chart.

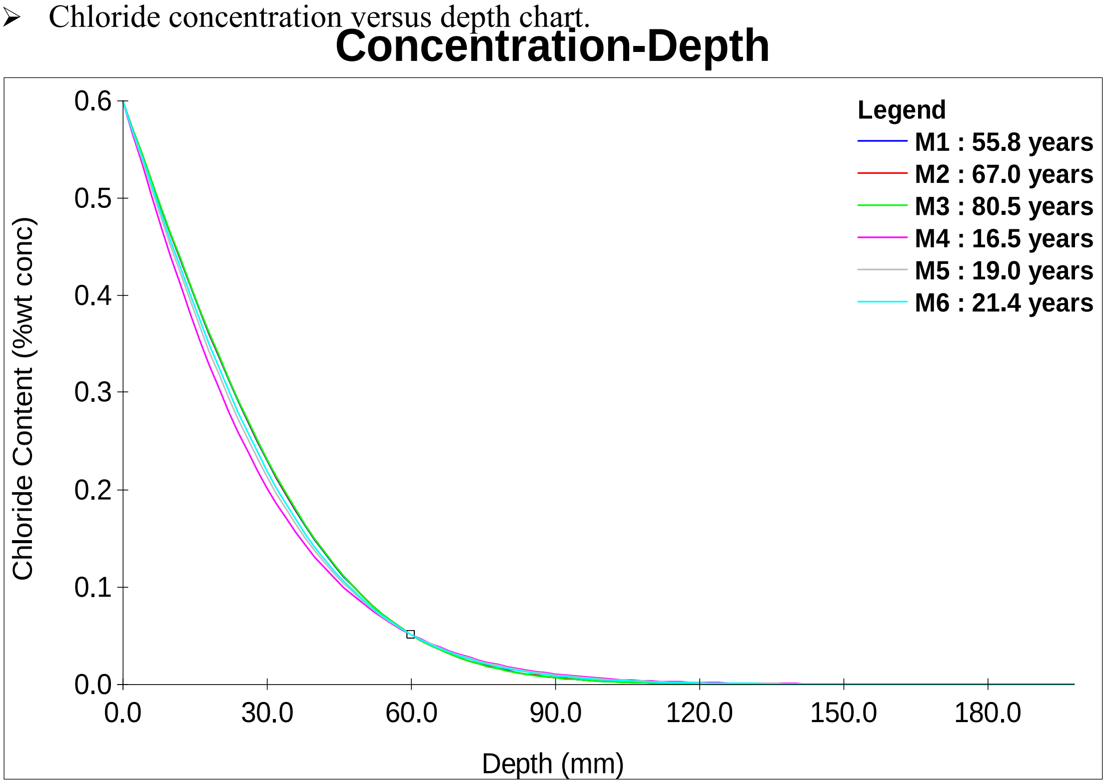


Figure 30. Chloride content (%wt concentration) Vs. Depth (mm).

The analyzed structure was modeled to be 1D slab/wall structure which has a clear cover of 60 mm and placed 800 m away from an ocean. The design life of the structure is 75 years. The temperature of the city of Dubai was considered in the analysis as shown in the annual temperature history in Figure 29. Figure 30 shows that the addition of 1% and 2% dosages of nano-silica increased the service life of the 70% GGBS concrete mixtures by 11.2 and 24.7 years, respectively, compared to the control mixture (M1). On the other hand, Figure 30 also shows that the addition of 1% and 2% dosages of nano-silica to the 30% GGBS concrete mixtures increased the service life by 2.5 and 4.9 years, respectively, compared to the control mixture (M4). Moreover, Figure 29 demonstrates that the incorporation of 1% and 2% dosages of nano-silica to the 70% GGBS concrete mixtures reduced the chloride diffusion at 28 days by 15.1% and 27.7%, respectively, compared to the control mixture (M1). Similarly, Figure 29 also demonstrates that incorporating 1% and 2% dosages of nano-silica to the 30% GGBS concrete mixtures reduced the chloride diffusion at 28 days by 15.2% and 28.1%, respectively, compared to the control mixture (M4).Thus, using nano-silica increases the amount of time it takes the chloride ingress to expand and reach higher depths which extends the service life of the concrete.

3.9. Embodied Energy Calculation

Embodied energy is defined as the total primary energy consumed from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate [37]. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate [37]. Due to the lack of information of the embodied energy of nano-silica, the embodied energy of nano-silica was assumed as equal to the embodied energy of silica fume. Table 41 and Figure 31 show the embodied energy of each mixture.

Table 41. Embodied energy of all the mixtures.

Material	Embodied Energy (MJ/kg)	M1 (MJ/m^3)	M2 (MJ/m^3)	M3 (MJ/m^3)	M4 (MJ/m^3)	M5 (MJ/m^3)	M6 (MJ/m^3)
Cement	5.5 [38]	660.0	638.0	616.0	1540.0	1518.0	1496.0
GGBS	1.6 [38]	448.0	448.0	448.0	192.0	192.0	192.0
Nano-silica	0.036 [39]	0.0	0.1	0.3	0.0	0.1	0.3
Coarse aggregate	0.083 [38]	85.7	85.7	85.6	86.3	86.2	86.2
Fine aggregate	0.081 [38]	72.7	72.7	72.7	73.3	73.2	73.1
Water	0.01 [38]	1.6	1.6	1.6	1.6	1.6	1.6
Superplasticizer	9 [39]	40.5	40.5	42.8	31.5	36.0	45.0
Total Embodied Energy (MJ/m^3)		**1308.5**	**1286.6**	**1266.9**	**1924.7**	**1907.2**	**1894.2**

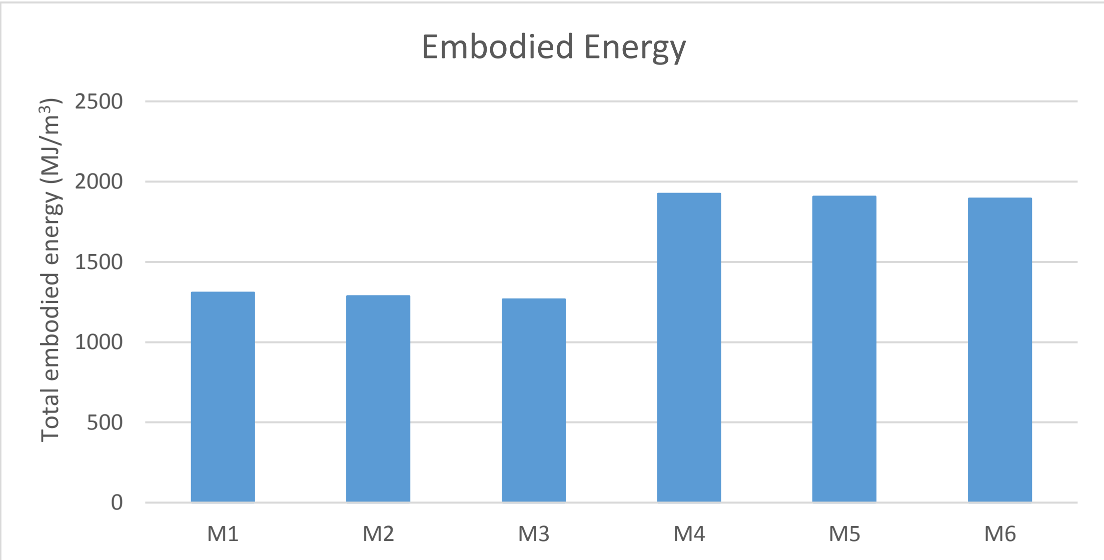


Figure 31. The total embodied energy of the mixtures.

3.10. Summary of the Results

Table 42 includes a numerical summary of almost all the conducted tests' results in this study, which are the slump, unit weight, 7-day compressive strength, modulus of elasticity, modulus of rupture, rapid chloride permeability test, Ca/Si ratio, service life, and the embodied energy of the 70% and 30% GGBS concrete mixtures.

Table 42. Summary of all the tests' results.

	M1	M2	M3	M4	M5	M6
Slump (mm)	240	230	220	240	230	230
Unit weight (Kg/m^3)	2581	2482	2540	2513	2513	2540
Compressive strength at 7 days (MPa)	61.7	52.8	54.2	55.6	60.6	58.1
Modulus of elasticity (GPa)	59.4	84.7	61.0	57.0	60.6	58.1
Modulus of rupture (MPa)	11.7	12.1	15.9	14.4	15.0	12.7
RCPT (Coulombs)	775.5	505.5	367.0	1458.3	614.7	967.0
Ca/Si	1.4	1.4	1.4	1.2	1.4	1.7
Service life (Years)	55.8	67.0	80.5	16.5	19.0	21.4
Embodied Energy (MJ/m^3)	1308.5	1286.6	1266.9	1924.7	1907.2	1894.2

Chapter 4: Conclusion and Recommendation

4.1. Conclusion

This research presents the influence of nano-silica on the properties of the 70% and 30% GGBS concrete mixtures in terms of strength and durability. Fresh and hardened concrete tests along with the rapid chloride permeability test, scanning electron microscopy, Life-365 service life modeling, and embodied energy calculation were applied on each mixture. Based on the obtained results, the following conclusion were drawn:

- Adding 1% dosage of nano-silica to the 30% ground granulated blast-furnace slag (GGBS) concrete mixture (M5) increased the 1-day, 3-day, 7-day, and 28-day compressive strength by 13.5%, 7.8%, 8.1%, and 2.2%, respectively, compared to the control mixture (M4). Whereas, adding 2% dosage of nano-silica to the 30% ground granulated blast-furnace slag (GGBS) concrete mixture (M6) had less influence on the strength development compared to the 1% dosage of nano-silica. This possibly due either the agglomeration effect, the mixing process, or the released calcium hydroxide from the Portland cement during the hydration process was consumed more efficiently by the combination of 30% ground granulated blast-furnace slag (GGBS) and 1% nano-silica. The majority of the compressive strength's development which was caused by the addition of nano-silica was within the first 7 days. On the other hand, adding 1% and 2% dosages of nano-silica to the 70% ground granulated blast-furnace slag (GGBS) concrete mixtures decreased the 28-day compressive strength by 19.4% and 17.7%, respectively, compared to the control mixture (M1). The reduction in compressive strength associated with the addition of nano-silica could be due the released calcium hydroxide from the Portland cement in the hydration process was consumed entirely by the 70% ground granulated blast-furnace slag (GGBS).
- Nano-silica increased the young's modulus due to the nano-filler effect which reduced the concrete's deformability making it brittle.
- The modulus of rupture of the 70% ground granulated blast-furnace slag (GGBS) concrete mixtures (M2 and M3) increased by 3.4% and 35.9% due to the incorporation of 1% and 2% dosages of nano-silica, respectively. On the

other hand, the flexural strength of the 30% ground granulated blast-furnace slag (GGBS) concrete mixtures had similar behavior as the 28-day compressive strength.

- The rapid chloride permeability test results illustrated that adding nano-silica to the 70% and 30% ground granulated blast-furnace slag (GGBS) concrete mixtures reduced the chloride ingress due to the high pozzolanic activity and the packing effect of nano-silica which made the microstructure of concrete more homogenous and less porous.
- The scanning electron microscopy (SEM) images show that adding nano-silica increased the bond strength of the cementitious paste-aggregate interface and made the microstructure more homogenous due to the nano-filler effect and the accelerated hydration process. The effect of adding nano-silica on the microstructure and the interface structure was more pronounced on the 30% ground granulated blast-furnace slag (GGBS) concrete mixtures in comparison to the 70% ground granulated blast-furnace slag (GGBS) concrete mixtures. The scanning electrom microscopy (SEM) images confirmed the drawn conclusion from the rapid chloride permeability test's (RCPT) results that nano-silica improves the concrete's durability.
- According to Life-365 service life prediction model, partially replacing the Portland cement by nano-silica increased the service life of the 70% ground granulated blast-furnace slag (GGBS) concrete mixtures (M2 and M3) by 11.2 and 24.7 years, respectively, compared to the control mixture (M1). On the other hand, nano-silica addition extended the service life of the 30% ground granulated blast-furnace slag (GGBS) concrete mixtures (M5 and M6) by 2.5 and 4.9 years, respectively, compared to the control mixture (M4). Therefore, the service life of the concrete increased as the nano-silica's dosage increased.
- Despite the fact that nano-silica act as a seeding agent to form additional C-S-H gel, adding 1% and 2% dosages of nano-silica to the 70% ground granulated blast-furnace slag (GGBS) concrete mixtures did not decrease the Ca/Si. This indicates that the released calcium hydroxide from the Portland cement during the hydration process was consumed almost entirely by the high dosage of ground granulated blast-furnace slag (GGBS).
- Nano-silica's particles are very small which makes its specific surface very large. Consequently, its water demand is very large. Comparing the nano-silica

mixtures to their respective control mixtures showed that the addition of nano-silica reduced the slump and the flow spread values which indicated that nano-silica had negative influence on the workability of the concrete due to its high water demand. Furthermore, as the nano-silica dosage increased, the workability of mixtures decreased. Moreover, comparing the slump and flow results after thirty and sixty minutes to the initial values demonstrated that nano-silica accelerated the hydration process and reduced the setting time.

4.2. Recommendation

- To apply the x-ray analysis on a large number of locations (spectrums) on each mixture's specimen to obtain representative Ca and Si concentrations.
- More investigation would be beneficial to study the uniform dispersion and agglomeration due to the ultra-fine particle size of nano-silica
- Not to use nano-silica in concrete mixtures that incorporates very high dosages of pozzolanic materials such as GGBS and micro-silica because its effect could be highly limited in the hydration process.
- To study the interaction between fly ash and nano-silica

References

[1] F.U.A. Shaikh, S.W.M. Supit, P.K. Sarker, "A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes," *Materials and Design,* vol. 60, pp. 433-442, 2014.

[2] Mohamed Heikal, A.I. Ali, M.N. Ismail, S. Awad N.S. Ibrahim, "Behavior of composite cement pastes containing silica nano-particles at elevated temperature," *Construction and Building Materials* , vol. 70, pp. 339-350, 2014.

[3] S. Abd.EI.Aleem, Mohamed Heikal, W.M. Morsi, "Hydration characteristic, thermal expansion and microstructure of cement containing nano-silica," *Construction and Building Materials,* vol. 59, pp. 151-160, 2014.

[4] Hongjian Du, Suhuan Du, Xuemei Liu, "Durability performances of concrete with nano-silica," *Construction and Building Materials,* vol. 73, pp. 705-712, 2014.

[5] A.M. Said, M.S. Zeidan, M.T. Bassuoni, Y. Tian, "Properties of concrete incorporating nano-silica," *Construction and Building Materials* , vol. 36, pp. 838-844, 2012.

[6] Ye Qing, Zhang Zenan, Kong Deyu, Chen Rongshen, "Influence of nano-SiO2 addition on properties of hardened cement paste as compared with silica fume," *Construction and Building Materials,* vol. 21, pp. 539-545, 2007.

