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Evaluation of Performance of Metakaolin and Nano Materials Based Self-Compacting Concrete

A Thesis

Submitted to the College of Engineering at the University of Babylon in Partial Fulfillment of the Requirements for the Master Degree in Engineering /Civil Engineering / Construction Materials

By

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

﴿فَتَعَالَى اللَّهُ الْمَلِكُ الْحَقُّ وَلَا تَعْجَلْ بِالْقُرْآنِ مِنْ قَبْلِ أَنْ يُقْضَى إِلَيْكَ وَحْيُهُ وَقُلْ رَبِّ زِدْنِي عِلْمًا﴾ [طه: 114]

صدق الله العظيم

ABSTRACT

With the current focus on sustainable development in the civil engineering field, it is necessary to develop construction and building materials with reasonable costs and low environmental impacts in order to reduce CO_2 emissions from the cement industry as a whole. This thesis studies the effect of using metakaolin (MK), also called Calcined kaolin clay (CKC) and nanomaterials (Nano calcium carbonate (NC), and Nano alumina (NA)) as partial replacements for Portland limestone cement (PLC) on the sustainability of self-compacting concrete (SCC) and improves its structural properties.

This thesis developed three blend systems: binary, ternary, and quaternary. The fresh properties of SCCs were measured by slump flow (D), and T_{500}, V-funnel, L-box, and segregation resistance tests to evaluate the filling ability, passing ability, and segregation resistance of concrete mixes. The bulk density, compressive strength, splitting tensile strength, and ultrasonic pulse velocity (UPV) tests were carried out to assess the performance of SCC mixtures in hardened states at various ages. Besides, the durability performance of SCCs was investigated in terms of water absorption, porosity, and sorptivity.

The results revealed that when utilizing MK, NC, and NA in binary, ternary, and quaternary blends, they reduced the fresh properties, and the slump flows, flow times, and segregation tests are good enough for SCCs development. In addition, the L-Box height ratio values ranged from 0.791 to 0.982 without any tendency to blockage. Thus, all the SCC mixtures fulfilled the properties in a fresh state.

There is a significant improvement in the test results of the hardened properties and durability performance of the SCC in quaternary blend system, where the hybrid blends of 3%NC and 2%NA particles with MK in quaternary blends are more beneficial than the single use of nanoparticles with MK. At 90

days of age, SCC mix of (30%MK3%NC2%NA) exhibited the highest compressive strength, splitting tensile strength, and UPV of (61.8Mpa,4.61Mpa, and 4905m/s), respectively. It also showed the best durability properties as a result of low water absorption, porosity, and sorptivity of specimens, which were (2.98%, 7.82%, and 0.031 $mm/min^{0.5)}$ at 90 days of age, respectively. The model was developed to predict compressive strength with different variables. The coefficients of determination (R^2 = 86.2%) for the general model, indicate a very good correlation and a better model to fit the experimental data. This study achieved its goals through sustainable development of SCC incorporating MK and hybrid nanoparticles that could contribute to reducing cement demand, CO2 emission rate, and making durable and eco-friendly SCC.

Certification

I certify that this thesis, titled " **Evaluation of Performance of Metakaolin and Nano Materials Based Self-Compacting Concrete**", has been prepared by "**Ruwaida Kareem Khoman Gabbar**" under my supervision at the Department of Civil Engineering, the University of Babylon, in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

Signature

Supervisor *name: Asst. Prof.Dr. Haider M. Owaid*

Date: / / 2022

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*First of all, I have to thank "***Allah***" who gave me the power, patience, and continuation to be able to complete my study.*

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✍

Ruwaida Kareem
2022

Dedication

To the soul of my dear father, God have mercy on him

To my dear mother, God prolong her life

To those who made an effort to help me and were the best support

(my brothers and sister)

To my friends and colleagues

To all of them: I dedicate this work.

✍
Ruwaida Kareem
2022

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Nomenclatures/Abbreviations

Symbol	Description
CO_2	Carbon dioxide
GJ	Gigajoule
MJ	Megajoule
SCMs	Supplementary Cementitious Materials
HPC	High-Performance Concrete
SCC	Self-Compacting Concrete
CKC	Calcined Kaolin Clay
MK	Metakaolin
NPs	Nanoparticles
NC	Nano Calcium Carbonate $CaCO_3$
NA	Nano Alumina Al_2O_3
PLC	Portland Limestone Cement
SAI	Strength Activity Index
FA	Fine Aggregate
CA	Coarse Aggregate
SP	Superplasticizer
SF	Slump Flow
PA	Passing Ability
t_v	V-Funnel Flow Time
SR	Segregation Resistance
Fc	Compressive Strength
T	Splitting Tensile Strength
V	Pulse Velocity
WA	Water Absorption
S	Sorptivity
I	Absorption
CPM	Calcined Pozzolanic Materials
LOI	Loss on Ignition
B/A	Binder/Aggregate
CH	Calcium Hydroxide
C-S-H	Calcium-Silicate- Hydrate
C-A-H	Calcium Aluminate Hydrates
MRA	Multiple Regression Analysis
R	Correlation Coefficient
R^2	Determination Coefficient
SPSS	Statistical Package for the Social Sciences
UPV	Ultrasonic Pulse Velocity
AASA	Activated Alum Sludge Ash
PUNDIT	Portable Ultrasonic Non-Destructive Digital Indicating Tester
POFA	Palm Oil Fuel Ash

Nomenclatures/Abbreviations

HRWR	High-Range Water Reducing
VMA	Viscosity-Modifying Admixture
VEA	Viscosity Enhancement Admixture
AEA	Air-entraining admixture
wt	Weight
NVC	Normal Vibrated Concrete
W/B	Water / Binder Ratio
ITZ	Interfacial Transition Zone
SF	Silica Fume
GGBS	Ground Granulated Blast Furnace Slag
LSP	Limestone Powder
CC	Calcined Clay
NP	Natural Pozzolana
KC	Kaolin Clay
SSA	Specific Surface Area
STS	Splitting Tensile Strength

CHAPTER ONE

INTRODUCTION

Chapter One
Introduction

1.1 Background

Self-Compacting Concrete, born in Japan in late 80's to solve problems of pouring and setting concrete in high rebar densities structures, has slowly spread all over the world, showing many other characteristics and attracting attention first in laboratories and then in application. The most relevant performances of SCC are already well known and have been confirmed in large scale applications. High filling capacity, no vibration needed, reducing noise and unhealthy tasks for workers, high flow for longer distance pouring, homogeneity due to absence of poor workmanship in casting, high strength and durability, excellent surface are the main performances recognized to the product. SCC's high performances offers excellent performance in terms of filling ability, passing ability, segregation resistance, strength, transport properties, and durability **(Khayat,1999; Russell,1999; Borroni,2006)**.

Cement is a popular material in construction all over the world. This is an energy exhaustive material and is responsible for more CO_2 emissions. Carbon dioxide emissions from Portland cement manufacturing are one of the major environmental issues facing the concrete industry. Universally, cement manufacturing creates approximately 8% of CO_2 emissions into the atmosphere, of which 50% is from the chemical process and 40% from burning fuel **(Hawileh et al.,2017)**. The combustion of fuel is required to generate the heat necessary for the clinker mineral forming reactions to take place. The production of one tonne of cement results in about one tonne of CO_2; it consumes approximately 5.6 GJ of energy and requires roughly 1.5 tonnes of raw materials to manufacture **(O'Rourke et al., 2009)**. In 2015, the world's total cement production was around 4.6 billion tonnes. However, because of the rapid development of the construction industry worldwide and an expected increase in the world population, it is estimated that the production of cement will reach around 9 billion tonnes by 2050 **(Shubbar et al., 2018)**. Hence, to enhance the environment, there is a need to reduce the amount of cement used in the construction process without influencing either the strength or long-term durability characteristics of concrete.

The utilization of pozzolans is a trend getting much greater attention and will increase with increasing awareness of environmental protection and sustainable construction **(Papadakis&Tsimas,2002)**. Currently, studies on low-carbon concrete, in which cement is replaced with supplementary cementitious materials (SCMs) in large quantities, have been actively conducted **(Lee et al., 2019)**. These are used as alternatives to cement in concrete around the world to reduce the amount of cement and to improve its properties. Also, increasing the usage of pozzolanic materials enhances the durability of concrete, because durable structures require less repair and maintenance. In this manner, the service life of structures is also increased **(Guneyisi et al., 2008)**. Common SCMs such as fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK), and lime powder (LP) are commonly used. Through the addition of these materials, concrete has become a more environmentally acceptable material due to the reduced quantity of cement, which results in fewer CO_2 emissions into the atmosphere during cement production **(Skazlić& Vujica,2012)**.

In this study, the main pozzolan used was metakaolin (MK) or called calcined kaolin clay (CKC) in different combinations. Pozzolans can be of natural or industrial origin. Metakaolin ((MK)) is a cementitious material that conforms to **(ASTM C618, 2005)**, Class N pozzolan specifications. The prefix "meta" in the term is used to denote change, and kaolin is a stone having a higher percentage of kaolinite, also known as china clay or kaolin. It is traditionally used in the manufacturing of porcelain, i.e., ceramic material. Calcined kaolin ($Al_2Si_2O_7$) is a pozzolanic material that is thermally activated by firing kaolinite clay within a temperature range of 700–800 °C **(Liew et al., 2012; Abo-El-Enein et al., 2014).** Production of metakaolin requires lower calcining temperatures (600 to 900°C), compared to Portland cement (1450°C) **(Scrivener, 2014)**. This lower calcination temperature leads to lower energy consumption and, consequently, lower production costs. It is estimated that to manufacture one tonne of metakaolin requires about 2950–3300 MJ **(Mitchell & Floe,2002; Cassagnabere,2013)**, while cement needs about 3000–6500 MJ/tonne of clinker, depending on the manufacturing process **(Vizcaíno-Andrés et al.,2015)**. Its environmental acceptability results from the fact that fewer CO_2 emissions are generated during metakaolin production when compared to cement production. The CO_2 emission from MK production (1 tonne of MK produced = 175 kg of CO_2) comes from the process only (extraction of raw materials, kiln, etc.) and not from the chemical reaction (dehydroxylation). For cement production, this release is due to the decarboxylation of $CaCO_3$ (clinkerization) and the process (1 ton of clinker produced = 1 ton of CO_2). Furthermore, the production of MK requires less thermal energy (1 tonne of MK requires 2.95 GJ) than the production of cement (1 tonne of cement requires 4.65 GJ) **(Cassagnabère et al., 2010)**. **(Kavitha et al., 2016)** found that increasing the replacement level of cement with (0 to 15% MK) reduces energy consumption (-2.14% to -5.56%) and CO_2 emissions (-4.15% to -11.21%). (CKC) is a pozzolanic material that has a higher surface area compared with portland cement and belongs to the class N pozzolana. It is highly reactive and contains 50–55% of SiO_2 and 40–45% of Al_2O_3, and on a chemical reaction with calcium hydroxide, it forms a secondary calcium silicate hydrate (C-S-H) gel which enhances the strength and durability of concrete by refining the pore structure. It is typically used in amounts ranging from 10% to 25% of the total cement mass. (**Al Menhosh et al.,2018)** studied the effect of metakaolin on the concrete and its performance. The compressive strengths of the MK modified concrete showed that the MK/C ratio in the range of 15–20% presents the maximum compressive strength at the ages of 7 and 28 days but decreased compared to the control specimen for (30% and 40%) cement replacement with MK, respectively.