[7] D. Adak, M. Sarkar, S. Mandal, "Effect of nano-silica on strength and durability of fly ash based geopolymer mortar," *Construction and Building Materials* , vol. 70, pp. 453-459, 2014.

[8] Morteza Bastami, Mazyar Baghbadrani, Farhad Aslani, "Performance of nano-silica modified high strength concrete at elevated temperatures," *Construction and Building Materials* , vol. 68, pp. 402-408, 2014.

[9] Kiachehr Behfarnia, Niloofar Salemi, "The effects of nano-silica and nano-alumina on frost resistance of normal concrete," *Construction and Building Materials* , vol. 48, pp. 580-584, 2013.

[10] Min-Hong Zhang, Jahidul Islam, Sulapha Peethamparan , "Use of nano-silica to increase early strength and reduce setting time of concretes with high volumes of slag," *Cement & Concrete Composites* , vol. 34, pp. 650-662, 2012.

[11] Wail Nourildean Al-Rifaie, Omar Mohanad Mahdi, Waleed Khalil Ahmed, "Development of nano cement mortar as construction material," in *2nd International Conference on Sustainable Materials* , Penang, 2013.

[12] M. Berra, F. Carassiti, T. Mangialardi, A.E. Paolini, M. Sebastiani, "Effects of nanosilica addition on workability and compressive strength of portland cement pastes," *Construction and Building Materials* , vol. 35, pp. 666-675, 2012.

[13] L.P. Singh, S.R. Karade, S.K. Bhattacharyya, M.M. Yousuf, S. Ahalawat, "Beneficial role of nanosilica in cement based materials- A review," *Construction and Building Materials* , vol. 47, pp. 1069-1077, 2013.

[14] Sattawat Haruehansapong, Tawich Pulngern, Somchai Chucheepsakul, "Effect of the particle size of nanosilica on the compressive strength and the optimum replacement content of cement mortar containing nano-SiO2," *Construction and Building Materials,* vol. 50, pp. 471-477, 2014.

[15] Bibhuti Bhusan Mukharjee, Sudhirkumar V. Barai, "Influence of Nano-silica on the properties of recycled aggregate concrete," *Construction and Building Materials* , vol. 55, pp. 29-37, 2014.

[16] Ehsan Ghafari, Mahdi Arezoumandi, Hugo Costa, Eduardo Julio, "Influence of nano-silica addition on durability of UHPC," *Construction and Building Materials* , vol. 94, pp. 181-188, 2015.

[17] G. Quercia, P. Spiesz, G. Husken, H.J.H. Brouwers, "SCC modification by use of amorphous nano-silica," *Cement & Concrete Composites* , vol. 45, pp. 69-81, 2014.

[18] Ramesh. N, Eramma. H. , "Behaviour of GGBS and nano-silica on strength properties of concrete," *International Journal of Research in Engineering and Technology* , vol. 5, no. 6, pp. 142-148, 2016.

[19] D. V. Prasada Rao, U. Anil Kumar, "An expermental investigation on strength properties of concrete containing micro-silica and nano-silica," *International Journal of Civil Engineering and Technology* , vol. 5, no. 8, pp. 89-97, 2014.

[20] Maitri Mapa, Hemalatha, T. , Rama Chandra Murthy A., "Investigation on mechanical properties of silica and GGBS incorporated cement mortar," *International Journal of Research in Engineering and Technology,* vol. 4, no. 13, pp. 30-34, 2015.

[21] Hongru Zhang, Yuxi Zhao, Tao Meng, Surendra P. Shah, "The modification effects of a nano-silica slurry on microstructure strength, and strain development of recycled aggregate concrete applied in an enlarged structural test," *Construction and Building Materials* , vol. 95, pp. 721-735, 2015.

[22] Jing Xu, Binbin Wang, Junqing Zuo, "Modification effects of nanosilica on the interfacial transition zone in concrete: A multiscale approach," *Cement and Concrete Composites,* vol. 81, pp. 1-10, 2017.

[23] A. Ghazy, M. T. Bassuoni, and A. Shalaby, "Nano-modified fky ash concrete: A repair option for concrete pavements," *ACI Materials Journal,* vol. 113, no. 2, pp. 231-242, 2016.

[24] "Safety Data Sheet," Elkem , Kristiansand , 2009.

[25] T. C. Holland, "Silica Fume User's Manual," United States Department of Transportation , Washington DC, 2005.

[26] "Sharjah Cement Factory," Sharjah Cement & Industrial Development Co., 2015. [Online]. Available: http://www.sharjahcement.com/en/portland-cement/. [Accessed 13 september 2015].

[27] "Megaflow 1000 polycarboxylated superplasticizer," Conmix Limited, 1 2011. [Online]. Available: http://asengineersbd.com/ans_admin/images/product_photo/13MegaFlow1000.pdf. [Accessed 3 5 2017].

[28] Michael S. Mamlouk, John P. Zaniewski, *Material for Civil and Construction Engineers*, New Jersey: Pearson Education , 2011.

[29] Henry G. Russell, "HPC Bridge Views," Federal Highway Administration and the National Concrete Bridge Council, November 2010. [Online]. Available: http://www.hpcbridgeviews.com/i64/Article4.asp. [Accessed 2 April 2016].

[30] J. S. Martin, "An Experimental Investigation of Bond in Reinforced Concrete," M.S. Thesis, University of Washington , Washington, 2006.

[31] D. P. Bentz, "A virtual rapid chloride permeability test," *Cement & Concrete Composites* , vol. 29, pp. 723-731, 2007.

[32] Prakash Joshi, Cesar Chan, "Rapid Chloride PermeabilityTesting," Hanley-Wood, LLC, Washington, D.C., 2002.

[33] W. J. Abdulkatib, "Design and performance of sustainable/green concrete," M.S. Thesis, American University of Sharjah , Sharjah, 2016.

[34] "ASTM International," CrossRef, 2010. [Online]. Available: https://www.astm.org/Standards/C1723.htm. [Accessed 10 October 2016].

[35] R.V. Balendran H.W. Pang H.X. Wen, "Use of scanning electron microscopy in concrete studies," *Structural Survey,* vol. 16, no. 3, pp. 146 - 153 , 1998.

[36] E. C. Bentz, M. D. A. Thomas, "Life-365 Service Life Prediction Model," Silica Fume Association, 2001.

[37] Geoffrey Hammond, Craig Jones , "Embodied Carbon," BSRIA, 2011.

[38] Geoff Hammond, Craig Jones, "Inventory of Carbon & Energy (ICE) Version 2.0," University of Bath, Bath, 2011.

[39] Aysha. H, T. Hemalatha, N. Arunachalam, A. Ramachandra Murthy, Nagesh R. Iyer, "Assessment of embodied energy in the production of Ultra High Performance Concrete (UHPC)," *International Journal of Students Research in Technology & Management* , vol. 2, no. 3, pp. 113-120, 2014.

Appendix A: Scanning Electron Microscopy Images

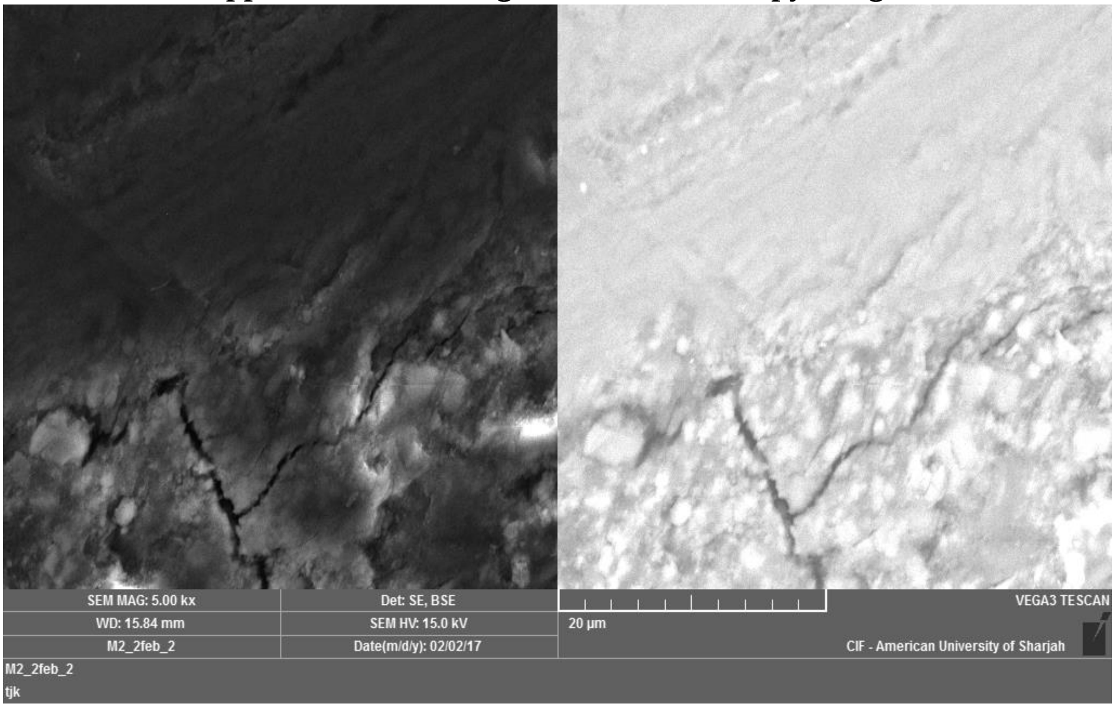


Figure 32. Additional SE and BSE SEM image of M1 at 5.00 KX magnification.

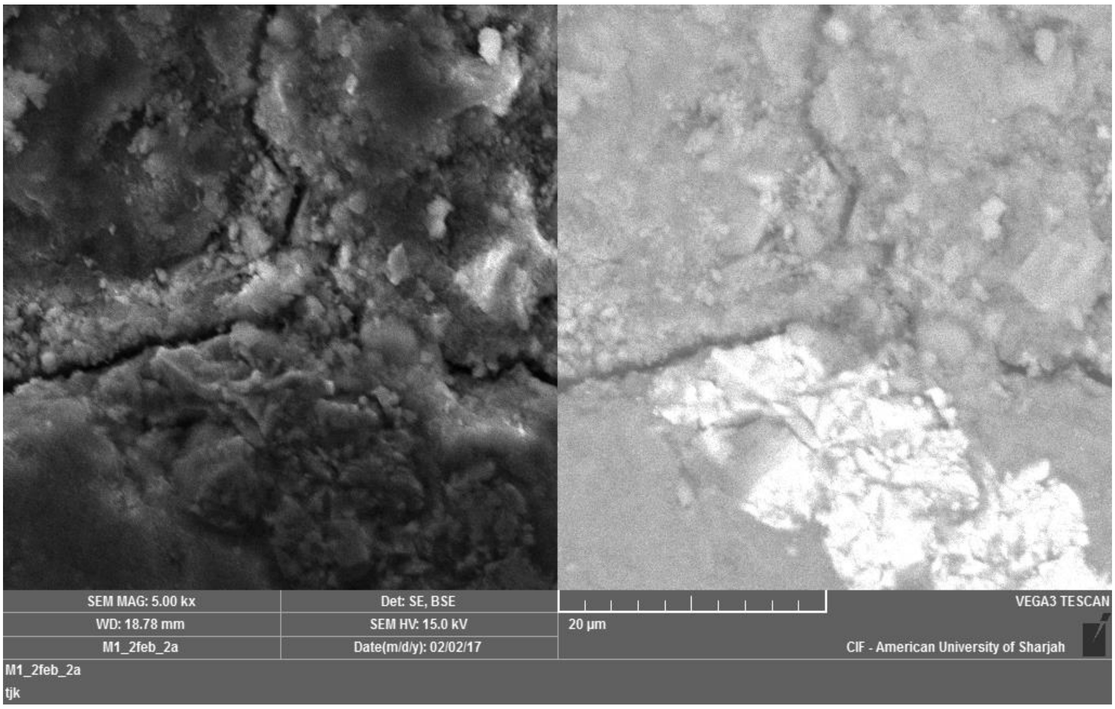


Figure 33. Additional SE and BSE SEM image of M2 at 5.00 KX magnification.

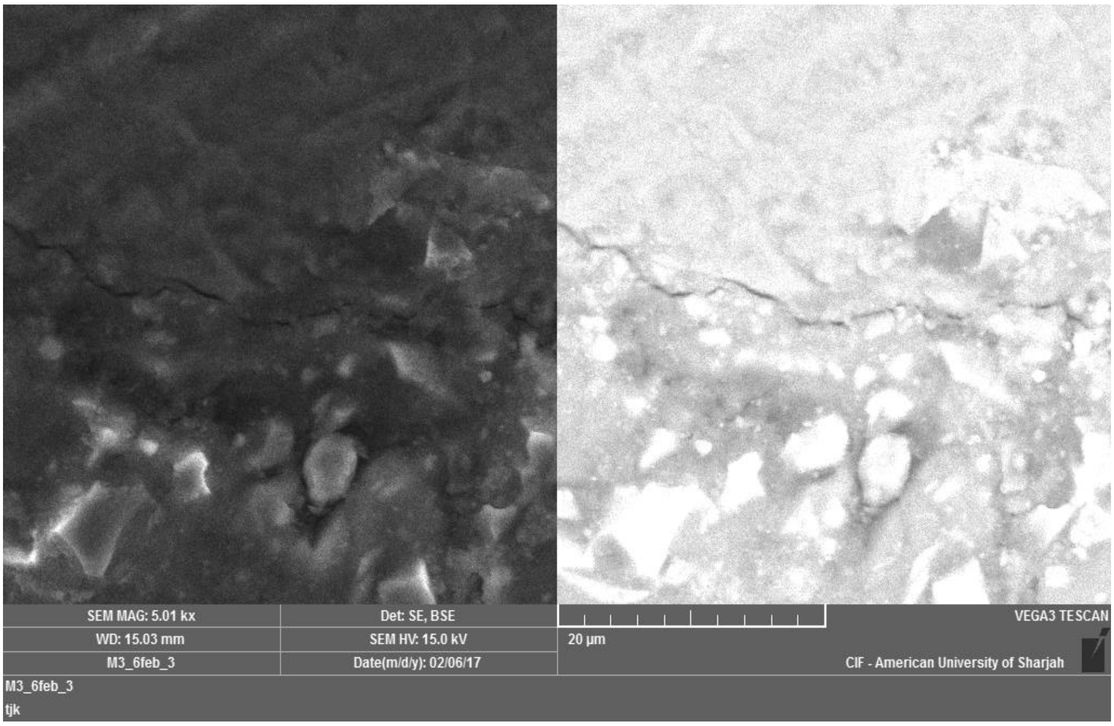


Figure 34. Additional SE and BSE SEM image of M3 at 5.01 KX magnification.