Nanotechnology is taken into account as a brand new field of science in materials science and materials engineering, which is considered another solution to reduce the greenhouse gas effect induced by the use of cement in concrete. The word "Nano" was derived from the Greek word "dwarf," which indicates the billionth part. Nanotechnology is the use of very small particles on the scale of 1–100 nanometers. A nanometer is 1/1000 of a micron, or 1 billionth of a meter, which is about three atoms set side by side. It has an extremely large specific surface area to volume ratio. Meanwhile, nanoparticles have gained great attention and have been used in several engineering applications because of their unique properties and the ultrafine size of their particles. Nanoparticles can act as fillers to fill up voids and lead to the densification of the interfacial transition zone (ITZ). Lastly, by adding several types of nanoparticles to concrete, novel properties can be obtained. Nanoparticles were found to improve the structure of conventional concrete, accelerate the formation of calcium silicate hydrate (C-S-H), and the development of early-age strength, as well as improve the durability. The addition of nanoparticles can improve the properties of concrete due to the effect increased surface area has on reactivity and through filling the Nano pores of the cement paste **(Zhang & Li, 2011; Said et al., 2012; Khotbehsara et al., 2018)**.

Several types of nanoparticles have been used to enhance the mechanical and durability properties of concrete. Studies have explored the use of TiO_2, Al_2O_3, Fe_2O_3, ZnO_2, SiO_2, $CaCO_3$ nanoparticles in mortar and concrete and their effects on concrete properties **(Nazari & Riahi, 2010; Nazari & Riahi, 2011a; Nazari & Riahi, 2011b; Nazari & Riahi, 2011c; Khoshakhlagh et al., 2012)**. Moreover, improving the technical properties of concrete through the use of nanoparticles also reduces the negative environmental effects of concrete production due to reduced demand for cement production and consumption. In this study, nano calcium carbonate (NC) and nano alumina (NA) were used in hybrid blends to provide better performance than single blends.

Nano calcium carbonate (NC) is one of the most widely used nanoparticles in the construction sector as a partial replacement of cement **(Cao et al., 2019). (Li & Gao, 2006)** reported that nano-$CaCO_3$ may be involved in the hydration reaction with C_3A in the concrete because nano-$CaCO_3$ particles are very small and have high activity. **(Kadhum & Owaid,2020)** found that the addition of 3% of nano $CaCO_3$ to the mixture leads to an increase in the viscosity of SCHPC (i.e., slump flow diameter, L-box height ratio, and segregation resistance) decreases while the V-funnel increases compared to the reference mixture. Also, adding 3% of nano $CaCO_3$ with calcined clay (5, 10, and 15%) in ternary mixtures increases the compressive strength and the splitting tensile strength values when compared to the reference mixture and the mixture with CC. **(Al Ghabban et al.,2018)** studied the combined effect of 3% (nano SiO_2+nano $CaCO_3$). The results showed that incorporation of nano $CaCO_3$ and nano SiO_2 particles led to increased packing and enhanced mechanical and durability properties of concrete.

Nano-alumina is another nano-sized material used in cement-based materials, with reported benefits including refined microstructure (pore structure and transition interface zone) and enhanced strength **(Li et al.,2006; Nazari&Riahi,2011a; Li et al,2017)**. The effects of nano-alumina on mechanical properties have been attributed to its physical effect (filler effect), which accelerates early-age hydration **(Li et al., 2017; Chen et al., 2018)**. The use of (NA) results in the formation of C.A.S (calcium-alumina-silica) gel in concrete, and the reaction rate depends on surface area (particle), leading to fast hydration, which results in high compressive strength enhancement **(Rasin & Kadhim, 2017)**. (**Nazari et al.,2010)** investigated the compressive strength and workability of concrete by partial replacement of cement with nano-phase Al_2O_3 particles. They found that the use of nano-Al_2O_3 particles up to a maximum replacement level of 2.0% produced concrete with improved strength but decreased its workability. **(Shekari& Razzaghi,2011)** investigated effect of different nanomaterials on the durability and mechanical properties of high-performance concrete. It can be seen that the nano-Al_2O_3 is the most effective nano-particle among the examined nanoparticles in the improvement of the mechanical properties of high-performance concrete. **(Orakzai,2021)** found that the combination of nano-Al_2O_3 and nano-TiO_2 improves the pore structure, resulting in highly optimized mechanical properties. Nanoparticles serve as nucleation sites for the formation of additional C-S-H gel and regulate $Ca(OH)_2$ growth in the cement system. Therefore, the addition of a combination of nano-particles is more beneficial than the individual use of nano-particles.

1.2 Research Significance

The main aim of this study was to provide a low-carbon binder and investigate the effect of the hybrid blends of nanoparticles (nano calcium carbonate (NC), and nano alumina (NA)) with high volume metakaolin (MK) on the performance of SCC at ambient temperatures. There is a little studies found in the literature that focuses on the characteristics of self-compacting concrete using those materials in ternary, and quaternary combinations. The consumption of metakaolin (MK) in high volume as supplementary cementitious materials in concrete construction has benefits such as less cement demand, which results in fewer CO_2 emissions into the atmosphere during cement production, saving the production cost, improvement of the durability properties of concrete, improving performance, and producing "green" environmentally-friendly concrete. Moreover, using nanoparticles is considered another solution to reduce the greenhouse gas effect induced by the use of cement in concrete and improve the technical properties of the concrete.

Production and application of SCC containing metakaolin and hybrid nanomaterials seem to be a promising and energy-saving step toward sustainable construction and building technology. The incorporation of (MK) is helpful for long-term strength, and the incorporation of nanomaterials can improve early-age strength, improve their durability and provide an effective solution for a more sustainable environment. Consequently, there is a need for more studies into the behavior of this concrete using those materials. For this, fresh properties, hardened properties, as well as durability performance tests of SCCs have been carried out. In addition, empirical models have been developed for prediction the compressive strength of SCCs.

1.3 Scope and Objectives of the Study

The scope of this study was to develop suitable mix designs to satisfy the requirements of SCC in the plastic state using local pozzolanic materials such as metakaolin and hybrid nanomaterials represented by nano calcium carbonate (NC) and nano alumina (NA) and then to determine the hardened and durability properties. More specifically, the research had the following objectives:

1. To identify and evaluate the physical and chemical properties of MK, NC and NA.
2. To determine the pozzolanic activity of MK, NC and NA by measuring their strength activity index to determine their suitability to replace cement partially.
3. To develop an optimal mix that produces SCC utilizing MK, NC, and NA.
4. To evaluate the fresh properties of SCC mixtures. As fresh state tests, the slump flow (D (mm) and T_{500mm} (s)), V-funnel time, L-box, and segregation resistance were performed.
5. To investigate the hardened properties of SCCs, including the bulk density, compressive strength, splitting tensile strength, and ultrasonic pulse velocity (UPV) at different ages.
6. To investigate the durability characteristics, including water absorption, porosity, and sorptivity of SCCs.

7. To predict the compressive strength of SCCs at different ages using the multiple regression analysis method and to determine the relationship between measured and predicted compressive strengths. Also, to determine a correlation between the compressive strength and ultrasonic pulse velocity (UPV).

1.4 Structure of the Thesis

This thesis has a total of five chapters. Each chapter is described as follows:

Chapter One: provides a short overview of the present thesis, the significance, objectives, scope, and structure of this thesis.

Chapter Two: primarily gives the definition and briefly describes the characteristics of SCC. Then, it provides production approaches and focuses on the performance criteria of SCC. This chapter also introduces common pozzolanic materials and nanoparticles. In this regard, the properties of (MK) as calcined pozzolanic materials, nano calcium carbonate (NC), and nano alumina (NA), which are used in this study, are described based on the published kinds of literature and documents. Finally, this chapter emphasizes the major fresh, hardened, and durability properties of concrete using these materials.

Chapter Three: describes the experimental work "materials used, mold preparation, mixing, casting, curing, testing the specimens that were used in this study, and analysis using the SPSS program.

Chapter Four: presents the results and discussion of the different experiments (as mentioned in Chapter three).

Chapter Five: provides a summary of the research findings and gives several recommendations for future study.

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Background

Technologies change perceptions. In the last two decades, concrete has no longer remained a material consisting only of cement, aggregates, and water, but has become an engineered, custom-tailored material with several new constituents to meet the many varied requirements of the construction industry. Self-compacting or self-consolidating concrete (SCC), which can be considered as one of the most significant developments in the construction industry, was first initiated in Japan as an underwater placement technology, then developed as a niche product and a problem solver, but now it is going to be a sustainable and clean technology **(Newman& Choo, 2003; Brouwers & Radix, 2005).**

SCC is a concrete that can flow and consolidate under its weight, pass through the spaces between the reinforcement bars to fill the formwork, and simultaneously maintain its stable composition. Thus, lower yield stress for higher mobility and higher viscosity to prevent segregation are the most important traits to be achieved coincidentally. SCC requires excellent filling ability, good passing ability, and adequate segregation resistance. The concepts of self-compacting and high performance concrete can be combined to meet the performance requirements of self-compactability, high compressive strength and good durability**(Newman& Choo, 2003; EFNARC, 2005; Safiuddin, 2008).**

This chapter presents a background and review of SCC. It primarily gives the definition and briefly describes the characteristics of SCC.

Then, it provides production approaches and focuses on the performance criteria of SCC. Also the properties of (MK) as pozzolanic materials, nano calcium carbonate (NC), and nano alumina (NA) used in this study are described based on the published literature and documents. The influence of this material as partial cement replacement on the major fresh, hardened, and durability properties of concrete that relate to this study is discussed and reviewed in this chapter.

2.2 Self-Compacting Concrete

The definition, characteristics, and advantages of SCC are briefly discussed below.

2.2.1 Definition

Self-compacting concrete (SCC) is one of the innovative concrete that is progressively used for experimental jobs and actual projects. It spreads through the congested reinforcement, reaches every corner of the formwork, and is consolidated under its weight. While providing these characteristics, SCC keeps its stability without segregation or bleeding **(Libre et al., 2012).** Some of its advantages are shortened concrete construction time due to increasing productivity levels, constructing heavily reinforced sections, improving in situ concrete quality, reducing noise and injuries related to vibration and casting works which lead to a better work condition, and the excellent concrete surface quality **(Safiuddin et al., 2010)**.

Furthermore, high-performance concrete is concrete that is designed to provide high strength and excellent durability, which has been widely used in the construction industry for the past few decades and it has evolved with time. This is due to increasing demand for more durable concrete to the extent of the service life and at the same time to reduce the maintenance cost of concrete structure **(Jalal et al., 2012)**.

SCC's high performances show good flowability and stability while offering high strength and great durability properties with the service life specifications under a given set of materials, loads, and exposure conditions. Constructing concrete structures needs a detailed placing and good compaction of fresh concrete to achieve higher hardened properties and durability **(Jalal et al., 2015)**. However, the proper placement and compaction were not always achievable with normal concretes, even though placed by skilled laborers. The lack of skilled laborers was also a great concern in the construction industry. Then, the concept of SCC first came out in Japan to build durable concrete structures and to offset the growing shortage of skilled laborers. The technology of SCC has been tailored and optimized in Japan during the last decade. The Japanese concrete industry commercialized SCC under the trade names of "Non-vibrated Concrete," "Super-quality Concrete," and "Biocrete" (**Bartos, 2000**). At the same time, SCC has become familiar in North America, Europe, and other parts of the world (**Wallevik & Níelsson, 2003)**.

2.2.2 Characteristics

Self-compacting concrete (SCC) differs from normal concrete concerning its performance in fresh and hardened states that are mainly driven by exceptional material components and mixture proportions. It incorporates several special ingredients such as high range water reducing (HRWR) admixture to provide adequate flowability, and a high contents quantity of powder materials and/or viscosity-modifying admixture

(VMA) to achieve high resistance to segregation, in addition to the basic materials used for normal vibrated concrete (NVC). The proportions of component materials in SCC are also significantly different from those of NVC **(Okamura & Ouchi, 2003).**

SCC includes a much higher quantity of binder, a lower water content, a greater fine aggregate content, and a lesser amount of coarse aggregate than normal concrete. One of the most important differences between self-compacting concrete and conventional concrete is the incorporation of a mineral admixture. Figure 2.1 shows a typical comparison of SCC and normal vibrated concrete **(Ghanbari,2011)**. The water/binder ratio (W/B) of SCC is also much lower than that of NVC. While conventional concrete has a W/B ratio mostly above 0.50, SCC needs a W/B ratio that typically ranges from 0.20 to 0.40 **(Persson, 2001).**

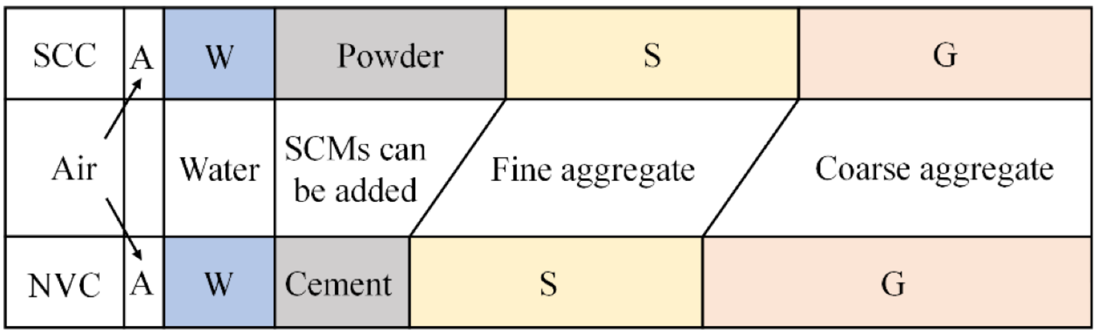

Figure 2.1: Typical Comparison of SCC and Normal Vibrated Concrete **(Ghanbari,2011)**

The basic principles of SCC can be produced by achieving self-compaction capacity through optimum flowing ability (filling ability and passing ability) and optimum segregation resistance, as illustrated in Figure (2.2). The optimum flowing ability can be obtained by using HRWR, limited coarse aggregate content, and an increased amount of cementing materials at a low W/B ratio **(Dehn et al., 2000; Okamura & Ouchi, 2003)**. Conversely, the optimum segregation resistance can be attained either by limited coarse aggregate content and increased cementing materials at a low W/B ratio, or by using a viscosity enhancement admixture (VEA)**.** In addition, the aggregate size influences both flowing ability and segregation resistance of SCC **(Saak et al., 2001; Bui et al., 2002).**

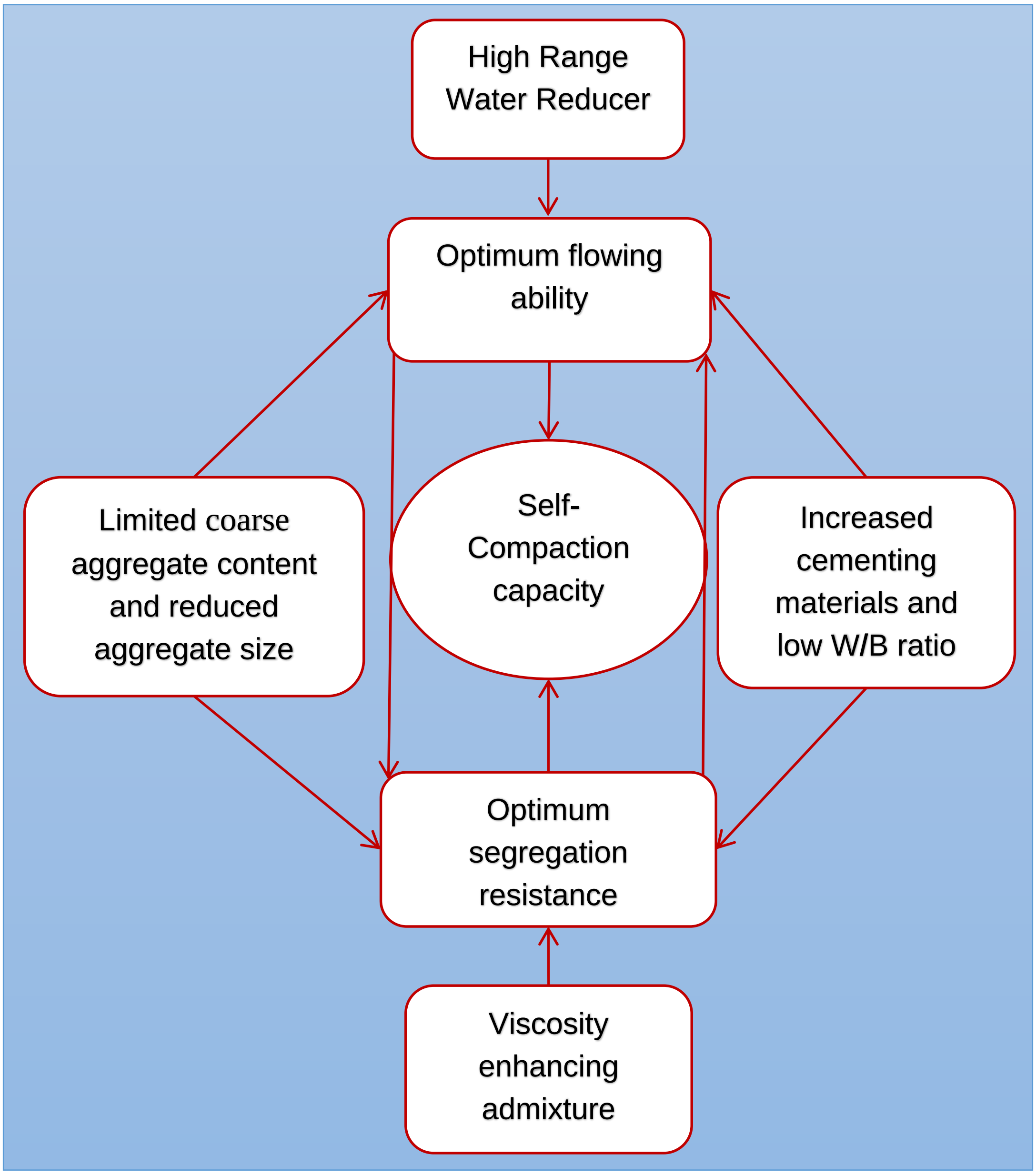

Figure 2.2: Basic Principles of SCC **(Okamura & Ozawa, 1995).**

2.2.3 Economy

SCC is generally stronger than ordinary concrete. Therefore, the structural components will be made of thinner sections, and thus savings can be attained due to a less amount of concrete. The productivity improvement also reduces the cost involved in formwork. Moreover, SCC offers better mechanical and durability performance and greater service life than ordinary concrete. The use of SCC in a high-rise building, bridge, offshore platform, and other special structures will be economical. The overall cost will be low due to a drastic reduction in the geometry of the structural components, reduced number of laborers, decrease in reinforcement percentage, ease of conveyance and placement, and reduction in formwork and shoring. Indirect benefits can also be gained through durability improvement leading to maintenance savings. The maintenance and repair costs are expected to be low in SCC. Thus, a lot of savings will be achieved particularly for large projects if SCC is used **(Ouchi et al., 2003; Okamura & Ouchi, 2003; Watson,2003)**.

2.3 Performance Criteria for Self-Compacting Concrete

SCC exhibits great flow ability, stability, providing good hardened properties and high durability. The performance criteria for the properties of SCC are presented in Table 2.1 and 2.2 according to **(EFNARC, 2005)** and **(Safiuddin, 2008)**, respectively.

Table 2.1: Performance Criteria for SCC**(EFNARC, 2005)**

Assessment	Testing	Classes		
Filling ability	Slump flow test	***Slump class***	***Slump flow (mm)***	
		SF1	550-650	
		SF2	660-750	
		SF3	760-850	
	T500 , V-funnel	***Viscosity class***	***T_{500} time (s)***	***V-funnel time (s)***
		VS1/VF1	≤ 2	≤ 8
		VS2/VF2	>2	9 - 25
Passing ability	L-box test	***Passing class***	***h_2/h_1***	
		PA1	≥ 0.8 with two bars	
		PA2	≥ 0.8 with three bars	
Segregation resistance	Sieve segregation test	***Class***	***Segregation Percentage %***	
		SR1	≤ 20%	
		SR2	≤ 15%	

Table 2.2: Performance Criteria for SCC's high performances

(Safiuddin, 2008)

Method	**Property**	**Performance criteria**
Slump flow	Filling ability, Segregation resistance	550 – 850 mm
V- funnel flow	Filling ability, Segregation resistance	5 –14 sec
Orimet flow	Filling ability, Segregation resistance	2.5 – 9 sec
Filling percentage infill box	Filling ability, passing ability	90 – 100%
Blocking ratio in L-box	Filling ability, passing ability, and Segregation resistance	> 0.8
Filling height in U-box	Filling ability, passing ability	≤ 30mm
Slump cone J-ring flow	Reduction in slump flow as a measure of passing ability	≤ 50mm
Penetration depth	Segregation resistance	≤ 8mm
Sieve Segregation	Segregation resistance	≤ 18mm
Air content by pressure method	Fresh air content	4 – 8 %
Axial compression on cylinders	Early age compressive strength	> 20 MPa
	28 and 91 days compressive strength	> 40 MPa
Ultrasonic Pulse Velocity by PUNDIT	Physical quality or condition (packing, uniformity, etc.	≥ 4575 m\s
Porosity by fluid displacement method	Total porosity as an indicator of strength and transport properties	7 – 15 %
Absorption by water saturation technique	Water absorption as an indicator of durability	3 – 6 %

Table 2.3 shows applications for each class of fresh SCC according to **(EFNARC,2005)**.

Table 2.3: Applications for each Class of SCC **(EFNARC,2005)**

European Slump-flow Classes		
SCC Classification	***Slump flow (mm)***	***Application***
SF1	550-650	• unreinforced or slightly reinforced concrete structures that are cast from the top with free displacement from the delivery point (e.g. housing slabs) • casting by a pump injection system (e.g. tunnel linings) • sections that are small enough to prevent long horizontal flow (e.g. piles and some deep foundations).
SF2	660-750	suitable for many normal applications (e.g. walls, columns)
SF3	760-850	typically produced with a small maximum size of aggregates (less than 16 mm) and is used for vertical applications in very congested structures, structures with complex shapes, or for filling under formwork. SF3 will often give a better surface finish than SF2 for normal vertical applications but segregation resistance is more difficult to control.
European Viscosity Class		
Class	***T_{500}***	***Application***
Class 1	≤ 2	High filling ability using densely packed reinforcement; a good surface finish with the potential for bleeding.
Class 2	>2	with increasing flow time it is more likely to exhibit thixotropic effects, which may help limit the formwork pressure or improve segregation resistance.
European Passing Ability Class (L-Box Blocking Ratio)		
Class	***Passing Ability***	***Application***
Class 1	≥ 0.8	Structures with a gap of 80 mm to 100 mm. (e.g. housing, vertical structures)
Class 2	≥ 0.8	Structures with a gap of 60 mm to 80 mm. (e.g. civil engineering structures)

European Segregation Resistance Class		
Class	***Segregation Resistance (%)***	***Application***
Class1	≤ 20	Thin slabs; flow distance is shorter than 5 m and a confinement gap greater than 80 mm.
Class 2	≤ 15	Vertical applications with flow distance greater than 5 m with a confinement gap greater than 80 mm to take care of segregation during flow. may also be used for tall vertical applications with a confinement gap of less than 80 mm if the flow distance is less than 5 meters

2.4 Pozzolanic Materials

Pozzolan is defined as siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will in finely divided form and presence of moisture, chemically react with calcium hydroxide at normal temperature to form compounds possessing cementitious properties **(ASTM C311, 2005)**. Additionally, **(Neville, 2011)** also described pozzolans as a natural or artificial material containing amorphous silica in a reactive form. The silica can combine with calcium hydroxide ($Ca(OH)_2$) in cement, in the presence of water to form stable calcium silicates which have cementitious properties.