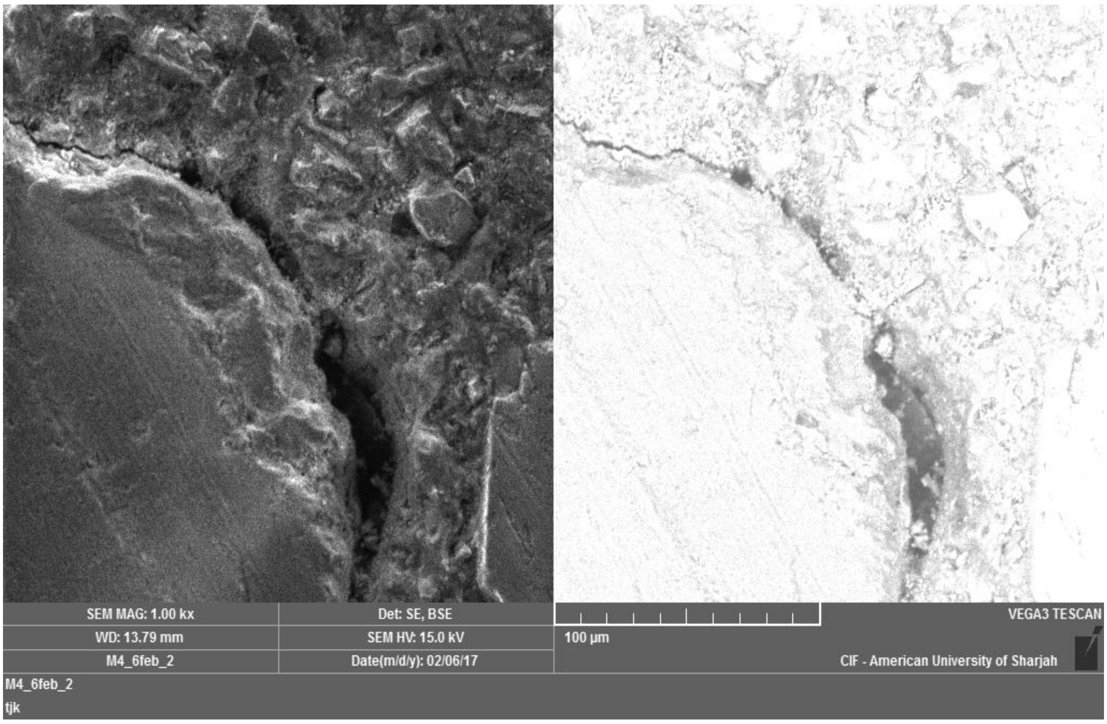


Figure 35. Additional SE and BSE SEM image of M4 at 1.00 KX magnification.

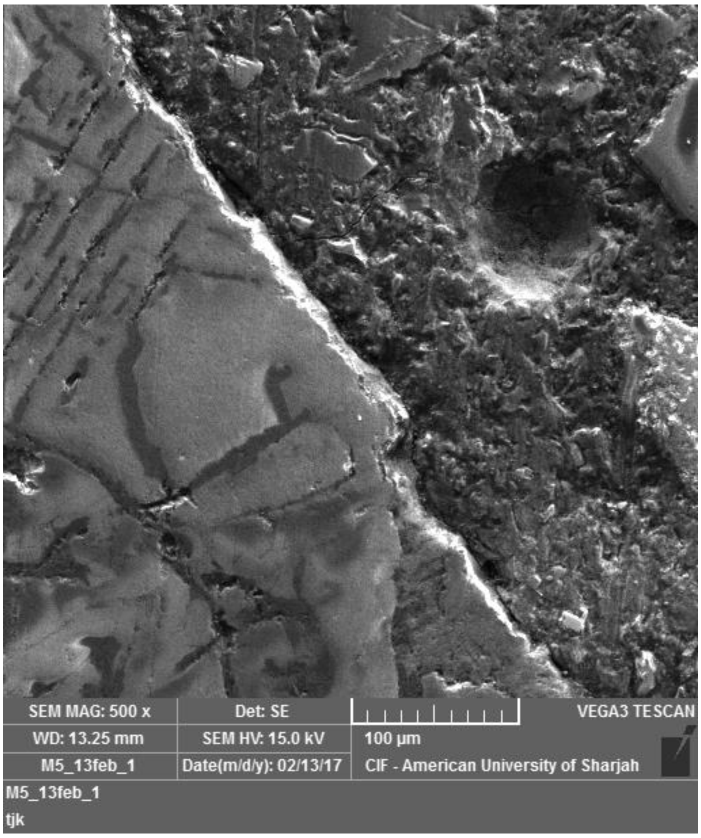


Figure 36. Additional SE SEM image of M5 at 5.00 KX magnification.

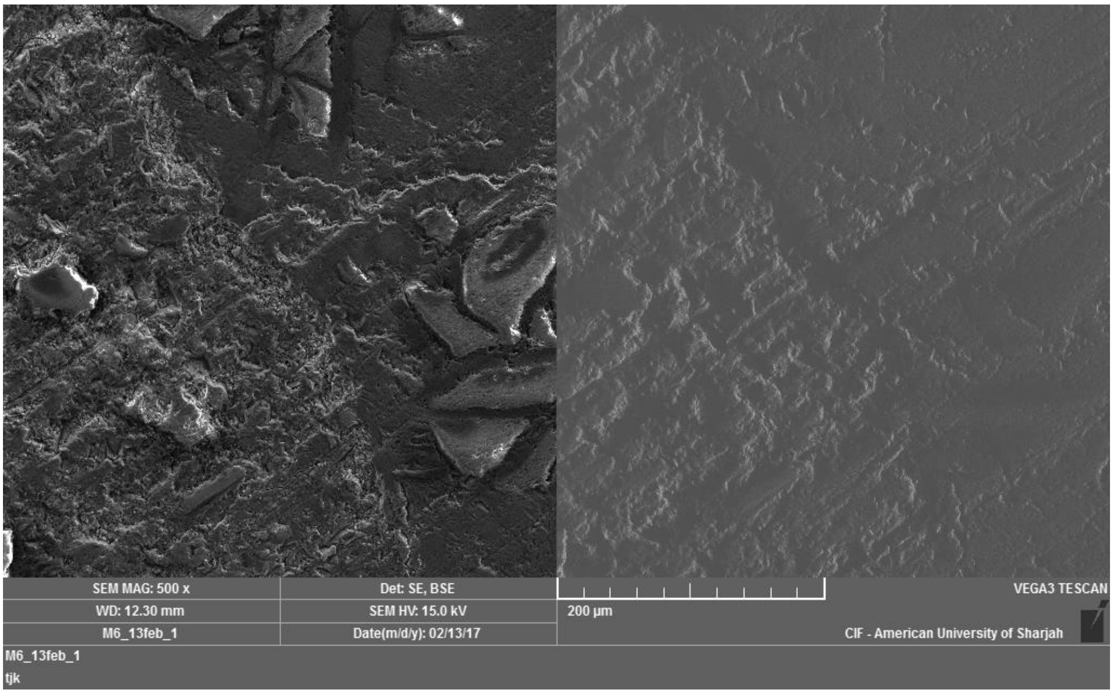


Figure 37. Additional SE and BSE SEM image of M6 at 5.00 X magnification

Appendix B: Material Properties

بلدية مدينة الشارقة
SHARJAH CITY MUNICIPALITY

الإدارة المشاريع
Project Department
Construction Materials Laboratory Section
Tel : 06 5436755 Fax : 06 5437560

REPORT ON	: **FINE AGGREGATE**
LABORATORY	: **AGGREGATE**
REPORT NO.	: 136009~ MAY , 2016 — **Date :20/06/2016**

CONTRACT NO. : –
MANUFACTURER : CONMIX LTD
CONSULTANT : —
PROJECT NAME : QUALITY CONTROL SAMPLE
LOCATION : INDUSTRIAL AREA # 12 , SHARJAH
DESCRIPTION : (0-5)mm CRUSHED ROCK SAND
SOURCE : AL SHAMSI CRUSHER, FUJAIRAH

RELATIVE DENSITY & WATER ABSORPTION BS 812 : PART 2 : 1995 CLS. 5.5	APPARENT RELATIVE DENSITY	2.67
	RELATIVE DENSITY ON OVEN DRY BASIS	2.57
	RELATIVE DENSITY ON S.S.D. BASIS	2.61
	WATER ABSORPTION (%)	1.41
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)	3.2
	SULPHATE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 118 : 1988)	0.14
	CHLORIDE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 117 : 1988) (AS Cl)	0.03
	CLAY LUMPS AND FRIABLE PARTICLES (% BY MASS OF DRY SAMPLE (ASTM C 142-78(REAPPROVED 1990))	0.2
	MAGNESIUM SULPHATE SOUNDNESS (% BY MASS OF DRY SAMPLE) (ASTM C 88 – 99a)	2.0
	ORGANIC IMPURITIES TEST (ASTM C 40 - 04)	NIL

SIEVE SIZE (mm)	% PASSING
6.3	100
5.00	98
2.36	65
1.18	39
0.600	23
0.300	12
0.150	6
0.075	3.2

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

CHECKED BY: OFFICER INCHARGE:

إدارة المشاريع
قسم مختبر مواد البناء
Project Dept
Construction Materials Lab Section

Tel: +971 6 562 3333 - Fax: +971 6 5626 455 - P.O.Box: 22 Sharjah U.A.E.
www.shjmun.gov.ae e-mail: info@shjmun.gov.ae

بلدية مدينة الشارقة
United Arab Emirates – Sharjah Government
SHARJAH CITY MUNICIPALITY

الإدارة المشاريع
Project Department
قسم بحوث مواد البناء
Construction Materials Laboratory Section
Tel : 06 5436755 Fax : 06 5437560

REPORT ON	: **FINE AGGREGATE**
LABORATORY	: **AGGREGATE**
REPORT NO.	: 136009~ MAY , 2016 **Date : 20/06/2016**

CONTRACT NO. : -
MANUFACTURER : CONMIX LTD
CONSULTANT : –
PROJECT NAME : QUALITY CONTROL SAMPLE
LOCATION : INDUSTRIAL AREA # 12 , SHARJAH
DESCRIPTION : UNCRUSHED SAND (DUNE SAND)
SOURCE : AL AIN

RELATIVE DENSITY & WATER ABSORPTION BS 812 : PART 2 : 1995 CLS. 5.5		APPARENT RELATIVE DENSITY	2.68
		RELATIVE DENSITY ON OVEN DRY BASIS	2.63
		RELATIVE DENSITY ON S.S.D. BASIS	2.65
		WATER ABSORPTION (%)	0.65
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)	2.7
SIEVE SIZE (mm)	% PASSING	SULPHATE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 118 : 1988)	0.08
0.600	100	CHLORIDE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 117 : 1988) (AS Cl)	0.01
0.300	100	ORGANIC IMPURITIES TEST (ASTM C 40 - 04)	NIL
0.150	72		
0.075	2.7		

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

CHECKED BY:

OFFICER INCHARGE:

إدارة المشاريع
قسم مختبر مواد البناء
Project Department
Construction Materials Lab Section

بلدية مدينة الشارقة
SHARJAH CITY MUNICIPALITY

الإدارة المشاريع
Project Department
Construction Materials Laboratory Section
Tel : 06 5436755 Fax : 06 5437560

REPORT ON	: **COARSE AGGREGATE**
LABORATORY	: **AGGREGATE**
REPORT NO.	: 136009~ MAY , 2016 **Date : 20/06/2016**

CONTRACT NO. : -
MANUFACTURER : CONMIX LTD
CONSULTANT : --
PROJECT NAME : QUALITY CONTROL SAMPLE
LOCATION : INDUSTRIAL AREA # 12 , SHARJAH
DESCRIPTION : 10 mm CRUSHED ROCK AGGREGATE
SOURCE : AL JABER CRUSHER. R.A.K.

RELATIVE DENSITY & WATER ABSORPTION ASTM C 127 - 01		APPARENT RELATIVE DENSITY	2.95
		RELATIVE DENSITY ON OVEN DRY BASIS	2.90
		RELATIVE DENSITY ON S.S.D. BASIS	2.91
		WATER ABSORPTION (%)	0.62
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)	0.7
SIEVE SIZE (mm)	% PASSING	SULPHATE CONTENT (% BY MASS OF DRY SAMPLE) (BS 812 - 118 : 1988)	0.09
		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)	14
		ELONGATION INDEX (% BY MASS OF DRY SAMPLE) (BS 812 - 105.2 :1990)	24
14.0	100	RESISTANCE TO DEGRADATION OF SMALL SIZE COARSE AGGREGATE BY ABRASION & IMPACT IN THE LOS ANGELES MACHINE (% LOSS BY MASS) -(ASTM C 131-03)	12
10.0	98		
6.30	47	CLAY LUMPS & FRIABLE PARTICLES (% BY MASS OF DRY SAMPLE) (ASTM C 142-97)	0.1
5.00	14		
2.36	1	MAGNESIUM SULPHATE SOUNDNESS (% LOSS BY MASS OF DRY SAMPLE) (ASTM C 88 - 99A)	0.8
0.075	0.7		

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

CHECKED BY : OFFICER INCHARGE:

إدارة المشاريع
قسم مختبر مواد البناء
Project Dept
Construction Materials Lab Section

Tel: +971 6 562 3333 - Fax: +971 6 5626 455 - P.O.Box: 22 Sharjah U.A.E.
www.shjmun.gov.ae e-mail: info@shjmun.gov.ae

بلدية مدينة الشارقة

SHARJAH CITY MUNICIPALITY

الإدارة المشاريع
Project Department
Construction Materials Laboratory Section
Tel : 06 5436755 Fax : 06 5437560

REPORT ON	: **COARSE AGGREGATE**
LABORATORY	: **AGGREGATE**
REPORT NO.	: 136009- MAY, 2016 **Date : 20/06/2016**

CONTRACT NO. : -
MANUFACTURER : CONMIX LTD
CONSULTANT :
PROJECT NAME : QUALITY CONTROL SAMPLE
LOCATION : INDUSTRIAL AREA # 12 , SHARJAH
DESCRIPTION : 20 mm CRUSHED ROCK AGGREGATE
SOURCE : AL JABER CRUSHER. R.A.K.