The American Society for Testing and Materials **(ASTM C618, 2005)** is a standard specification for coal fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete where cementitious or pozzolanic activity is needed. There are three classes of pozzolans: class N, class F and Class C. Table 2.4 shows the chemical and physical characteristics of the Specification for all forms of pozzolans. The main reasons for the application of inert and pozzolanic additions are:

1- To improve the stability and the rheology.
2- To extend the consistency retention of fresh concrete.
3- To reduce hydration heat and therefore reduced risk of cracking due to thermal strains.
4- To lower the probability of damages that may be caused by the alkali-silica reaction.
5- To Increase the concrete strength to obtain SCHSC.

Table 2.4: Chemical and Physical Requirements of Pozzolanic Materials **(ASTM C618, 2005)**

Chemical and physical requirements	**Class of pozzolanic materials**		
	N	**F**	**C**
SiO_2 + Al_2O_3 + Fe_2O_3, min (%)	70.0	70.0	50.0
SO_3, max, (%)	4.0	5.0	5.0
Moisture content, max (%)	3.0	3.0	3.0
Loss on ignition, max (%)	10.0	6.0	6.0
Na_2O, max (%)	1.5	1.5	1.5
Fineness, amount retained when wet-sieved on 45 µm (No. 325) sieve, max (%)	34	34	34
Minimum strength activity index at 7 days compared with OPC, percent of control	75	75	75
Minimum strength activity index at 28 days compared with OPC, percent of control	75	75	75
Water requirement, max, percent of control	115	115	105
Soundness, Autoclave expansion, max (%)	0.8	0.8	0.8
Density, max variation from average, (%)	5	5	5

2.4.1 Pozzolanic Activity

The term ‘pozzolanic activity’ covers all reactions occurring among the active constituents of pozzolanic materials, lime, and water. The pozzolanic reaction is the chemical reaction that occurs in portland cement upon the addition of pozzolans. The pozzolanic reaction converts a silica-rich precursor with no cementing properties into a calcium silicate with good cementing properties. Cementitious products are also formed as a result of the chemical reactions between alumina and calcium hydroxide, which form calcium aluminate hydrates. In this process, the hydration of the CaO liberates $Ca(OH)_2$, which causes increased pH values up to approximately (12.4). Under these conditions, pozzolanic reactions occur: the Si and Al combine with the available Ca, resulting in cementitious compounds called calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H) **(Yong & Ouhadi, 2007; Chen & Lin, 2009).**

Due to the pozzolanic activity of these materials, they have been used in concrete construction as supplements to cement. Therefore, this approach will be a useful way to reduce cement demand. Utilizing pozzolanic materials as alternative cementitious materials in concrete provides a more sustainable concrete technology through the creation of a balance between development and the environment **(Safiuddin, 2008)**. Moreover, the carbon dioxide emissions associated with cement production can cause serious environmental impacts **(Şahmaran et al.,2009)**. The current study focused on a type of pozzolanic material called metakaolin, which is generally available.

2.4.2 Metakaolin

Pozzolans can be of natural or industrial origin. (MK) is unique in that it is not the by-product of an industrial process nor is it entirely natural; it is derived from a naturally occurring mineral and is manufactured specifically for cementing applications. Unlike by-product Pozzolans, which can have variable compositions, (MK) is produced under carefully controlled conditions to refine its color, remove inert impurities, and tailor particle size. As such, a much higher degree of purity and pozzolanic reactivity can be obtained **(Justice,2005; Ahmed,2021)**. (CKC) has great promise as a cementitious material, as it can improve many properties of concrete while also reducing cement consumption. these pozzolanic materials are mostly composed of silica and alumina. The calcined clay pozzolana was widely used in the last couple of decades in several countries in the world **(Lea, 2004)**. The raw material input in the manufacture of Metakaolin is kaolin clay.

Minerals gain a distinct pozzolanic activity when burned at temperatures between 600°C and 900°C **(Scrivener,2014)**. The development of pozzolanic properties in calcined clays mainly depends on the nature and abundance of clay minerals in the raw material, on the calcination conditions, and the fineness of the final product **(Ibrahem& Wahab, 2008)**.

2.4.2.1 Reactivity and Calcination Process

Clays can be thermally activated by heating to a given temperature to remove structural water, the crystal structure is destroyed, and new material with pozzolanic property is formed. This phenomenon is called dehydroxylation.

MK is an off-White ultrafine powdered form of anhydrous alumino-silicate derived from the calcination of raw kaolin clay(**Ibrahem& Wahab,2008)**.

Production of metakaolin requires lower calcining temperatures. Several studies have been evaluated the optimum activation temperature of different standard clayey materials and assessed the reactivity of the calcined clays when mixed with cement. **(Sabir et al., 2001;Bich et al., 2009; Siddique & Klaus, 2009)** conducted that the varying ideal activation temperature was in the range 650-850 °C, depending on its minerals purity and impurities, characterization process, etc. The dehydroxylation of kaolinite is shown in Equations (2-1),respectively. (MK) is a reactive pozzolan that reacts with free calcium hydroxide ($Ca(OH)_2$), a pozzolanic reaction takes place whereby new cementitious compounds will contribute cementitious strength and enhanced durability properties to the system in place of the otherwise weak and soluble calcium hydroxide **(Poon et al., 2006; Aiswarya et al., 2013).**

$$\underset{\textbf{Kaolinite}}{Al_2O_3.2SiO_2.2H_2O} \xrightarrow{\textbf{650-850°C}} \underset{\textbf{Metakaolin}}{Al_2O_3.2SiO_2} + \underset{\textbf{Steam}}{2H_2O} \qquad (2\text{-}1)$$

The calcination process emits less aggressive gases that lead to environmental pollution. Nevertheless, the exploitation and processing of the raw material for metakaolin, if sustainable development practices are not implemented, may also lead to environmental destruction such as soil erosion, water pollution, and destruction of natural reserves **(Asante-Kyei & Addae, 2016)**

2.5 Fresh Properties of Self-Compacting Concrete

The key fresh properties of SCC are the filling ability, passing ability, and segregation resistance. These properties must be satisfied regardless of the sophistication of the mixture design and other considerations such as cost. The filling ability and stability of self-compacting concrete in the fresh state can be defined by four key characteristics. Each characteristic can be addressed by one or more test methods are presented in Table 2.5. A variation of one property will normally affect one or both of the others. For example, poor filling ability, as well as poor segregation, can cause insufficient passing ability, i.e. blocking. Increasing filling ability can increase the risk of segregation. SCC is a compromise between filling ability and segregation resistance **(Liu,2009)**.

Table 2.5: Tests Method for Assessment Properties of Fresh SCC

Characteristic	Preferred test method
Flowability	Slump-flow test
Viscosity (assessed by the rate of flow)	T_{500} Slump-flow test or V-funnel test
Passing ability	L-box test
Segregation	Segregation resistance (sieve) test

2.5.1 Filling Ability

Filling ability is described as the ability of the fresh concrete to flow into and fill the spaces within the formwork under its weight **(Bartos,**

2000; EFNARC, 2005). It is associated with the formability, self-leveling capacity, and finishing ability of SCC. The filling ability is an essential property of SCC to achieve self-consolidation capacity. This property is crucial for concrete placement with proper casting technique **(ACI 237R, 2007)**. The filling ability depends primarily on the aggregate amount, the ratio W/B, the amount of the binder, and the HRWR dosage of concrete **(Okamura& Ozawa,1995)**. To achieve high flowing ability, it is necessary to reduce inter-particle friction among solid particles (coarse aggregates, sand, and powder) in the concrete by using a superplasticizer and a lower coarse aggregate content **(Khayat, 1999; Sonebi&Bartos,2002)**. Adding more water could improve flowing ability by decreasing inter-particle friction, but it also reduces viscosity, thus leading to segregation. Too much water also leads to undesirable influences on strength and durability. Unlike water addition, which reduces both the yield stress and viscosity, the incorporation of a superplasticizer not only reduces the inter-particle friction by dispersing the cement particles but also maintains the deformation capacity and viscosity. It also impairs the hardened properties less than does additional water.

The particle size distribution also affects the flowing ability. Inter-particle friction can be reduced by using continuously graded materials **(Khayat, 1999; Sonebi et al., 2001)**. By reducing the coarse aggregate amount and increasing the amount of cementing materials thus incorporating a proper dosage of HRWR, a good filling ability can be realized **(Okamura & Ozawa, 1996).**

2.5.2 Passing Ability

Passing ability is defined as the ability of fresh concrete to flow through tight openings, such as spaces between steel reinforcing bars, without segregation or blocking **(Bartos, 2000; EFNARC, 2005)**. Where structures are heavily reinforced, the good passing ability of SCC enables it to be placed and consolidated through dense reinforcing bars without any aggregate blockage **(ACI 237R, 2007).** The factors affecting the filling ability also influence the passing ability of concrete. In addition, the passing ability depends on the number and spacing of the reinforcing bars. A good passing ability can be achieved by increasing the filling ability of fresh concrete and by limiting the segregation of coarse aggregates. Some aggregates may bridge or arch at small openings which block the rest of the concrete, as shown in Figure 2.3.

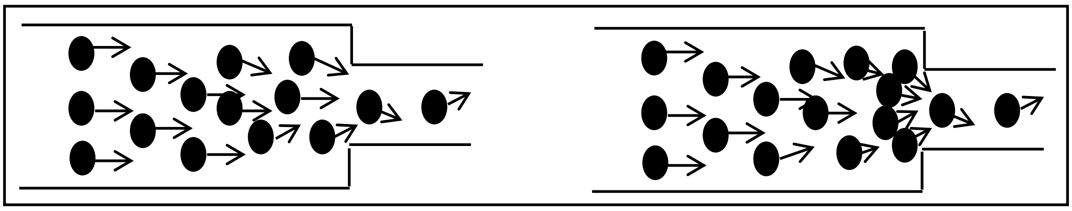

Figure 2.3: Schematic of Blocking

A reduction in the coarse aggregate content and its size are both effective in preventing blocking. The paste volume of the concrete is also an important factor in blocking **(Billberg et al., 2004)**. Blocking depends mainly on the yield stress, whereas the plastic viscosity does not influence the passing ability of the SCC. However, a paste with sufficient viscosity also prevents local increases in coarse aggregate volume, and hence blocking is avoided. Therefore, the passing ability is achieved by a reduction in the coarse aggregate size and content and by the use of VMA or by a proper selection of the powder.

2.5.3 Segregation Resistance

The segregation resistance (also called stability) is the ability of fresh concrete to remain uniform during and after placement without any loss of stability due to bleeding, mortar separation, and coarse aggregate settlement **(EFNARC 2005).** In particular, the distribution of aggregates becomes non-uniform if SCC does not possess sufficient segregation resistance. This might affect the properties and durability of concrete. A recent study has reported that the water absorption and chloride penetration of SCC can be affected under poor segregation resistance **(Daczko, 2002).** A good segregation resistance can be attained in SCC by a proper mixture composition. An increased amount of cementing materials, a small nominal maximum size of aggregate, a limited content of well-graded coarse aggregates, and a low W/B ratio should be used to achieve good segregation resistance **(Bonen & Shah, 2005)**.In addition, the segregation resistance of SCC can be improved by using VEA **(Okamura & Ozawa, 1996).**

2.6 Hardened Properties of SCC

Compressive strength, tensile strength, ultrasonic pulse velocity is some of the key hardened properties of SCC. They are briefly discussed below.

2.6.1 Compressive Strength

Compressive strength is the most important mechanical property of concrete. In general, for a given set of cement and aggregates, and under the same mixing, curing, and testing conditions. **(ACI 363R,2010)** defined High-strength concrete as having a specified compressive strength of 8000 psi (55 MPa) or greater. The compressive strength of concrete primarily depends on the W/B ratio, binder/aggregate (B/A) ratio, mixture composition, and degree of compaction. However, it is the W/B ratio that mainly controls the development of compressive strength in concrete. The limits of the W/B ratio to achieve a targeted compressive strength in high-strength HPC are as follows (**Lessard et al., 1995)** :

50 MPa – 75 MPa, for $0.30 \leq W/B \leq 0.40$

75 MPa – 100 MPa, for $0.25 \leq W/B \leq 0.35$

100 MPa – 125 MPa, for $0.20 \leq W/B \leq 0.30$

125 MPa and above, for $W/B \leq 0.20$

Also **(Nawy,2001)** classified compressive strength of high performance concrete as high, very high and ultra-high strength of ranges from (42–100 MPa with w/c ranges (0.3-0.45), 100–150 MPa with w/c ranges (0.24-0.3) and >150 MPa with w/c less than 0.24), respectively, while normal concrete generally produces a compressive strength in the range of 20 to 40 MPa. The compressive strength of SCC is much higher than that of normal concrete. For a compressive strength varying from 50 to 125 MPa, the aforementioned range of W/B ratios is also valid for SCC. Another observation is that kinetics of strength increase is notably faster in SCC as compared to normal concrete due to increased gel/space ratio at a lower W/B ratio **(Persson, 2001)**.

2.6.2 Splitting Tensile Strength

Although concrete is not usually designed to withstand direct tension stress, tensile strength knowledge is of value in estimating the load under which cracking can occur. The absence of cracking is of great significance in maintaining the continuity of a concrete structure and in many cases in avoiding problems with durability **(Neville, 2011).**

Flexural and tensile strength is related to compressive strength. An increase in compressive strength leads to an increased flexural and tensile strength, however, the increasing rate of flexural and tensile strength is lower. The ITZ characteristics tend to be a very important factor influencing flexural and tensile strength, with a greater degree than compressive strength **(Koehler,2007; Mehta&Monteiro,2014)**. In comparison with traditional vibrated concrete, the flexural and tensile strength of SCC is typically improved, possibly due to the improved ITZ and the better microstructure of bulk cement matrix **(Klug& Holschemacher,2003; Zhu et al.,2004)**.

2.6.3 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity is defined as the traversed distance of the pulse or sonic wave per unit transit time. This is obtained from the path length (length of the interposed concrete specimen) and transit time. The ultrasonic pulse velocity of concrete is mainly influenced by the mixture composition of concrete, moisture and age of concrete, curing conditions, and temperature. Generally, a high ultrasonic pulse velocity through concrete indicates that the concrete is of good quality. An ultrasonic pulse velocity above 4575 m/sec states the‘ excellent’ quality of concrete whereas an ultrasonic pulse velocity below 2135 m/sec reveals the ‘very poor ’ condition of concrete**(Shetty, 2001).** Ultrasonic pulse velocity can be used to evaluate the physical quality of SCC. It is also useful to detect cracks and flaws and to study the freeze-thaw durability of SCC. The ultrasonic pulse velocity of SCC is expected to be much higher than that of ordinary concrete due to the refined pore structure and dense microstructure of SCC.

2.7 Durability Properties of SCC

The absorption, porosity, and sorptivity are some of the key durability properties of SCC. They are briefly discussed below.

2.7.1 Porosity

Porosity refers to a fraction of the total concrete volume that is occupied by the pores in bulk cement paste, interfacial transition zone, and aggregates. It is one of the major factors that control the strength of concrete **(Neville, 2011)**. Porosity also affects the electrical resistivity, and thus the corrosion resistance of concrete **(Claisse et al., 2001).** The porosity of concrete can be characterized into two forms–total and capillary or suction porosities **(Nokken & Hooton, 2002).** The total porosity is mainly comprised of capillary and air porosity. In contrast, the network of open pores mainly constitutes the capillary porosity of concrete. The capillary porosity has considerable effects on the transport properties and hence on the durability of concrete**(Hearn et al., 1994)**. The total and capillary porosities are expected to be low in SCC's high performances (7 to 15%) as compared to ordinary concrete due to compacted pore structure **(Safiuddin, 2008)**. The pore system in SCC is more refined than that in ordinary concrete. this is mainly because of a low W/B ratio. The higher degree of packing due to good consolidation, the greater degree of hydration due to deflocculation and dispersion of cement particles in the presence of HRWR, and the pozzolanic and micro-filling effects of SCM also contribute to form a refined pore structure in SCC **(Attiogbe et al., 2002**).

2.7.2 Water Absorption

Absorption is a process by which a liquid gets into and tends to fill the open pores in a porous solid body such as a component of concrete **(ASTM C125, 2004)**. The absorption is generally more significant in the surface layer than the core of concrete due to strong capillary action. The rate at which a dry concrete surface absorbs a liquid can be taken as a predictor of the durability of concrete. Water is the most common liquid with which the concrete comes in contact. Hence, water absorption is widely used to indicate the absorptivity of concrete. It can be determined based on the increase in mass of a concrete specimen due to the penetration of water into its open pores. Water absorption is directly related to concrete's resistance to water penetration, which plays an important role in various deterioration mechanisms and carries many deleterious agents from the surroundings. Like other engineering properties, the water absorption of concrete is directly influenced by porosity **(Hearn et al. 1994)**. The porosity controls the microstructure and thus the absorption of concrete, depending on the relative quantities of the pores of various types and sizes **(Hearn et al., 1997).** When the porosity decreases, the water absorption is also reduced. The water absorption of high-quality concrete (high-strength concrete or high-performance concrete) is generally less than 5% **(Kosmatka et al.,2002)**. Also, it was reported that SCC's high performances provides water absorption in the range of 3 to 6% **(Safiuddin, 2008).**

2.7.3 Sorptivity

Sorptivity (S) is a material property that characterizes the tendency of a porous material to absorb and transmit water by capillarity. The sorptivity is widely used in characterizing soils and porous construction materials such as brick, stone, and concrete. The cumulative water absorption (per unit area of the inflow surface) increases as the square root of elapsed time (t) (**Hall & Hoff, 2021)**. Minimizing sorptivity is important to reduce the ingress of deleterious materials which can cause extensive damage to a structure. Generally, concrete structures in cold climates are subjected to combinations of freeze-thaw deterioration and the corrosion of steel reinforcement due to the ingress of chlorides from deicing salts. In these environmental conditions, entire structures are susceptible to early deterioration, which can induce unnecessary costs. Also, many building materials used in the construction industry are porous. The ingress of moisture and the transport properties of these materials have become the underlying source for many engineering problems such as corrosion of reinforcing steel, and damage due to freeze-thaw cycling or wetting and drying cycles **(Shanker& Rao,2017)**.

2.8 The Effect of Metakaolin on the Fresh and Hardened Properties of Different Types of Concrete

(Kannan,2018) establish that when OPC was replaced from 0% to 30% by MK as a binary system in SCC, one thing was noticeable in all mixes: while increasing the replacement level of MK, the slump values gradually decreased, the V-funnel time increased, and the blocking ratio during the fresh properties test was reduced. The compressive strength increases with MK up to 15%, and then at 30% MK, the compressive strength attains a higher value than that of normal SCC at 28 and 90 days of curing. Thus, 30% replacement of MK with OPC is considered an optimal limit. The splitting tensile strength of MK (higher value at 15% MK) shows a similar trend to the compressive strength.

(**Shahidan et al., 2017)**, compared the physical and chemical properties of Self Compacting Concrete containing metakaolin with normal concrete, where 0%, 5%, 10%, and 15% of metakaolin were used as cement replacements. They concluded that MK as a cement replacement can increase both compressive and tensile strength, and the slump values decreased compared to normal concrete. The highest compressive strength was found in self-compacting concrete with 15% metakaolin replacement at 53.3MPa, while self-compacting concrete with 10% metakaolin replacement showed the highest tensile strength at 3.6MPa. On top of that, the finishing or concrete surface of both cube and cylinder samples made of self-compacting concrete produced a smooth surface with the appearance of fewer honeycombs compared to normal concrete.

(El-Din, 2017) investigated the mechanical properties of high-strength concrete with metakaolin at (10,15,20,30,40, and 50%). The highest compressive strength was achieved at a cement replacement of 15% by MK. At MK content of 50%, the compressive strength was lower than the corresponding value of the control specimen by 1.93%. A (9.16%) increase in splitting tensile strength has been observed in mixtures with 15% MK cement replacement at 28 d[illegible]. When the cement replacement with MK exceeded 15%, the split tensile strength was lower than the values obtained from the control mixture. However, the developed concrete showed very comparable compressive and tensile properties.

(Al Menhosh et al.,2018) studied the effect of metakaolin on the concrete and its performance. The metakaolin was replaced with 0, 10, 15, 20, 30, and 40% of the weight of the cement. The MK significantly reduces the workability of the modified mixes and the cubic compressive strengths of the MK. Modified concretes at the ages of 7 and 28 days showed that the MK/C ratio in the range of 15–20% presents the maximum compressive strength at the two ages but decreased compared to the control specimen for (30% and 40%) cement replacement with MK, respectively.

(Frieh et al., 2014) studied the effect of a high fractional volume of replacement metakaolin with a percentage of (0, 10, 20, 30, 40, 50, 60, and 70) %replacement by the cement content of the mix on some properties of concrete (compressive strength, splitting tensile strength, density, and ultrasonic pulse velocity). At 20% MK replacement, the maximum compressive strength is recorded. At MK content (30, 40, 50, 60, and 70) of cement replacement, the compressive strength decreased compared to the reference mixture. In general, the results demonstrate that all concrete mixes exhibit a continuous increase in compressive strength with an increase in curing age due to the continuity of the hydration process, which forms a new hydration product within the concrete. The maximum ultrasonic pulse velocity test and splitting tensile strength at 10% MK after that was decreased. For density test results, all mixes at 28 days are decreased compared to their reference.

2.9 The Effect of Metakaolin on the Durability Properties of Different Types of Concrete

According to **(Kannan & Ganesan, 2014)**, When MK was used to partially replace OPC (up to 30%) in SCC, the water absorption improved considerably and was lower than that for unblended SCC (100% OPC), and it can be seen that the sorptivity progressively decreases with increasing MK content up to 20%. It was observed from the sorptivity data that SCC specimens blended with 30% showed an 18.82% reduction in sorptivity at 28 days compared to unblended SCC.