RELATIVE DENSITY & WATER ABSORPTION ASTM C 127 - 01		APPARENT RELATIVE DENSITY	2.99
		RELATIVE DENSITY ON OVEN DRY BASIS	2.95
		RELATIVE DENSITY ON S.S.D. BASIS	2.96
		WATER ABSORPTION (%)	0.42
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
SIEVE SIZE (mm)	% PASSING	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)	0.01
		FLAKINESS INDEX (% BY MASS OF DRY SAMPLE) (BS 812 - 105.1 : 1989)	14
		ELONGATION INDEX (% BY MASS OF DRY SAMPLE) (BS 812 - 105.2 :1990)	25
28.0	100	RESISTANCE TO DEGRADATION OF SMALL SIZE COARSE AGGREGATE BY ABRASION & IMPACT IN THE LOS ANGELES MACHINE (% LOSS BY MASS) -(ASTM C 131-03)	13
20.0	99		
14.0	47	CLAY LUMPS & FRIABLE PARTICLES (% BY MASS OF DRY SAMPLE) (ASTM C 142-97)	0.1
10.0	7		
6.3	1	MAGNESIUM SULPHATE SOUNDNESS (% LOSS BY MASS OF DRY SAMPLE) (ASTM C 88 – 99a)	0.5
5.0	0.4		
2.36	0.4	DRYING SHRINKAGE OF AGGREGATE IN CONCRETE (BS 812-120:1989) (% BY MASS OF DRY SAMPLE)	0.072
0.075	0.3		

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

CHECKED BY : **OFFICER INCHARGE :**

الإدارة المشاريع
Project Dept
Constructional Materials Lab Section

Tel: +971 6 562 3333 - Fax: +971 6 5626 455 - P.O.Box: 22 Sharjah U.A.E
www.shjmun.gov.ae e-mail: info@shjmun.gov.ae

بلدية مدينة الشارقة

SHARJAH CITY MUNICIPALITY

REPORT ON	: CHEMICAL ANALYSIS OF WATER FOR CONCRETING PURPOSES				
LABORATORY	: CHEMICAL	DATE OF SAMPLE RECEIVED			26/05/2016
DATES OF SAMPLE ANALYZED		30-31/05/2016	DATE OF TEST REPORT ISSUED		2/6/2016
REPORT NO.	2016-136009	SAMPLE ID.	187249	SUB SAMPLE ID.	344927
PROJECT NAME	: QUALITY CONTROL				
MANUFACTURER	: CON MIX LTD				
LOCATION	: SHJ.INDUSTRIAL AREA NO.12				
SOURCE	: TARGET WATER SUPPLY - SHJ				
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	25	500	1000	ASTM D516-90(95)
CHLORIDES (Cl), mg/L	71	600	500	ASTM D512-89(94) (TM-B)
TOTAL DISSOLVED SOLIDS ,mg/L	196	2000	2000	BS 1377:P3:90:CL.8(AND9026)
CARBONATES , & BICARBONATES, mg/L	24	1000	1000	ASTM D1067-92(96) TEST METHOD B
pH VALUE	7.1	7 TO 9	NOT SPECIFIED	ASTM D1293-95:(TM-A)
TEMP. @ degrees Celsius	25.3			

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:

إدارة المشاريع
قسم مختبر مواد البناء
Projects Dept
Construction Materials Lab Section

بلدية مدينة الشارقة
SHARJAH CITY MUNICIPALITY

الإدارة المشاريع
Project Department
قسم مختبر مواد البناء
Construction Materials Laboratory Section
Tel : 06 5436755 Fax : 06 5437560

REPORT ON	: **DRYING SHRINKAGE OF AGGREGATES IN CONCRETE**
LABORATORY	: **AGGREGATE**
REPORT NO.	: 136009– MAY , 2016 **Date : 20/06/2016**

CONTRACT NO. : –
MANUFACTURER : CONMIX LTD
CONSULTANT : –
PROJECT NAME : QUALITY CONTROL SAMPLE
LOCATION : INDUSTRIAL AREA # 12 , SHARJAH

SOURCE, TYPE AND SIZES OF AGGREGATE SUBMITTED FOR TEST:

20 mm CRUSHED ROCK AGGREGATE	: FROM - AL JABER CRUSHER. R.A.K.
10 mm CRUSHED ROCK AGGREGATE	: FORM - AL JABER CRUSHER. R.A.K.
(0-5)mm CRUSHED ROCK SAND	: FROM - AL SHAMSI CRUSHER, FUJAIRAH
UNCRUSHED SAND (DUNE SAND)	: FROM – AL AIN

TEST RESULT

DRYING SHRINKAGE OF AGGREGATE	:	**0.072 %**
95 % CONFIDENCE LIMITS	:	**0.067 % TO 0.091 %**
CLASSIFICATION OF AGGREGATE	:	**" A "CATEGORY**

CATEGORIES OF USE

CATEGORY	RANGE OF SHRINKAGE VALUES (%)	USE
A	0 TO 0.075 %	All concreting purposes
B	Greater than 0.075 %	• Positions where drying out never occurs. • Mass concrete with air entrained concrete. • Members symmetrically and heavily reinforced not exposed to the weather.

SAMPLE BROUGHT IN BY : C.M. LAB. SECTION
TEST METHOD : BS 812 - 120 :1989
REMARKS This report represent only the received sample.

TESTED BY: OFFICER INCHARGE.

إدارة المشاريع
قسم مختبر مواد البناء
Project Dept.
Constructional Materials Lab Section

هاتف ٣٣٣٣ ٥٦٢ ٦ ٩٧١+ فاكس ٥٤٥٥ ٥٦٢٦ ٦ ٩٧١+ ص.ب ٢٢ الشارقة - إ.ع.م
Tel: +971 6 562 3333 - Fax: +971 6 5626 455 - P.O.Box: 22 Sharjah U.A.E.
www.shjmun.gov.ae e-mail: info@shjmun.gov.ae

SHARJAH CEMENT FACTORY
A Division of
Sharjah Cement & Industrial Development Co.

مصنع أسمنت الشارقة
احد اقسام
شركة الشارقة للأسمنت والتنمية الصناعية

MANUFACTURER'S CERTIFICATE

Our Ref: SR

Date : 29/08/2016

Portland Cement

Despatched to the order of ______________________________

to ______________________________

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

Test results relating to despatch samples for week ending 19/08/2016					
PHYSICAL TESTS			**CHEMICAL ANALYSIS**		
Test	Requirement	Result	Test	Requirement	Result %
Fineness Specific surface m^2 / kg	Not Specified	335	SiO_2	No Limit	20.5
			IR	5.0 % max	0.34
Setting time Minutes Initial	60 minimum	140	Al_2O_3	No Limit	5.0
Final	Not specified	190	Fe_2O_3	No Limit	3.9
Soundness Le-chatelier Expansion mm	10 maximum	1.0	CaO	No Limit	64.2
Compressive Strength			MgO	5.0 % max (for clinker)	1.5
			SO_3	3.5 % max	2.1
Mortar Prism MPa			= Na_2O	No Limit	0.50
2 day	10 minimum	25.9	LOI	5.0 % max	2.6
7 day	Not Specified	40.4	Cl^-	0.10 % max	0.02
W / E 29/07/2016 28 day	42.5 minimum 62.5 maximum	52.0	C_3A	No Limit	6.6

Test Temperature 22 ± 1 °C.
1 MPa = 1 N / mm²

For and on behalf of
SHARJAH CEMENT FACTORY

pp **WORKS MANAGER**

P.O. Box : 5419, Sharjah - U.A.E.
Tel.: 00971-6-5311583 / 5311584 / 5311783
Fax: 00971-6-5311181 / 5311589
E-mail : shjcement@emirates.net.ae
Web Site : www.sharjahcement.com

ص.ب ٥٤١٩ الشارقة - دولة الإمارات العربية المتحدة
البريد الإلكتروني shjcement@emirates.net.ae
الموقع الإلكتروني www.sharjahcement.com

SHARJAH CEMENT FACTORY
A Division of
Sharjah Cement & Industrial Development Co.

مصنـــع اسمنت الشـــارقـــة
شركة الشارقة للأسمنت والتنمية الصناعية

MANUFACTURER'S CERTIFICATE

Our Ref: SR

Date: 29/08/2016

Ground Granulated Blastfurnace Slag

Dispatched to the order of ______________________

to ______________________

is guaranteed to comply with BS 6699 : 1992

Test results relating to despatch samples for week ending 19/08/2016

PHYSICAL TESTS

Test		Requirement	Result
Moisture		1.0 % max	0.45
Fineness Specific surface m^2/kg		275 minimum	390
Setting time* Minutes Initial		60 minimum	275
Final		Not specified	350
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	8.4
P C -	2 day	10 minimum	26.1
	7 day	12 minimum	28.5
P C -	7 day	Not specified	40.6
W / E 29/07/2016	28 day	32.5 minimum	48.0
P C -	28 day	42.5 minimum 62.5 maximum	53.6

CHEMICAL ANALYSIS

Test	Requirement	Result %
SiO_2	No Limit	33.0
IR	1.5 % max	0.28
Al_2O_3	No Limit	14.7
Fe_2O_3	No Limit	0.4
CaO	No Limit	39.7
MgO	14.0 % max	7.7
SO_3	2.5 % max	0.08
S	2.0 % max	0.86
$\pm Na_2O$	No Limit	0.42
Mn_2O_3	2.0 % max	0.29
LOI**	3.0 % max	1.9
Cl^-	0.10 % max	0.01
CHEMICAL MODULAI SUM (CaO + MgO + SiO_2)	66.7 % min	80.4
Modulus (CaO+MgO) / (SiO_2)	1.0 min	1.4
Modulus (CaO) / (SiO_2)	1.4 max	1.2
Glass Content	67.0 % min	98.8

Test Temperature 22 ± 1 °C

* 70 % GGBS + 30 % P C Class 42.5 N - LA

**Loss on ignition correction for sulfide

For and on behalf of
SHARJAH CEMENT FACTORY

pp WORKS MANAGER

P.O. Box : 5419, Sharjah - U.A.E.
Tel : 00971-6-5311583 / 5311584 / 5311193
Fax : 00971-6-5311181 / 5311509
E-mail : shjcement@emirates.net.ae
Web Site : www.sharjahcement.com

FerroPem
Groupe • FerroAtlántica

AENOR AFAQ ISO 9001 ISO 14001 OHSAS 18001

FERROPEM
USINE DE LAUDUN
30290 LAUDUN
France

CONMIX LTD
PO BOX 5936
SHARJAH
EMIRATS ARABES UNIS

CERTIFICATE OF ANALYSIS

Order	861806	Dated 01/07/2016
Customer	CONMIX LTD	
Customer order	16204385/0	
Product	MICRO SILICA	
Packing	1 BB 1250KG FERROPEM / PALETTE	
Lot	EXE639 LAU2116 -2416 -2516 -2616 -2717 -2816	
Quantity	250 Tons	

Chemistry				
Elements	**Unit**	**Value**	**Mini**	**Maxi**
Moisture	%	0,140		3,000
Equivalent Alkalies	%	0,720		
SiO2	%	92,490	85,000	
Loss on ignition	%	3,700		6,000

Physical				
Elements	**Unit**	**Value**	**Mini**	**Maxi**
Retained on 45 micron sieve	%	2,540		10,000
Pozzolanic Activity Index (7 days)	%	134,000	105,000	
Bulk Density	kg /m3	551,000		
Specific Gravity	g/cm3	2,200		
Specific Surface	m^2/g	21,500	15,000	

Silica Fume conforming to the ASTM C1240-14 Standard

Date : 29/07/2016

GILLES BONNET
RESPONSABLE EXPÉDITIONS

Visa :

FerroPem
Groupe • FerroAtlántica
Société par Actions Simplifiée
642 005 177 RCS Chambéry
Siège Social :
517, avenue de la Boisse
73000 CHAMBERY - FRANCE
Tél. 04 79 68 31 00

FERROPEM
517, avenue de la Boisse - 73025 Chambery - France
Tél: +33 (0)4 79 68 31 00 / Fax: +33(0)4 79 68 31 44

MegaFlow 1000

Polycarboxylated Superplasticiser

DESCRIPTION

MegaFlow 1000 is a modified polycarboxylate ether based superplasticiser. Having unique carboxylic ether polymer with long lateral chains, it is an effective cement dispersant, fluidifier and high range water reducer as compared to conventional superplasticisers.

STANDARDS

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

USES

MegaFlow 1000 is specially intended for use in self compacting concrete, high strength concrete, durable concrete containing GGBS, micro silica, fly ash, etc. It is used in ready-mix concrete where extra ordinary slump retention is required in hot weather conditions. Extremely useful in high fines concrete.

ADVANTAGES

- Produces free flowing concrete without segregation and bleeding
- High strength concrete with low water content
- Produces self compacting concrete without segregation
- Improved surface finish
- Improved adhesion to reinforcing and stressing steel
- Lower permeability, better resistance to carbonation
- Increased flexural strengths
- Good slump retention for longer time
- Remarkably superior performance than normal superplasticiser

TYPICAL PROPERTIES at 25°C

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

COMPATIBILITY

MegaFlow 1000 can be used with all types of cements and cementitious materials like fly ash, GGBS, micro silica etc. It 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 1000** 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

MegaFlow 1000

	MegaAdd VE may be required at a dosage between 0.5 - 2.0 ltrs per cubic meter. (Dosage depends upon the material used)
EFFECT OF OVERDOSING	Overdosing may result in higher workability and delay in setting. In such cases, provided the concrete is properly cured, the ultimate strength will generally be higher than the regular concrete.
PACK SIZE	20 ltr, 200 ltr, 1000 ltr and Bulk
DISPENSING	**MegaFlow 1000** should be dispensed into the concrete mixer together with the mixing water.

GENERAL INFORMATION	**Shelf Life**	12 months from date of manufacture when stored under warehouse conditions in original unopened packing. Extreme temperature / humidity may reduce shelf life.
	Cleaning	Clean all equipments and tools with water immediately after use.
HEALTH and SAFETY	**PPE's**	Gloves, goggles and suitable mask must be worn.
	Precautions	Contact with skin, eyes, etc. must be avoided. If swallowed seek medical attention immediately.
	Hazard	Regarded as non-hazardous for transportation.
	Disposal	Do not reuse containers. To be disposed off as per local rules and regulations.
	Additional Information	Refer MSDS. (Available on request.)

TECHNICAL SERVICE	**CONMIX Technical Services** are available on request for onsite support to assist in the correct use of its products.