(Al Menhosh et al.,2018) studied the effect of metakaolin on the concrete and its performance. The metakaolin was replaced with (0, 10, 15, 20, 30, and 40%) of the weight of the cement. The results confirm that replacing Portland cement with 15% metakaolin (by weight) provides the optimum improvement for Portland cement concrete on durability properties.

(**Barkat et al., 2019)** studied the effect of adding local metakaolin in different proportions (5, 10, 15, 20, 25)% of the cement weight on self-compacting limestone cement concrete (SCLCC). The results showed that the concrete containing MK had a slightly lower porosity than the control PLC. The decrease in porosity was about 2% for lower MK content and (6% and 19% for 20MK and 25MK), respectively. A low capillary absorption for mixtures with MK is observed compared to control PLC, except for 10MK, at 90 days of curing, which exhibited higher capillary absorption.

(Frieh et al., 2014) studied the effect of a high amount of replacement metakaolin with a percentage of up to 70% replacement by cement content of the mix on water absorption of concrete. They found that water absorption was decreased with increased MK up to 20% MK, and after that, it increased with increased MK up to 70%.

2.10 Nano Technology in Concrete

2.10.1 General Aspects

Concrete is the most widely used construction material in the world. During the period of the second half of the previous century, the terms (nano-science) and (nano-technology) were not yet familiarly used as today. However, they were practiced and successfully applied to the progress in the field of material science and technology. For improving the properties of concrete, researchers have used many types of materials and technologies. One of the materials that recently have been used is nano-sized materials. The nanoparticle is usually defined as a particle of matter that is between 1 and 100 nanometers (nm) in diameter. Various nanoparticles have been developed and incorporated into cement-based materials. The production of nanoparticles based on mortar and concrete has been developed by several researchers **(Zhao & Sun, 2014; Sumesh et al., 2017).**

In the field of using nanoparticles in concrete, three main objectives are considered. Firstly, very high-strength concrete for specific applications can be obtained with the use of nanoparticles. Secondly, reducing the amount of cement needed in concrete for obtaining comparable or even higher strength can be achieved, which in turn reduces the emission of carbon dioxide into the atmosphere. Lastly, by adding several types of nanoparticles to concrete, novel properties can be obtained. Nanoparticles were found to improve the structure of conventional concrete, accelerate the formation of C-S-H and the development of early-age strength, as well as improve the durability of cement-based materials. Nanoparticles have a high surface area to volume ratio as shown in (Figure 2.4), providing the potential for tremendous chemical reactivity (**Sobolev & Gutierrez, 2005; Said et al., 2012).**

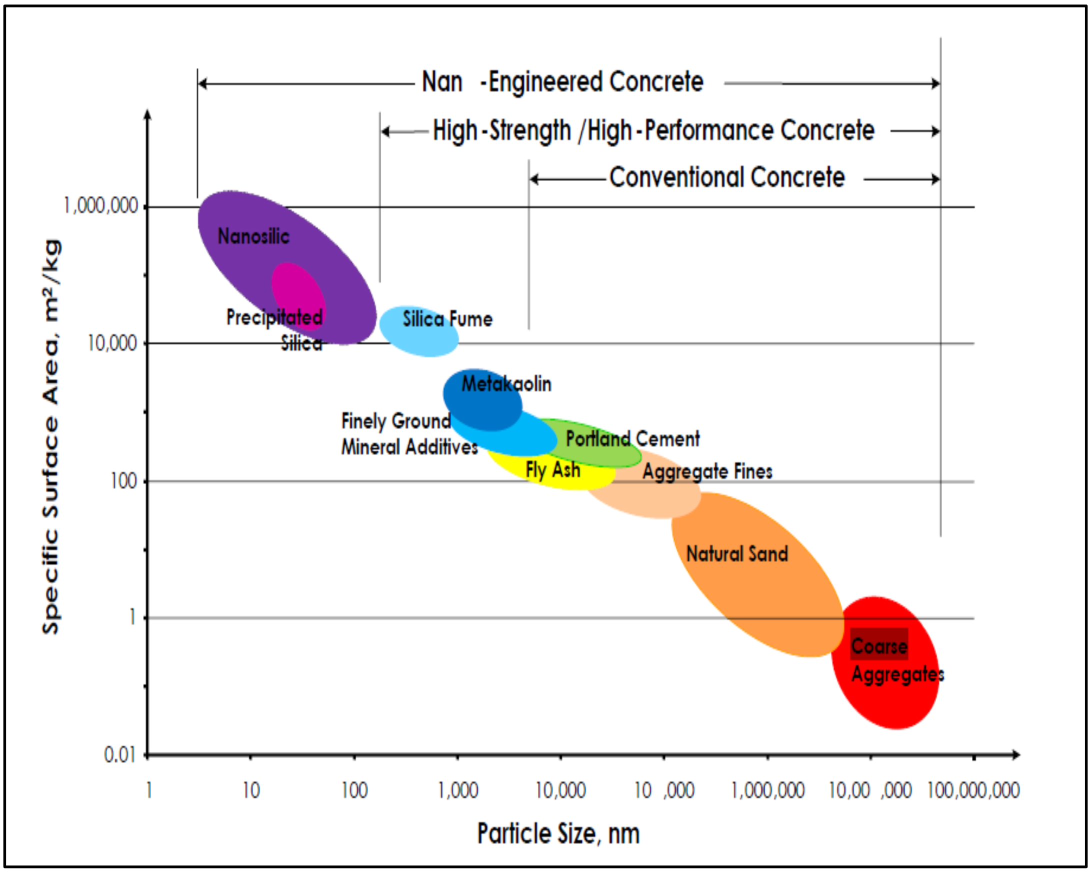

Figure 2.4: Particle Size and Specific Surface Area Related to Concrete Materials (**Sobolev & Gutierrez, 2005)**

2.10.2 Beneficial Effects of Nanoparticles in Concrete

The beneficial action of the nanoparticle on the microstructure and performance of cement-based materials and some useful applications in concrete are summarized as follows **(Mohseni et al., 2015; Rong et al., 2015; Ma et al., 2016; Shaikh et al., 2016)**.

- Well-dispersed Nano-particles increase the viscosity of the liquid phase, which helps to suspend the cement grains and aggregates, improving the segregation resistance and workability of the system.

- Nano-particles fill the voids between cement grains, which results in the immobilization of free water (filler effect).
- Nanoparticles were found to accelerate the formation of C-S-H and the development of early-age strength, as well as improve the durability of cement-based materials.
- Well-dispersed nano-particles act as centers of crystallization of cement hydrates, therefore accelerating the hydration.
- Nano-SiO_2 participates in the pozzolanic reactions, resulting in the consumption of $Ca(OH)_2$ and formation of an additional C-S-H.
- Nanoparticles improve the structure of the aggregates' contact zone, resulting in a better bond between aggregates and cement paste.
- Nanoparticles provide crack arrest and interlocking effects between the slip planes, which improve the toughness, shear, the tensile and flexural strength of cement-based materials.

2.11 Types and Properties of Nanoparticles

Nanoparticles can exhibit significantly different physical and chemical properties than their larger material counterparts. The current section focused on a two type of nanomaterials that used in this study such as nano-calcium carbonate (NC) and nano-Alumina (NA).

2.11.1 Nano Calcium Carbonate (Nano $CaCO_3$)

The incorporation of nanoparticles in cementitious composites can significantly improve their mechanical and durability properties **(Silvestre et al.,2016; Sikora et al.,2018)**. Among these nanoparticles, nano-calcium carbonate (NC) is one of the most widely used nanoparticles in the construction sector **(Cao et al., 2019)**. Though, these tiny white particles have been shown to improve the mechanical properties of concrete dramatically **(Shaikh& Supit, 2014)**. Calcium carbonate can be found in limestone, marble, chalk or produced artificially by combining calcium with CO_2 **(Camiletti et al., 2013)**. Nano-calcium carbonate has a fine particle size and a large specific area, and thereby a more significant effect on the hydration process, workability, mechanical properties, and durability of cementitious composites can be observed, even with only a small amount **(Cao et al.,2019)**. For compressive strength, with the increase in nano-calcium carbonate content, compressive strength initially increases and then decreases **(Liu et al.,2012; Ge et al.,2014; Wu et al.,2016; Wu et al.,2018)**. The reasons are that, on one hand, nano-calcium carbonate can accelerate the hydration process and react with C_3S and C_3A to form C-S-H and carboaluminates, and this effect is more effective with the increase of content to some extent.

The product (carboaluminates) is a low-carbon water-dioxide calcium aluminate (C_4ACH_{11}), which is one of the reasons that nano-$CaCO_3$ can improve the early strength of concrete. The optimal nano-$CaCO_3$ (NC) content can vary with mixture composition, water-to-cementitious ratio, and flowability of the mixture. The properties of nano calcium carbonate ($CaCO_3$) as found in the previous studies are presented in Table 2.6 **(Bakar& Rosli,2006; Assaedi et al.,2020)**. In general, incorporation of nano-calcium carbonate in cementitious composites can improve early-age strength, and incorporation of SCMs may be helpful for long-term strength **(Yang et al.,2018)**, so the hybrid use of nano-calcium carbonate and SCMs may have a synergic effect on both early-age and long-term strength.

Table 2.6: Properties of nano calcium carbonate ($CaCO_3$)

Property	Test Results **(Bakar& Rosli,2006)**	Test Results **(Assaedi et al.,2020)**
Appearance	White powder	White powder
Specific gravity	2.5-2.6	-
Spesific Surface area $m2/g$	>45	-
Whiteness %	>95	>90
Moisture content%	<0.5	0.5
Particle shape	Cubic	Cubic
$CaCO_3$ % (wt) (surface modified)	94.5	>97.5
pH	8.5-9.5	8-9
MgO content %	<0.5	<0.5
Alumina+Iron oxide %	<0.3	-
SiO_2 %	<0.3	-

2.11.1.1 The Effect of Nano $CaCO_3$ on the Fresh and Hardened Properties of Different Types of Concrete

(Kadhum & Owaid,2020) established that the addition of 3% of nano $CaCO_3$ to the mixture leads to an increase in the viscosity of SCHPC (i.e., slump flow diameter, L-box height ratio, and segregation resistance) decreases while the V-funnel increases compared to the reference mixture. The addition of nano $CaCO_3$ (3% of the cement weight) in the ternary mixtures with (calcined clay (5, 10, and 15%)) improves the compressive strength and splitting tensile strength of the concrete mixtures at all ages when compared to the reference mixture and mixture with CC.

(Al Ghabban et al.,2018) showed improvement in compressive strength with increasing the content of nanoparticles. The greater increment in compressive and splitting strength for nano $CaCO_3$ was found at 4% and 3%, respectively. For the hybrid mixture, the maximum compressive and splitting strengths were recorded at (3% nano SiO_2+3% nano $CaCO_3$) due to the dual effect of nano SiO_2+nano $CaCO_3$ on the concrete properties.

(Li et al.,2015) studied the effect of NC on mechanical properties of UHPC matrix. They found that the incorporation of 3% NC, by the mass of cement, improved compressive strength by about 11%-17% at 28 d of curing compared to the control mixture**.** It can be seen that the flow ability decreased as NC was incorporated into mixtures, incorporating 1.0% and 3.0% NC led to a 20% and 34% decrease in the flow ability, respectively**.** Incorporating 1% NS and 3.0% NC in hybrid blend under standard curing achieved higher flexural and compressive strengths of the UHPC matrix compared to the control mixture.