Manufacturer:
CONMIX LTD.
P.O. Box 5936, Sharjah
United Arab Emirates
Tel: +971 6 5314155
Fax: +971 6 5314332
Email: conmix@conmix.com

Sales Office:
Tel: +971 6 5582422
Fax: +971 6 5581442
www.conmix.com

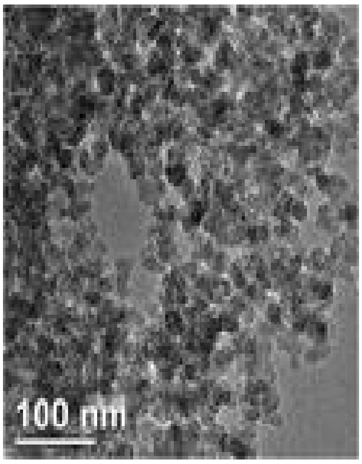
ISO 9001

Data Sheet

Silicon Oxide (99+%, 20 nm, Hydrophilic), Product# 4831HT

Silicon Oxide, SiO_2
Average Particle Size: 20 nm
Morphology of Particles: Spherical
Specific Surface Area: ≤120 m^2/g
Surface Performance: Hydrophilic
Crystallographic Structure: Amorphous
Bulk Density: 0.03-0.05 g/cm^3
Color: white
pH value: 5.5-6.5
Loss on Drying (110 ^oC/2h): ≤6.0 wt%
Loss on Calcination (850 ^oC/2h): ≤10.0 wt%

TEM Image



Nanostructured & Amorphous Materials, Inc.
16840 Clay Road, Suite #113, Houston, TX 77084, USA
Phone: (281) 858-6571• Fax: (281) 858-6507
E-mail: sales@nanoamor.com• Website: http://www.nanoamor.com

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: Additional Tests Results

- Compressive strength

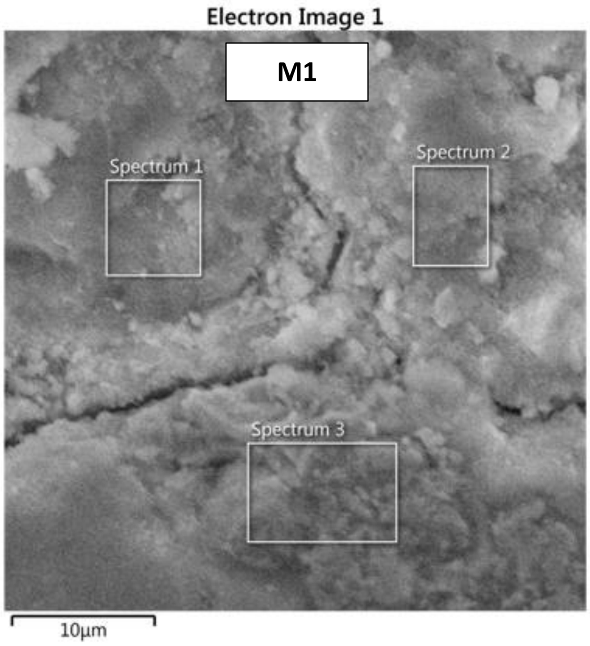
Table 43. Additional Proportions of concrete mixtures.

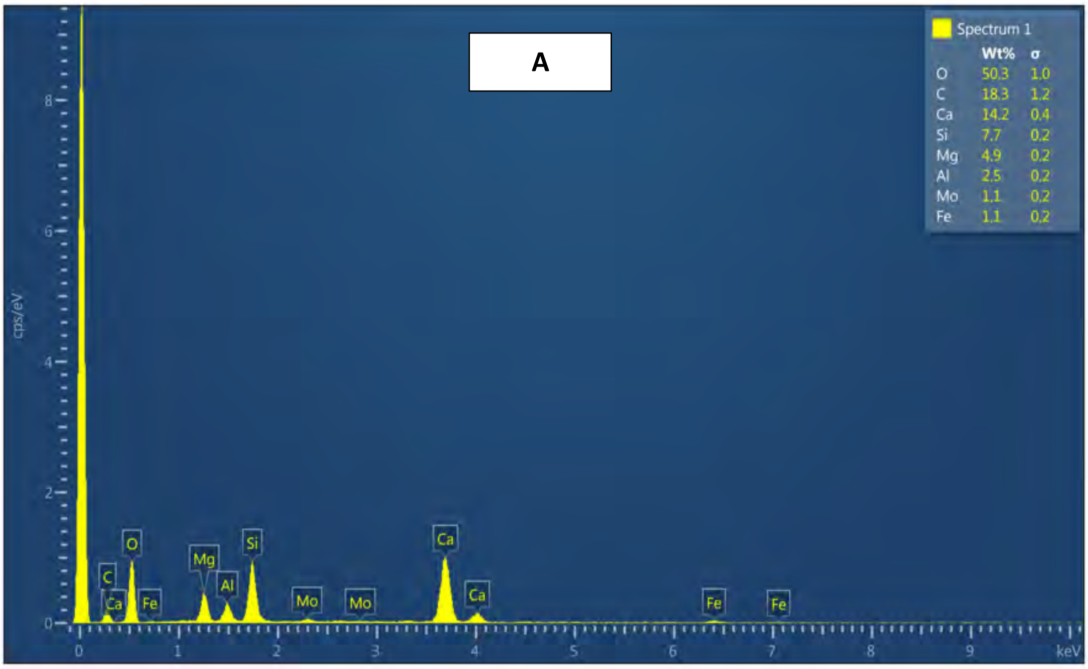
	Nano-silica (%)	Micro-silica (%)	GGBS (%)	OPC (%)
M1	0	5	70	25
M2	1	5	70	24
M3	2	5	70	23
M4	5	5	70	20

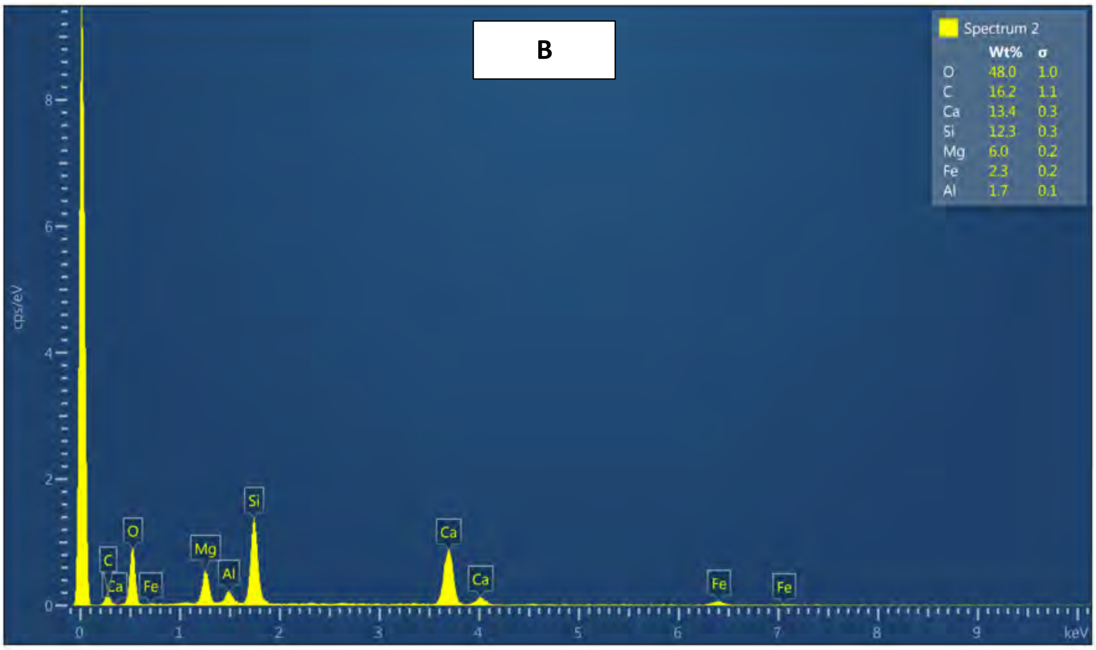
Table 44. Compressive strength resullts of the additional mixtures.

	M1		M2		M3		M4	
1 Day – Compressive strength (MPa) (Average of 3 specimens)	34.1		29.3		37.2		25.6	
	33.6	33.5	30.2	30.1	36.4	37.5	28.3	28.0
	32.9		30.9		38.8		30.0	
3 Days – Compressive strength (MPa) (Average of 3 specimens)	51.6		46.0		45.8		42.6	
	51.1	52.3	44.2	45.3	44.7	45.5	43.4	42.8
	54.3		45.6		45.9		42.4	
7 Days – Compressive strength (MPa) (Average of 3 specimens)	58.0		52.8		53.8		49.7	
	55.2	57.7	53.0	53.0	54.1	54.2	48.8	50.4
	59.8		53.2		54.6		52.6	
28 Days – Compressive strength (MPa) (Average of 3 specimens)	76.2		60.7		63.5		65.4	
	75.3	75.8	59.0	61.5	62.4	62.0	64.9	65.3
	75.8		64.8		60.7		65.6	

➢ Scanning Electron Microscopy (X-ray analysis)







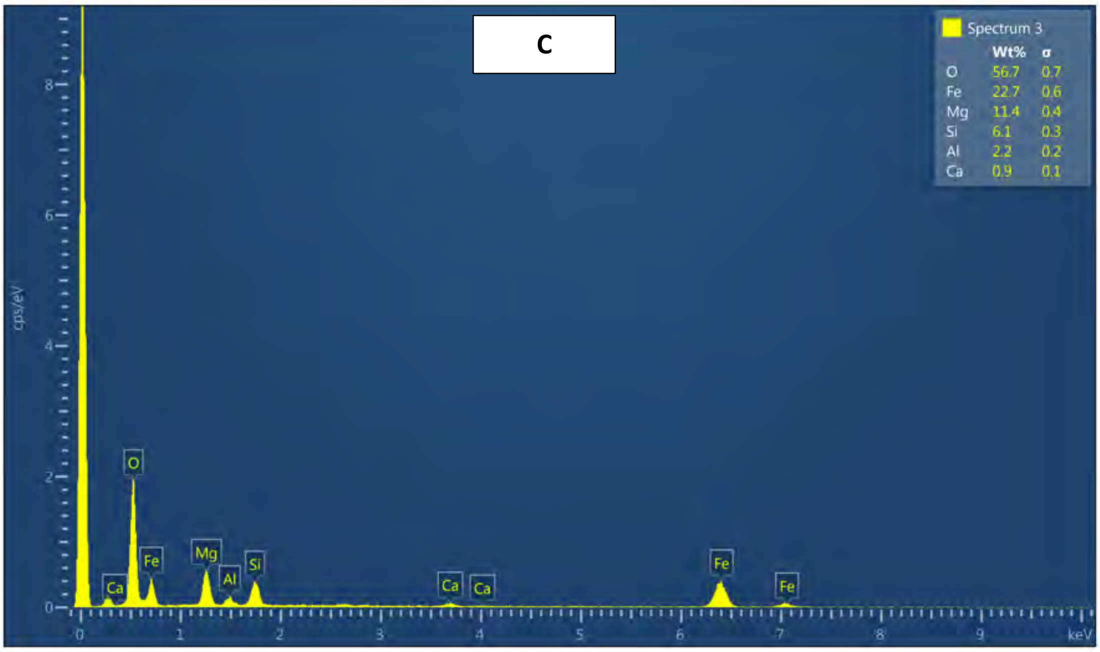
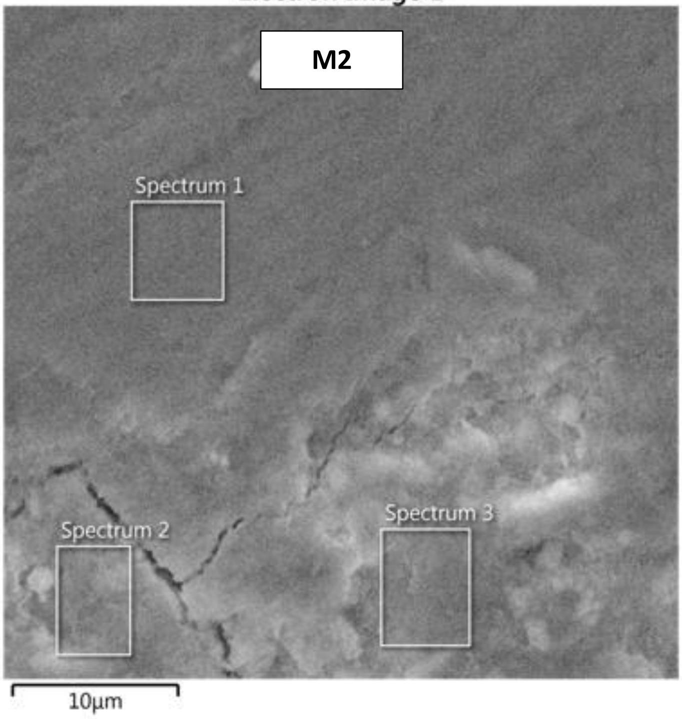
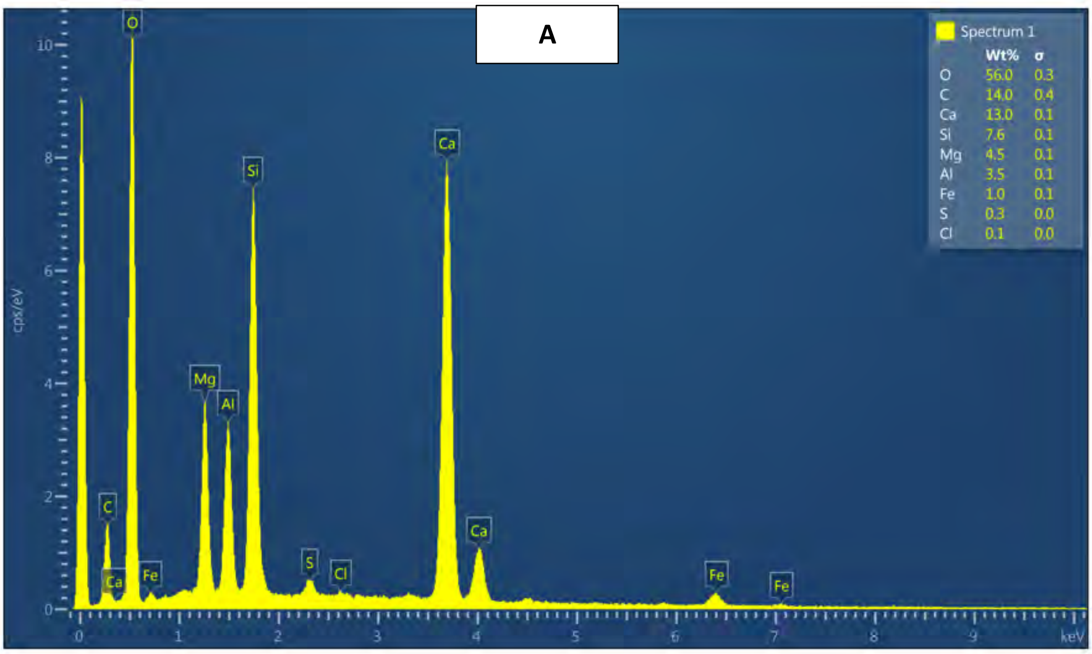
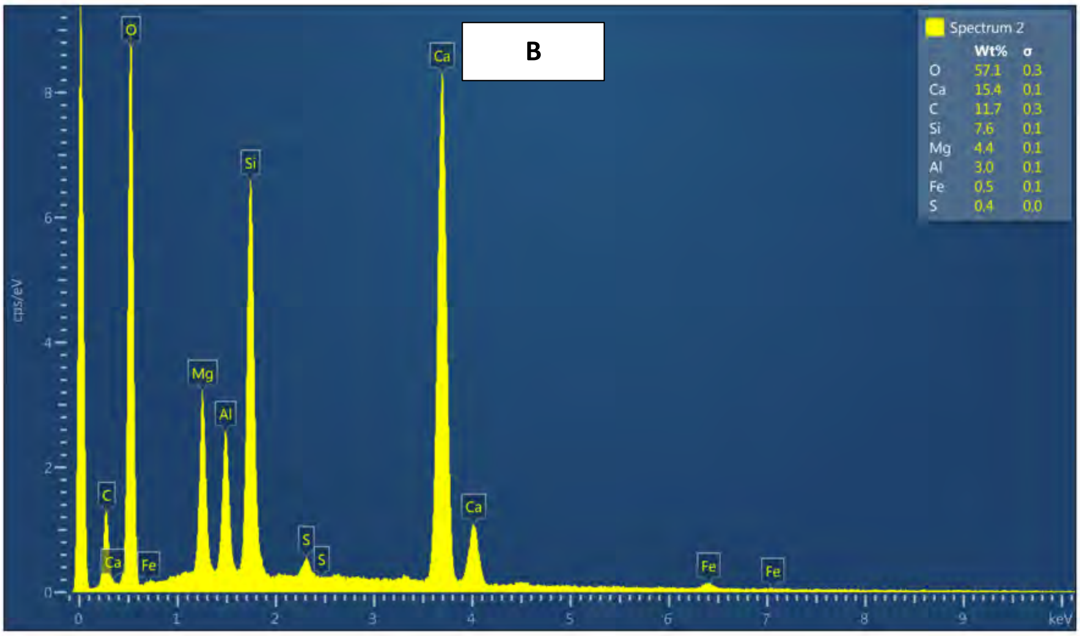


Figure 38. X-ray analysis of M1 A) Spectrum 1, B) Spectrum 2, and C) Spectrum 3.

Electron Image 1







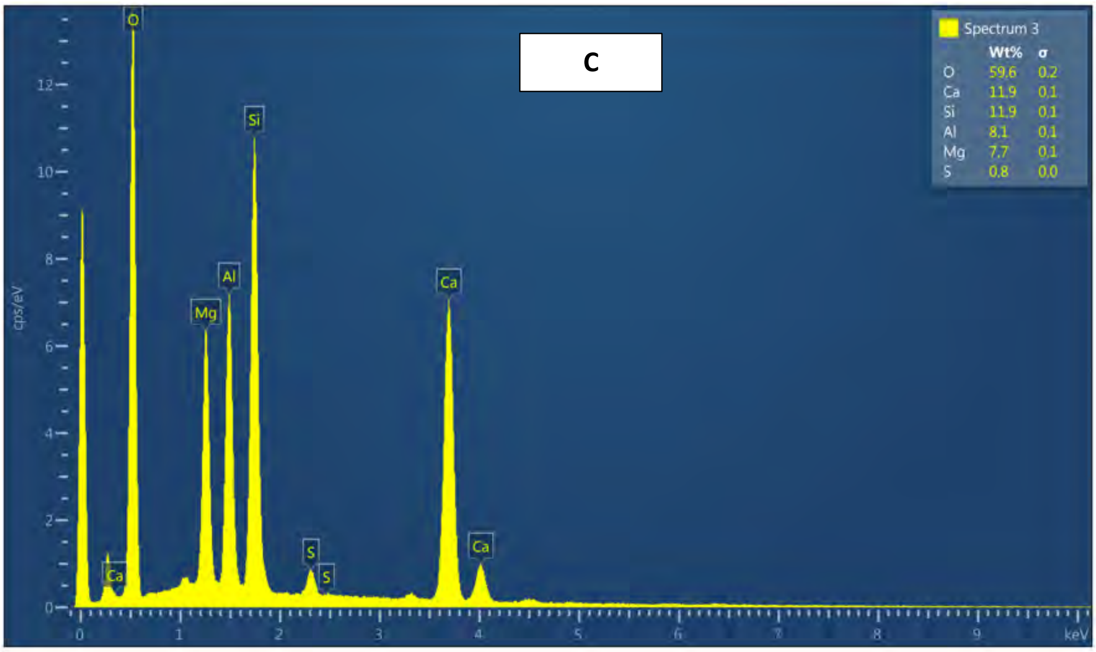
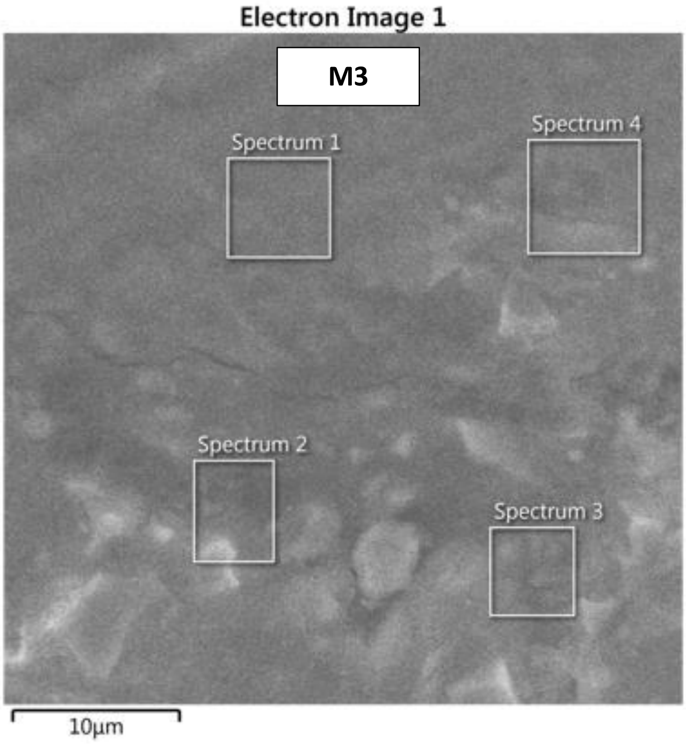
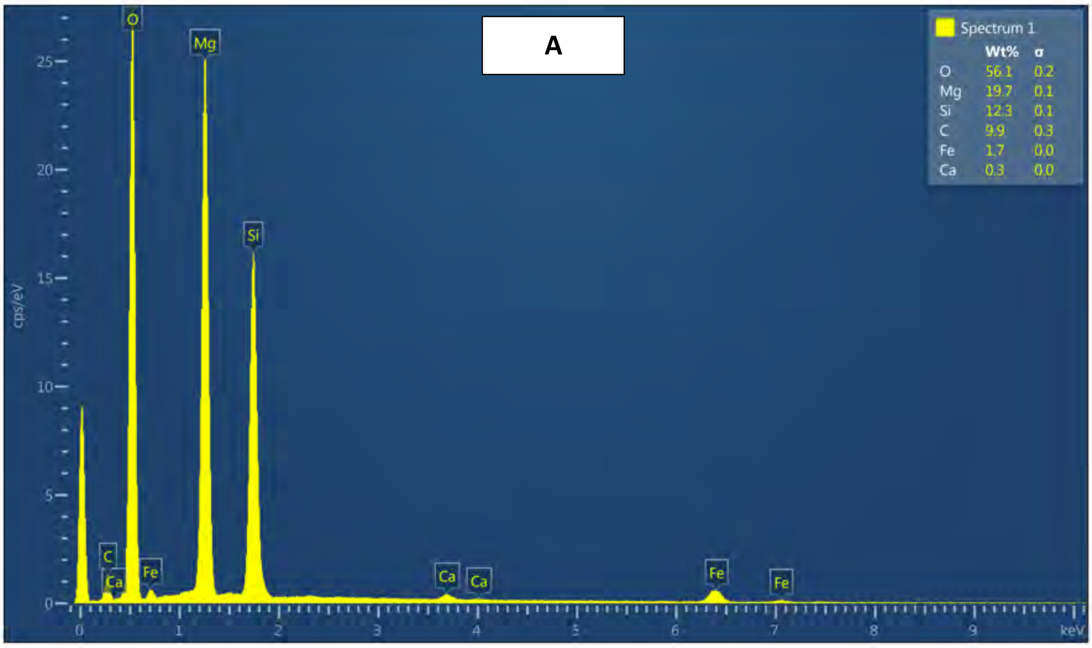


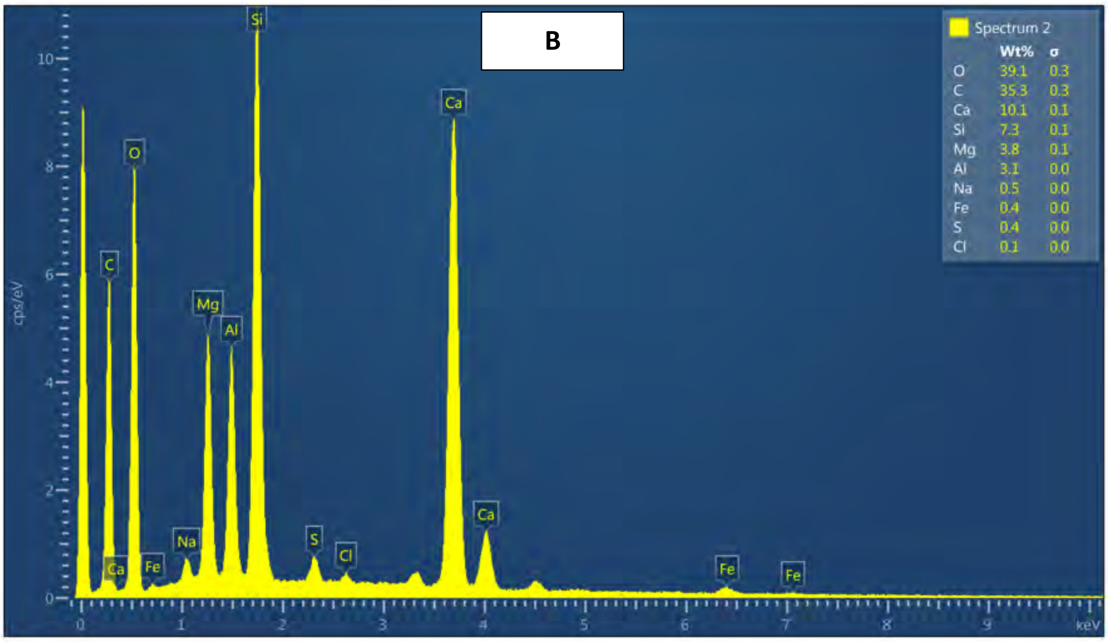
Figure 39. X-ray analysis of M2 A) Spectrum 1, B) Spectrum 2, and C) Spectrum 3.

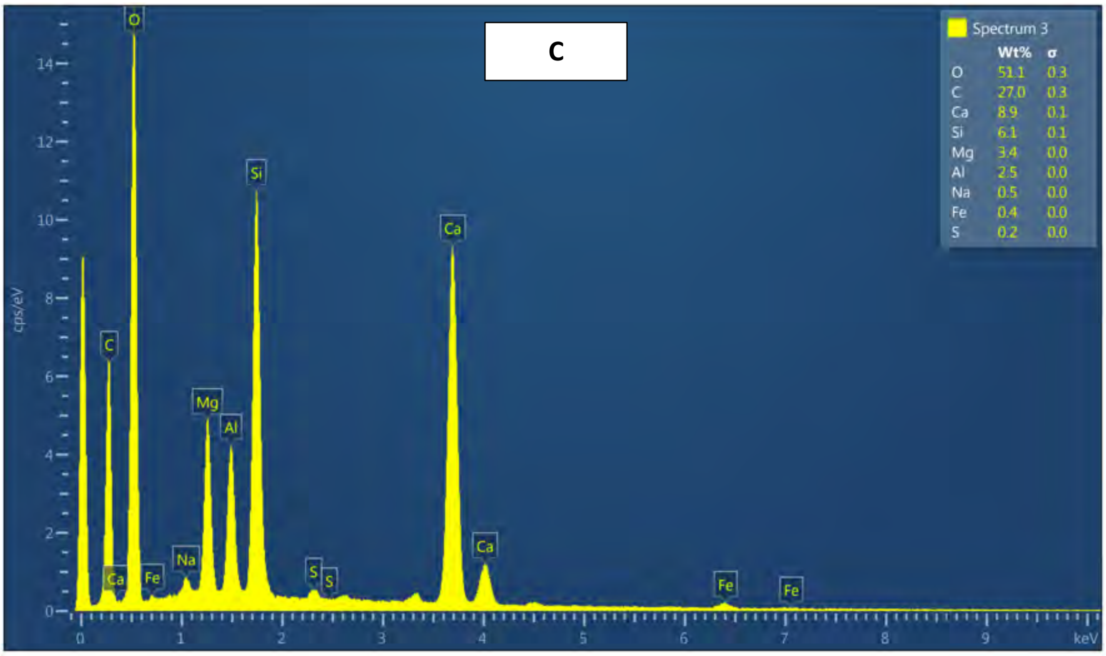


Electron Image 1
M3
Spectrum 1
Spectrum 4
Spectrum 2
Spectrum 3
10µm



A
Spectrum 1
Wt% σ
O 56.1 0.2
Mg 19.7 0.1
Si 12.3 0.1
C 9.9 0.3
Fe 1.7 0.0
Ca 0.3 0.0
cps/eV
keV


B
Spectrum 2
Wt% σ
O 39.1 0.3
C 35.3 0.3
Ca 10.1 0.1
Si 7.3 0.1
Mg 3.8 0.1
Al 3.1 0.0
Na 0.5 0.0
Fe 0.4 0.0
S 0.4 0.0
Cl 0.1 0.0
cps/eV
keV


C
Spectrum 3
Wt% σ
O 51.1 0.3
C 27.0 0.3
Ca 8.9 0.1
Si 6.1 0.1
Mg 3.4 0.0
Al 2.5 0.0
Na 0.5 0.0
Fe 0.4 0.0
S 0.2 0.0
cps/eV
keV