(Ding et al .,2020) investigated the effects of nano-$CaCO_3$ (NC) with different contents (i.e., 0–4% by mass of cement) on hydration, microstructure, and mechanical properties of ultra-high performance engineered cementitious composites (UHP-ECC). It can be seen that the addition of NC improved the compressive strength, tensile and flexural properties and an optimal NC content existed at 3%.

(Kumari et al., 2016), attempted to understand the effect of (nano TiO_2 + nano $CaCO_3$) with contents of 0.5, 1, 1.5, 2, 2.5, and 3% by the weight of cement upon the properties of the fly ash concrete. The results showed that the addition of NTC particles up to 2% increased the strength of the concrete and then decreased it. The mix blended with nanoparticles showed a decline in slump value as the percentage of nanoparticles increased in the mix.

(Chen et al., 2012) studied the improvement of mechanical properties by using nano $CaCO_3$, nano-silica, carbon nanotube (CNT), and nano Al_2O_3 with different contents as an incomplete cement substitution. Results showed the greatest strength in compression with nano-silica, nano $CaCO_3$, nano Al_2O_3, and carbon nanotube (CNT), respectively.

2.11.1.2 The Effect of Nano $CaCO_3$ on Durability of Different Types of Concrete

(Al Ghabban et al.,2018) found the addition of $CaCO_3$ nanoparticles exhibits a reduction in the water absorption potential of concrete. This reduction increased with the content of nano $CaCO_3$ until reaching 3% as a replacement of cement. The water absorption increases beyond 3% of nano $CaCO_3$ content. For mixes with (Nano SiO_2+Nano $CaCO_3$), the water absorption decreased with increased replacement ratio but increased beyond 2% replacement ratio.

(Shaikh& Supit, 2014) reported that the addition of $CaCO_3$ nanoparticles not only led to a much denser microstructure in the concrete matrix but also changed the formation of hydration products, hence contributing to the improvement of early-age compressive strength and durability properties of concrete. The addition of 1% and 2% nano-$CaCO_3$ reduced the concrete capillary pores and the rate of water absorption.

(Ding et al.,2020) investigated the effects of nano-$CaCO_3$ (NC) with different contents on the microstructure properties of ultra-high performance engineered cementitious composites (UHP-ECC). The total porosity decreased as the NC content increased from 0% to 3%. However, a further increase in NC content beyond 3% caused an increase in the total porosity.

2.11. 2 Nano Alumina (Al_2O_3)

Silica and alumina are two major chemicals involved in cement hydration. The function of silica in cement is to change strength properties where alumina controls the setting time of cement. Nano alumina (Al_2O_3) is formed from alumina itself. There are limited studies reported on the use of nano alumina in concrete. Nano alumina is a white powder that reacts with the calcium hydroxide produced from the hydration of calcium silicates. It was indicated that the (Nano-Al_2O_3) is the most effective nanoparticle of examined nanoparticles in the improvement of mechanical properties of concrete **(Shekari, et al.,2011)**. The addition of nano alumina to cement reduces segregation, acts as a nanofiller, and refines the microstructure, also acting as a dispersion agent in cement particles **(Rosenqvist, 2002; Jo et al., 2007; Nazari and Riahi, 2011d; Hosseini et al., 2014)**. Without nano alumina refining the hydration product, the hydration process would be slower because the internal structure of the hydration gel cannot be penetrated by silica component **(Richardson, 1999; Rosenqvist, 2002; Li et al., 2004)**. NA fills up the pores of inert materials and improves the compactness of samples **(Mohseni et al., 2016)**. As found in the previous study, Table 2.7 gives an overview of the properties of pure nano-alumina (Al_2O_3) when tested in manufacturing companies **(Jaishankar& Karthikeyan,2017)**. Using NA results in rapid consumption of crystalline $Ca(OH)_2$ and the formation of C.A.S (calcium-alumina-silica) gel in concrete. The reaction rate depends on surface area (particle) that leads to the fast increase of highly active atoms dense and results in fast hydration. That leads to a high enhancement of compressive strength in nano alumina concrete **(Rasin& Kadhim,2017).**

Table 2.7: Properties of Pure Nano- Alumina (Al_2O_3) **(Jaishankar& Karthikeyan,2017)**

Test item	Standard Requirement	Test result
Crystal structure and type Particle shape	Alpha spherical	yes yes
pH value	3.7-8.5	6
Loss on drying @105 ^{o}c	<1.5	0.47
Loss of ignition @1000 ^{o}c (%)	<2.0	0.66
SiO_2content	>99.8	99.88
Carbon content	<0.15	0.10

<u>2.11.2.1 The Effect of Nano Alumina (Al_2O_3) on the Fresh and Hardened Properties of Different Types of Concrete</u>

(Faez et al.,2020) studied the mechanical and rheological properties of self-compacting concrete (SCC) containing Al_2O_3 nanoparticles (AL_2O_3 NPs) at different amounts (up to 3% by weight of cement). The increase in nanoparticle content reduces flowability, increases yield, and decreases the filling ability of SCC. The concrete V-funnel passing time showed the homogeneity of concrete in all cases. The blockage ratio was decreased by increasing the amount of nanoparticles. Compressive and splitting tensile strength were increased by increasing the amount of

AL_2O_3 NPs and increasing the age of the concrete. In the presence of 2.5% AL_2O_3 NPs, the highest compressive and splitting tensile strength was obtained. Surface cracking of specimens without nanoparticles in comparison with those containing nanoparticles is severe because nanoparticles affect the concrete matrix and reduce its cracking. Reducing surface cracking of specimens with the use of AL_2O_3 NPs in the concrete specimen can reduce the cost of retrofitting after earthquakes.

(Shekari& Razzaghi,2011) investigated the influence of nano-Fe_3O_4 (NF), nano-ZrO_2 (NZ), nano-Al_2O_3 (NA), and nano-TiO_2 (NT) on the durability and mechanical properties of high-performance concrete, for different contents ranging from 0 to 2%. It can be seen that the influence of NA on the improvement of the compressive strength of concrete after 28 days is greater than that of other nano admixtures. Results of indirect tensile tests indicate samples with NA and NF have greater tensile strength compared to other specimens. So the results of this study seem to indicate that Nano-Al_2O_3 is the most effective nano-particle among the examined nanoparticles in the improvement of the mechanical properties of high-performance concrete.

(**Nazari & Riahi, 2011d)** demonstrated that adding a maximum of 2.0 wt% of Al_2O_3 nanoparticles enhances modified cement concrete properties. Partial replacement of cement by nano-Al_2O_3 particles decreased the setting time and workability of fresh concrete, and hence plasticizers were added to improve the workability of the specimens. The results also indicate that Al_2O_3 nanoparticles up to a maximum of 2.0% produce concrete with improved compressive strength and setting time.

(Guler et al.,2020) investigated the effects of nano-SiO_2 (NS), nano-Al_2O_3 (NA), nano-TiO_2 (NT), and nano-Fe_2O_3 (NF) particles in single and hybrid combinations on the compressive, splitting tensile, and flexural strengths of concrete. The largest increases in compressive and splitting tensile strength were obtained for 1.5% of NS and NA hybrid combinations, as 13.95% and 18.55%, respectively.

2.11.2.2 The Effect of Nano Alumina (Al_2O_3) on Durability of Different Types of Concrete

(**Nazari & Riahi, 2011a)** found that partial replacement of cement by nano-Al_2O_3 particles up to the maximum limit of 2.0% decreased the percentage of water absorption of concrete specimens. The percentage of water absorption of concrete samples decreases with the increase in the age of moist curing from 7 to 90 days for all series during the hardening process of the concrete. Utilizing up to 2.0 wt% Al_2O_3 nanoparticles could produce concrete with improved strength and water permeability.

(Nazari&Riahi,2011e) investigated the effects of Al_2O_3 nanoparticles on self-compacting concrete containing GGBFS as a binder. The results show that the percentage of water absorption in the N-GGBFS series at 28 and 90 ages of curing is decreased by increasing the Al_2O_3 nanoparticles content up to 4.0 wt% and then it is increased. With increasing Al_2O_3 nanoparticles up to 3.0 wt%, the total specific pore volumes of concrete are decreased, and the most probable pore diameters of the concrete shift to smaller pores and fall in the range of few-harm pore. On the one hand, nanoparticles can act as fillers to improve the resistance to water permeability of concrete at 7 and 28 days of curing and to enhance the density of concrete, which leads to the porosity of concrete being reduced significantly.

(Faez et al.,2020) studied the water absorption of self-compacting concrete (SCC) containing Al_2O_3 nanoparticles in different amounts up to 3% as a substitute for cement. The use of Al_2O_3 NPs in all mixtures has decreased the water absorption percentage. The use of 1 and 2% of aluminum nanoparticles reduced water absorption by 10% and 45%, respectively. This is a desirable property of concrete containing nanoparticles that enables them to be used in adverse environmental conditions, such as environments where concrete is exposed to successive freezing and melting. Reducing water absorption leads to an improvement in the durability of concrete.

(Behfarnia& Salemi, 2013) studied the frost resistance of concrete containing 1 wt%, 2 wt%, and 3 wt% of nano-alumina and nano-SiO_2. Experimental results showed that the frost resistance of concrete containing nano-particles was considerably improved as a result of a more compacted microstructure. It was also concluded that the frost resistance of concrete containing nano-Al_2O_3 was better than that of concrete containing the same amount of nano-SiO_2. The nano-Al_2O_3 and nano-SiO_2 particles recover the particle packing density of the concrete and, as a nanofiller, improve the microstructure of the concrete, so the water permeability of concrete is decreased by the replacement of cement with nano-particles partially.

2.12 Multiple Regression Analysis (MRA)

Multiple regression is an extension of simple linear regression. The purpose of MRA is to simultaneously identify two or more independent variables that explain variations in the dependent variable. The latter was chosen because of its ability to identify relationships among several variables **(Hashim et al., 2017)**. The variable we want to predict is called the dependent variable. The variables we are using to predict the value of the dependent variable are called the independent variables. For statistical analyses for the prediction of the compressive strength, multivariable linear regression analysis (MRA) was employed by using SPSS software. The ability of the developed model to explain the relationship between the independent and dependent parameters must be evaluated by calculating the coefficient of determination (R^2) **(Jafer et al., 2016)**. **(Shubbar et al.,2018)** used a multi-regression (MR) model to investigate the effects of curing time and content of ordinary portland cement (OPC), ground granulated blast furnace slag (GGBS), and high calcium fly ash (HCFA) on the compressive strength in binary and ternary blending systems and to identify the relationship between measured and predicted compressive strengths. The results revealed that the proposed model explained 89.3 percent of the variance in compressive strength and that there was a high level of agreement between predicted and experimental compressive strength, with an R^2 value of 0.8701. **(Byakodi &Patil,2017)** used multivariable linear regression analysis (MRA) to predict the compressive strength of admixture concrete before production. They considered compressive strength to be a dependent variable, while cement, rice husk ash, metakaolin, and temperature are independent variables. The results showed that statistical validation of experimental data was performed and satisfactory correlation coefficient (R) and determination coefficient (R^2) values were obtained.