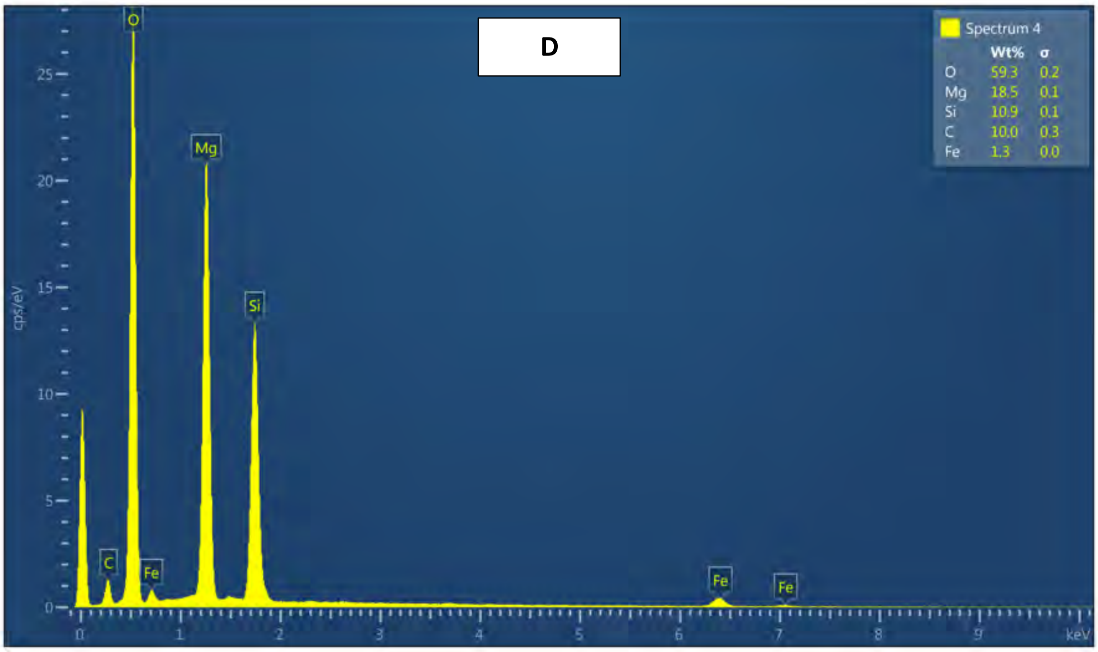
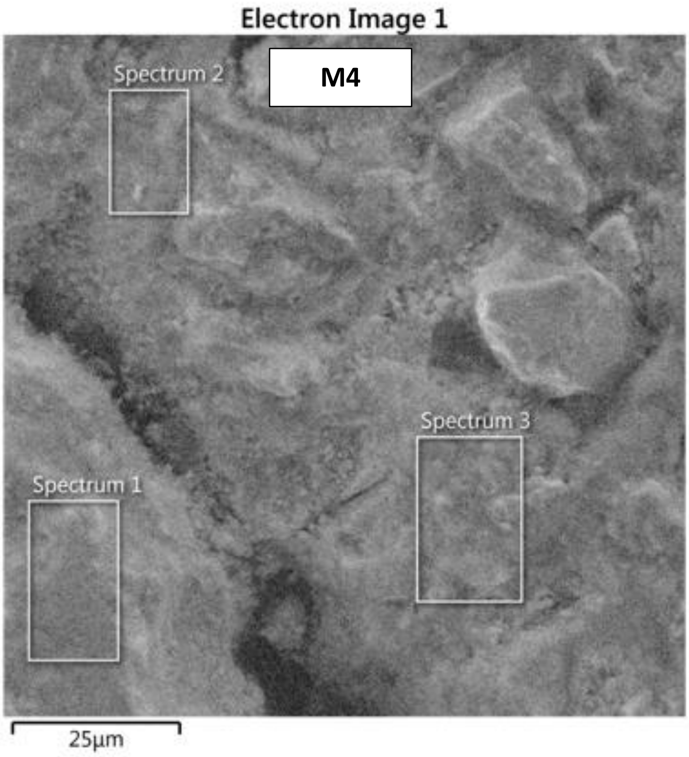
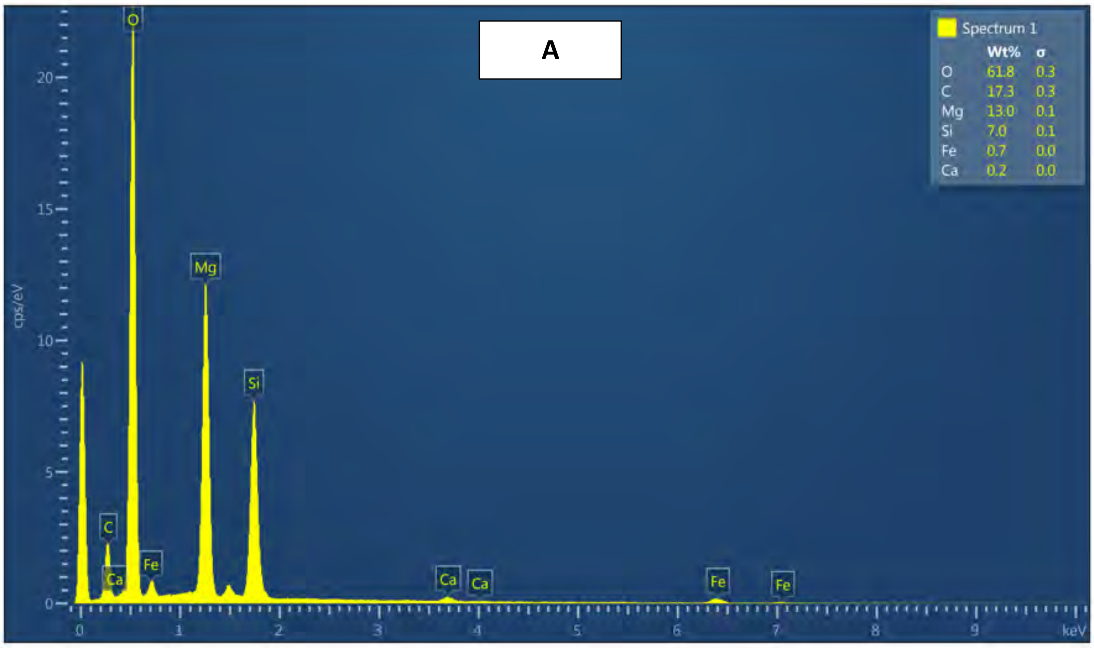
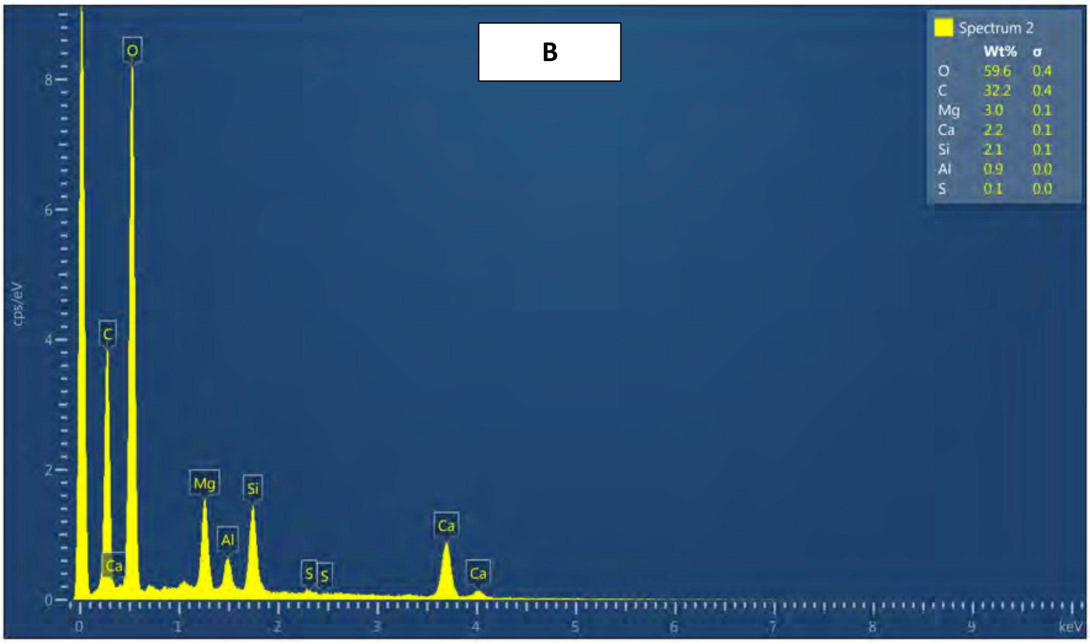


Figure 40. X-ray analysis of M3 A) Spectrum 1, B) Spectrum 2, C) Spectrum 3, and D) Spectrum 4.




A
Spectrum 1
Wt% σ
O 61.8 0.3
C 17.3 0.3
Mg 13.0 0.1
Si 7.0 0.1
Fe 0.7 0.0
Ca 0.2 0.0
cps/eV
keV


B
Spectrum 2
Wt% σ
O 59.6 0.4
C 32.2 0.4
Mg 3.0 0.1
Ca 2.2 0.1
Si 2.1 0.1
Al 0.9 0.0
S 0.1 0.0
cps/eV
keV

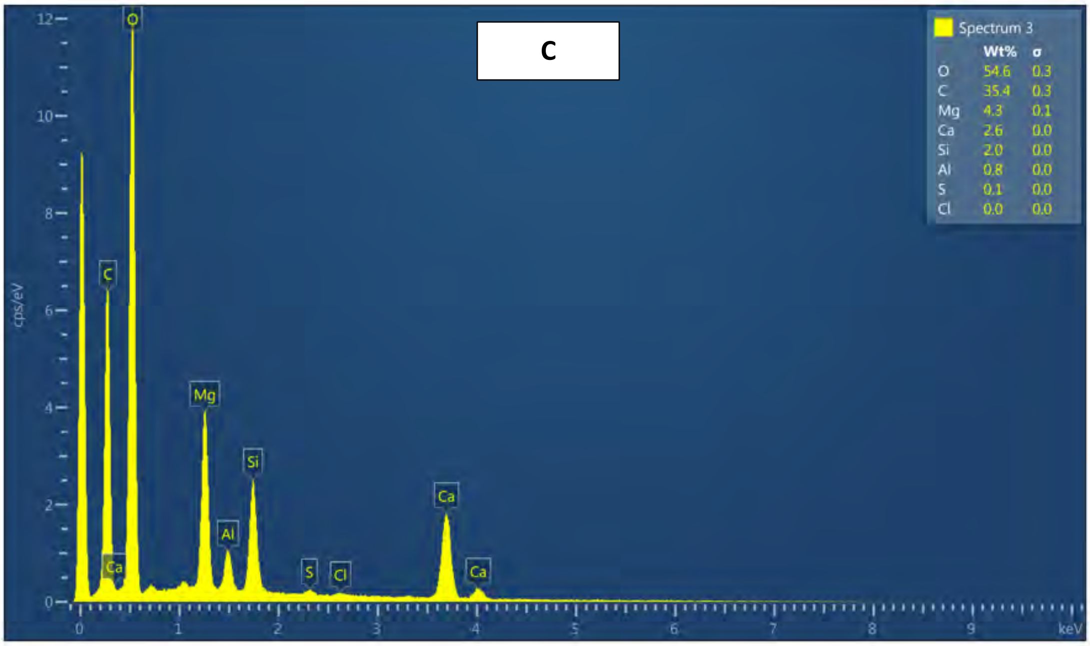
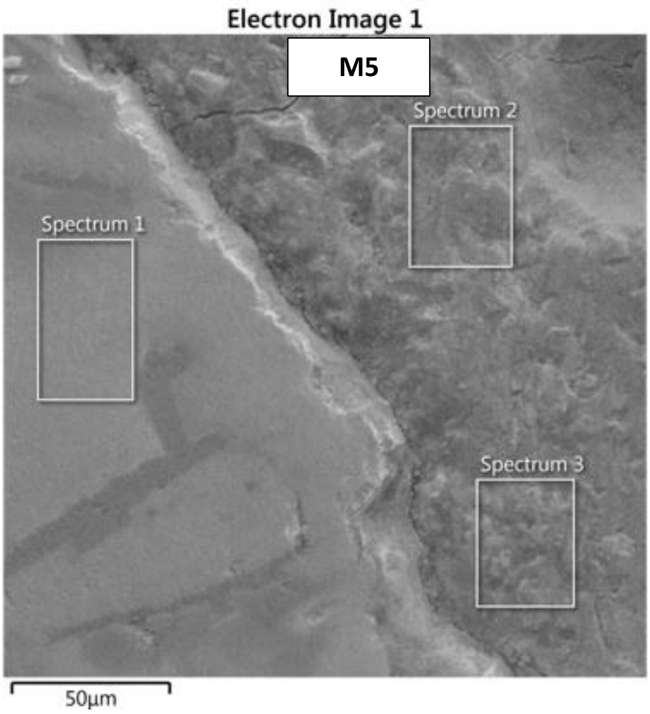
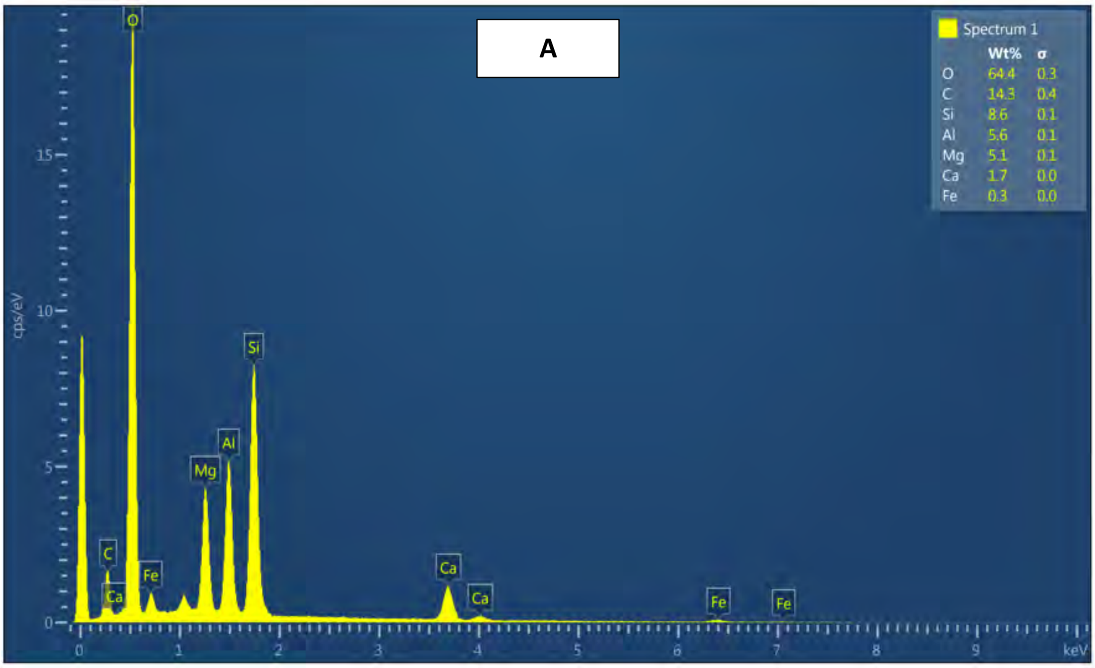
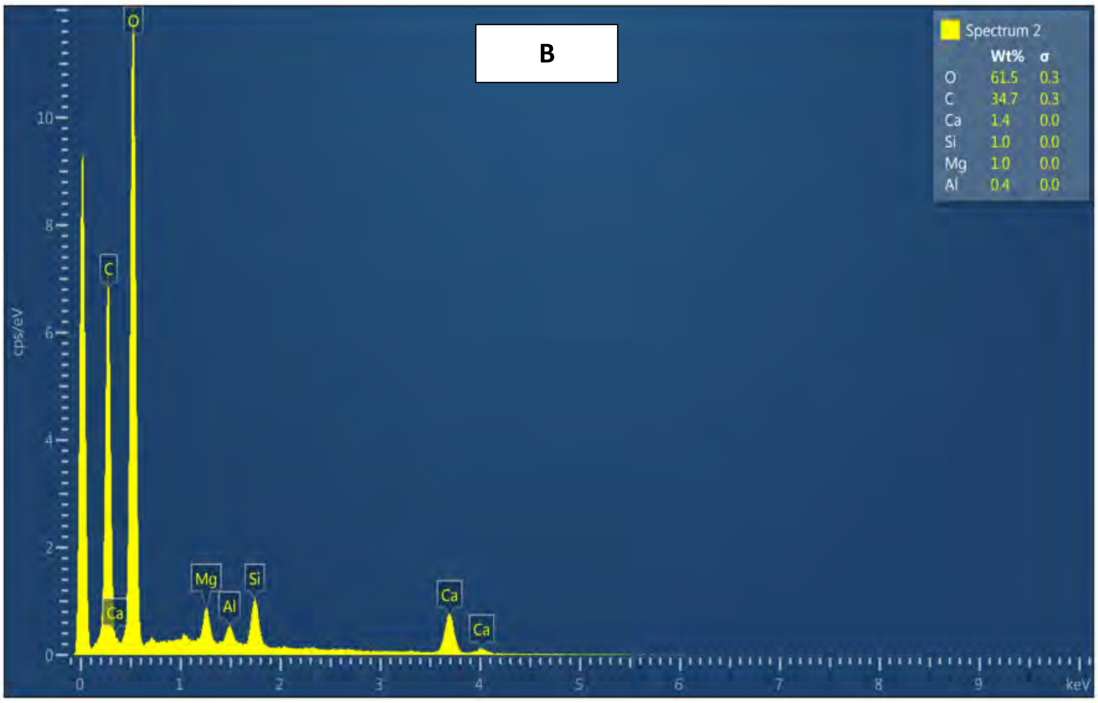


Figure 41. X-ray analysis of M4 A) Spectrum 1, B) Spectrum 2, and C) Spectrum 3.




A
Spectrum 1
Wt% σ
O 64.4 0.3
C 14.3 0.4
Si 8.6 0.1
Al 5.6 0.1
Mg 5.1 0.1
Ca 1.7 0.0
Fe 0.3 0.0
cps/eV
keV


B
Spectrum 2
Wt% σ
O 61.5 0.3
C 34.7 0.3
Ca 1.4 0.0
Si 1.0 0.0
Mg 1.0 0.0
Al 0.4 0.0
cps/eV
keV

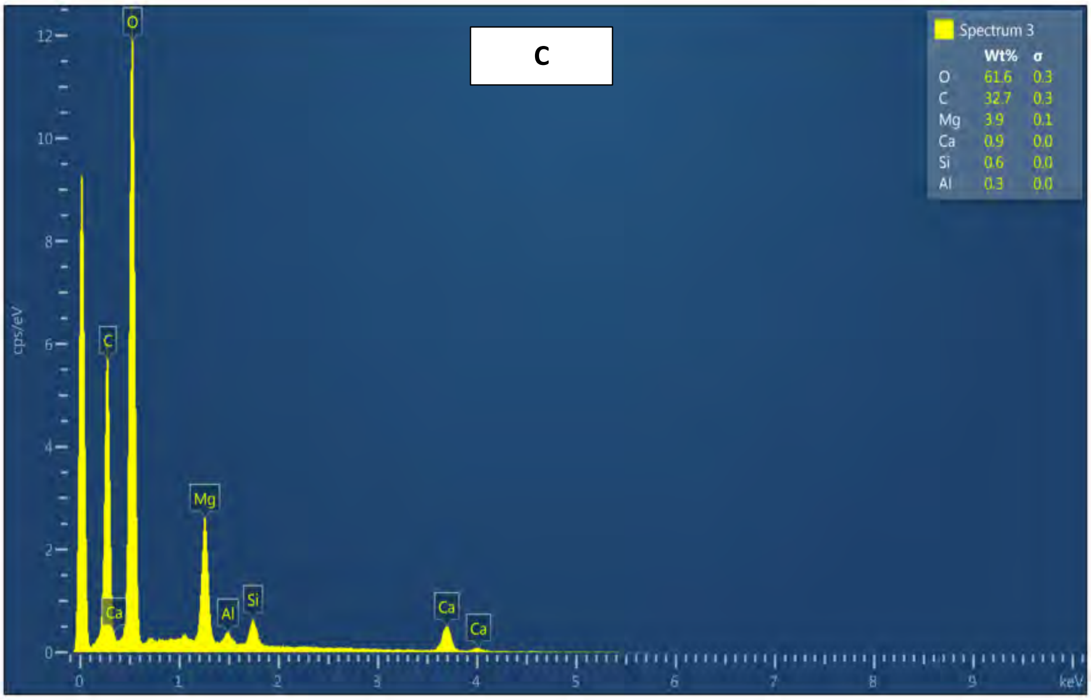
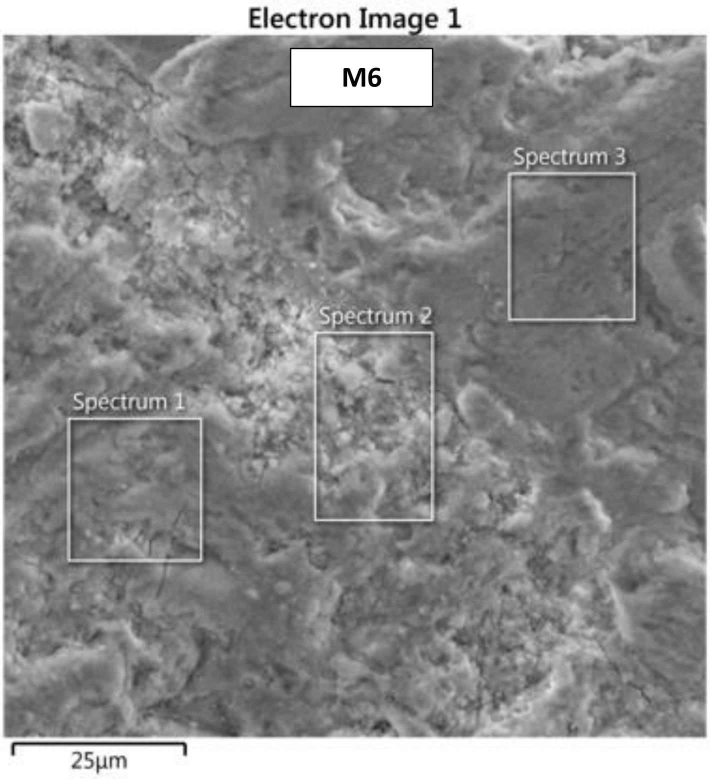
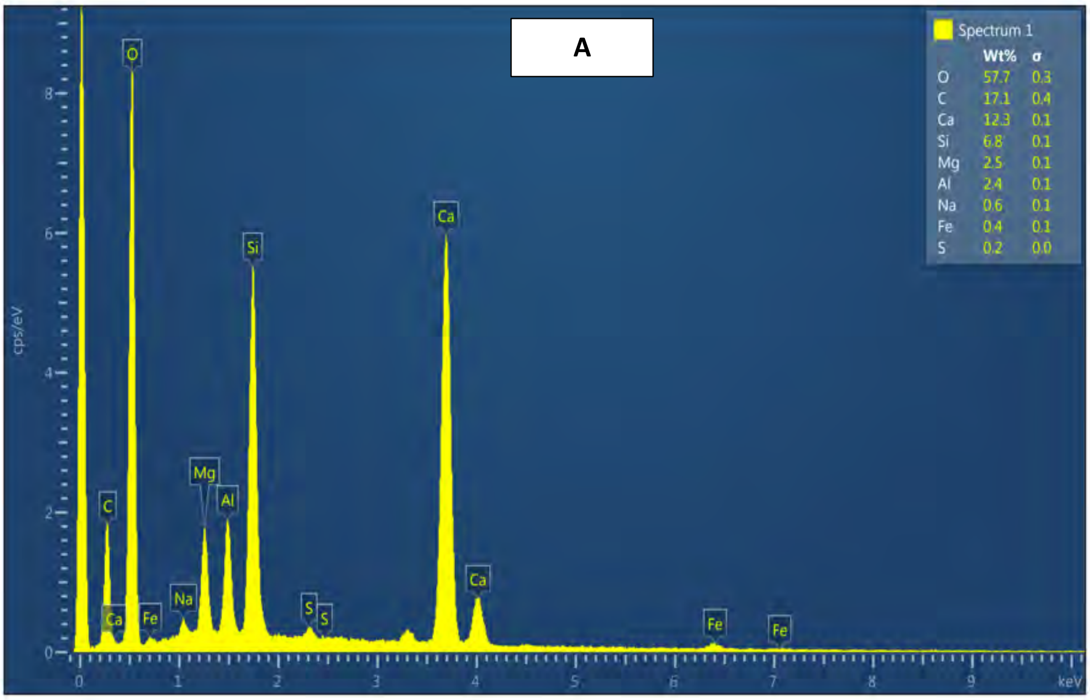
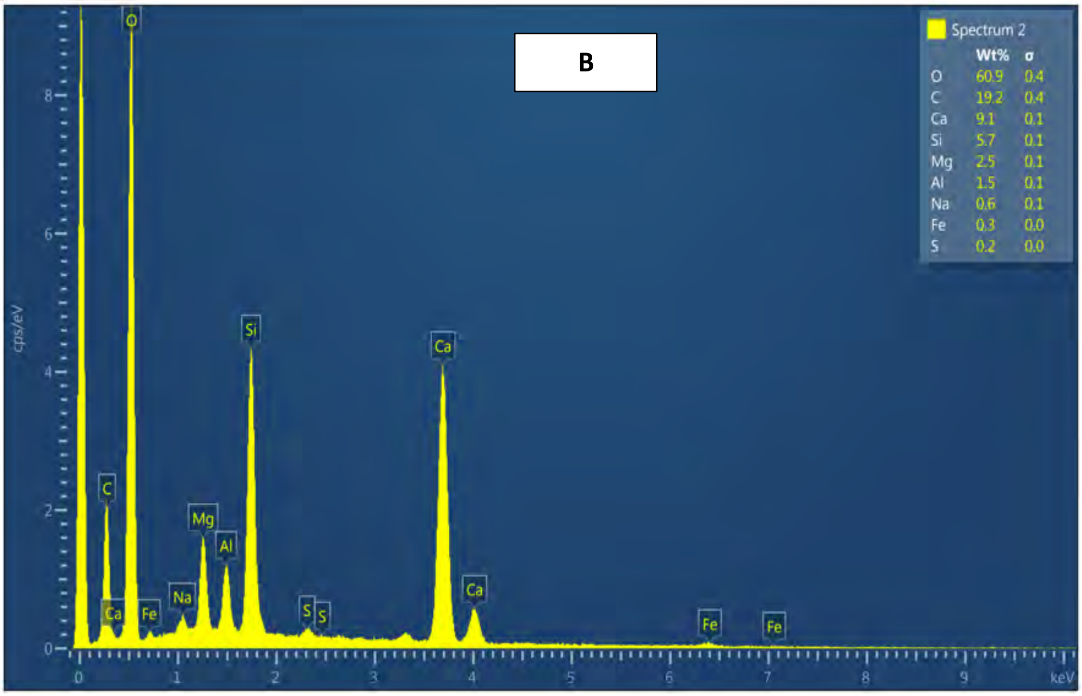


Figure 42. X-ray analysis of M5 A) Spectrum 1, B) Spectrum 2, and C) Spectrum 3.




A
Spectrum 1
Wt% σ
O 57.7 0.3
C 17.1 0.4
Ca 12.3 0.1
Si 6.8 0.1
Mg 2.5 0.1
Al 2.4 0.1
Na 0.6 0.1
Fe 0.4 0.1
S 0.2 0.0
cps/eV
keV


B
Spectrum 2
Wt% σ
O 60.9 0.4
C 19.2 0.4
Ca 9.1 0.1
Si 5.7 0.1
Mg 2.5 0.1
Al 1.5 0.1
Na 0.6 0.1
Fe 0.3 0.0
S 0.2 0.0
cps/eV
keV

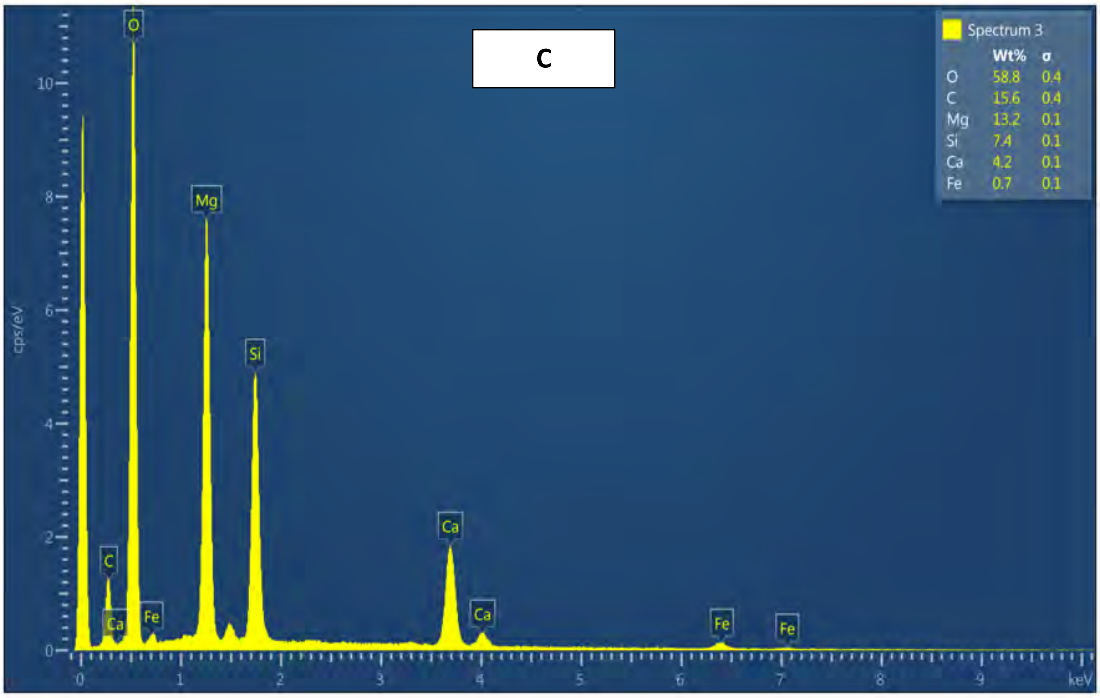


Figure 43. X-ray analysis of M6 A) Spectrum 1, B) Spectrum 2, and C) Spectrum 3.

Vita

Habib Alqamish was born on October 6, 1990, in Dubai, UAE. He was educated in the Institute of Applied Technology and graduated in 2008. After that, he studied civil engineering in the American University of Sharjah and graduated with a Bachelor of Science degree in 2014. Mr. Alqamish joined Dubai Municipality in 2014 as a senior civil maintenance engineer in the General Maintenance Department. In 2015, he began a Master's program in Civil Engineering at the American University of Sharjah. Since that time, Mr. Alqamish has published one paper in international conference regarding mechanical evaluation of nano-silica sustainable concrete.