2.13 Relationship Between Compressive Strength and Ultrasonic Pulse Velocity

(Tharmaratram & Tan, 1990) established a relationship between UPV in a concrete (Vc) and a concrete compressive strength (fc′) by general Equation (2-2) based on their experimental results. **(Demirboğa**

et al., 2004) noticed an exponential relationship between compressive strength and UPV for mineral admixture concrete and demonstrated that the general equation applies to all types of mineral admixtures as below:

$$fc' = a\, e^{bVc} \quad (2\text{-}1)$$

Where

fc′: compressive strength

Vc: Ultrasonic Pulse Velocity

a and b: Empirical constants

(Owaid et al., 2017) discovered positive exponential relationship between UPV and compressive strength, with a determined coefficient of correlation (R^2) of 0.889 between 3 and 90 days of curing when binary mixtures (varying amounts of activated alum sludge ash (AASA), silica fume (SF), ground granulated blast furnace slag (GGBS), and palm oil fuel ash (POFA)) and ternary mixtures (AASA + SF, AASA + GGBS, and AASA + POFA) were blended as partial replacements for cement by weight.

2.14 Summary

With increasing demand and the consumption of cement in concrete construction, the utilization of pozzolanic materials is increasing day by day. This can easily be understood from the numerous research interests regarding the application of these materials that have been cited in this chapter. Nowadays, the application of nanoparticles has received widespread attention to enhance concrete properties. So production and application of SCC containing low carbon binder by hybrid use of nanoparticles (NC and NA) with a high volume of MK seem to be a promising and energy-saving step toward sustainable construction and building technology. However, this would not be achieved without studying its performance before being widely adopted in construction. Also, the behavior of structural elements made with SCC needs better understanding, together with design provisions.

The utilization of pozzolanic materials in large volumes can reduce the demand for cement in concrete construction. Besides, their use in concrete not only improves the compressive strength, and enhances the durability properties of concrete significantly. In addition to that, they contribute to reducing CO_2 emissions due to less cement consumption. Also, using nanoparticles will help to reduce the cement content by partially replacing cement on a weight basis, and the mentioned literature reveals that fine nanomaterials will help in reducing the formation of micropores by acting as filler agents, producing very dense concrete. Their utilization in concrete will also be a remarkable step towards achieving the goal of sustainable SCC as well as sustainable development in the foreseeable future.

CHAPTER THREE

MATERIALS

&

EXPERIMENTAL WORK

Chapter Three

Materials and Experimental Work

3.1 Introduction

The research program was comprised of experimental investigation and modeling. The experimental investigation was carried out in the laboratory of construction materials in the Civil Engineering Department at Babylon University. In this chapter, the experimental plan and the materials that were used in this research were described in detail. The methods for producing self-compacting concrete specimens, including their mixing, casting, curing, and testing, had been explained. The chapter also contains details of testing instruments that were used in this research and their application methods for giving a wide range of views on the testing procedures.

Most of the experimental procedures in this research have been performed according to the American Society for Testing and Materials (ASTM) and/or British European (BS EN) and Iraqi specification (IQS) standards. The concept behind this experimental investigation is to develop SCCs containing a low carbon binder by using a high volume of locally available calcined pozzolanic materials such as (MK) and a hybrid blend of nanoparticles (NC and NA). This chapter discusses the research procedure and provides a flowchart for the overall experimental investigation.

3.2 Experimental Investigation of the Research

The experimental investigation for various SCCs was comprised of selection and testing of materials, testing of mortars, design of SCC mixtures, preparation and testing of fresh concrete, and preparation and testing of hardened concrete. The overall experimental investigation is shown in the flowchart given in Figure 3.1. The experimental investigation of this research included two stages:

In the first stage, the selection, preparation of materials, and physical and chemical testing of materials were used in this study to identify their suitability. Also, mortars containing Pozzolanic material and nanomaterials were tested to identify their suitability as partial replacements for cement. This stage also explains the concrete mix proportions of materials, the mixing method, casting, curing, and laboratory testing in the fresh state for self-compacting concrete. The following laboratory tests were performed in the fresh state: (slump flow (D (mm)), T_{500}, L-box test, V-funnel, and sieve segregation resistance tests), after which the concrete mixtures were poured into molds prepared for this purpose and placed in water to cure.

In the second stage, after curing in the required ages, laboratory tests were carried out to determine the hardened properties, represented by (bulk density, compressive strength, splitting tensile strength, and ultrasonic pulse velocity (UPV)) and durability performance, represented by (water absorption, porosity, and sorptivity) of the binary, ternary, and quaternary blends of different SCCs containing high volume metakaolin (MK), nano calcium carbonate (NC), and nano alumina (NA).

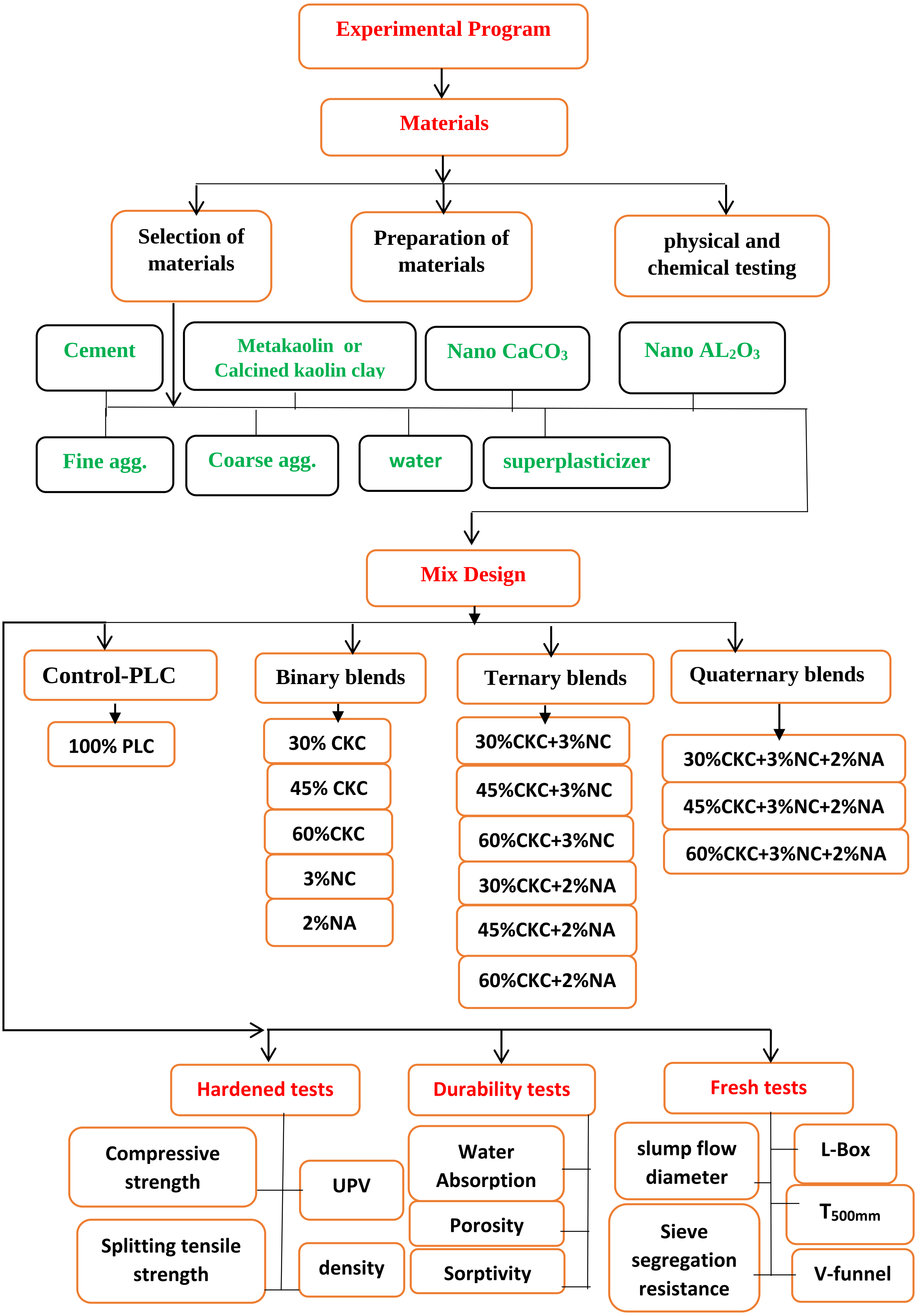

Figure 3.1: The Overall Experimented Investigation

3.3 Materials

As stated earlier, calcined kaolin clay (CKC), nano calcium carbonate (NC), and nano alumina (NA) were selected as calcined pozzolanic material and nanoparticles, respectively, to achieve the goal of this research in developing self-compacting concrete. Thus, a brief description regarding the source of materials, collection, and production is given below.

3.3.1 Cement

The locally available cement used in all SCHPC mixtures was Portland limestone cement (PLC), Karasta CEM II, produced by Lafarge Company, which conforms to the European Standard (**BS EN 197-1, 2011)**. The physical properties and the chemical analysis of the cement used in this investigation are provided in Tables (3.1) and (3.2), respectively.

Table 3.1: Physical Properties of Cement

Physical property	**Test Result**	**Limits According to BS EN 197-1**	**Conformed to BS EN 197-1**
Setting Time, min Initial Final	 119 191	 ≥ 60 min -------	 Ok
Fineness (Blaine), in m^2/Kg	314	Not specified	
Compressive Strength in MPa, at 2 days 28 days	 22 51	 ≥ 20 MPa ≥ 42.5 MPa, ≤ 62,5Mpa	 Ok Ok

Table 3.2: Chemical Compositions of Cement*

Chemical composition (%)	Test Result	Limits According to BS EN 197-1	Conformed to BS EN 197-1
Lime (CaO)	62.79		
Silicon dioxide (SiO_2)	20.58		
Aluminum trioxide (Al_2O_3)	5.60		
Iron oxide (Fe_2O_3)	3.28		
Magnesia oxide (MgO)	1.94		
potassium oxide (K_2O)	0.56		
sodium oxide (Na_2O)	0.29		
Sulfur trioxide (SO_3)	2.35	$\leq$ 4%	Ok
Free Lime	0.84		
Loss on ignition (L.O.I)	1.94		
Insoluble Residue %	1.00		
Lime saturation factor (L.S.F)	0.91		
Main compounds (Bogue's equation) percentage by weight of cement			
Tri-calcium silicate (C_3S)	50.12		
Di-calcium silicate (C_2S)	21.26		
Tri-calcium aluminate (C_3A)	9.29		
Tetra-calcium aluminoferrite (C_4AF)	9.98		

* Chemical tests were conducted in The National Center for Construction Laboratories and Research (NCCLR) in Babylon

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3.3.2 Metakaolin

Metakaolin (MK) is a type of mineral admixture and is generally known as calcined kaolin clay (CKC), which is one of the recently developed supplementary cementing materials. It is produced by calcining purified kaolin clay at a specific temperature range to drive off the chemically bound water and destroy the crystalline structure. This process results in the formation of a quasi-amorphous material that is reactive with lime. The reactivity of the calcined clay with lime depends on the quasi-amorphous nature of the collapsed structure. Therefore an optimum calcination temperature exists for each clay, at temperatures beyond the optimum, re-crystallization begins, while at a temperature below the optimum the clay lattice structure is still intact **(Ibrahem& Wahab, 2008).** The origin of CKC or metakaolin (MK) was Iraqi Kaolin clay collected from the Dewekhla region in the Al Ramadi desert in the west of Baghdad, Iraq. The kaolin clay was ground and then burned in a furnace up to 800ºC± 20ºC, for 2 hours at a heating rate of 5 ºC/min, to produce the MK, and then was cooled gradually to room temperature for 24 hours, according to **(Kadhum & Owaid,2020),** after that, ground by the air blast technique in AL-Zahra′a Shop in Baghdad, to obtain reactive material with more fineness. Figure 3.2 shows kaolin clay (KC) and the obtained calcined kaolin clay (CKC).

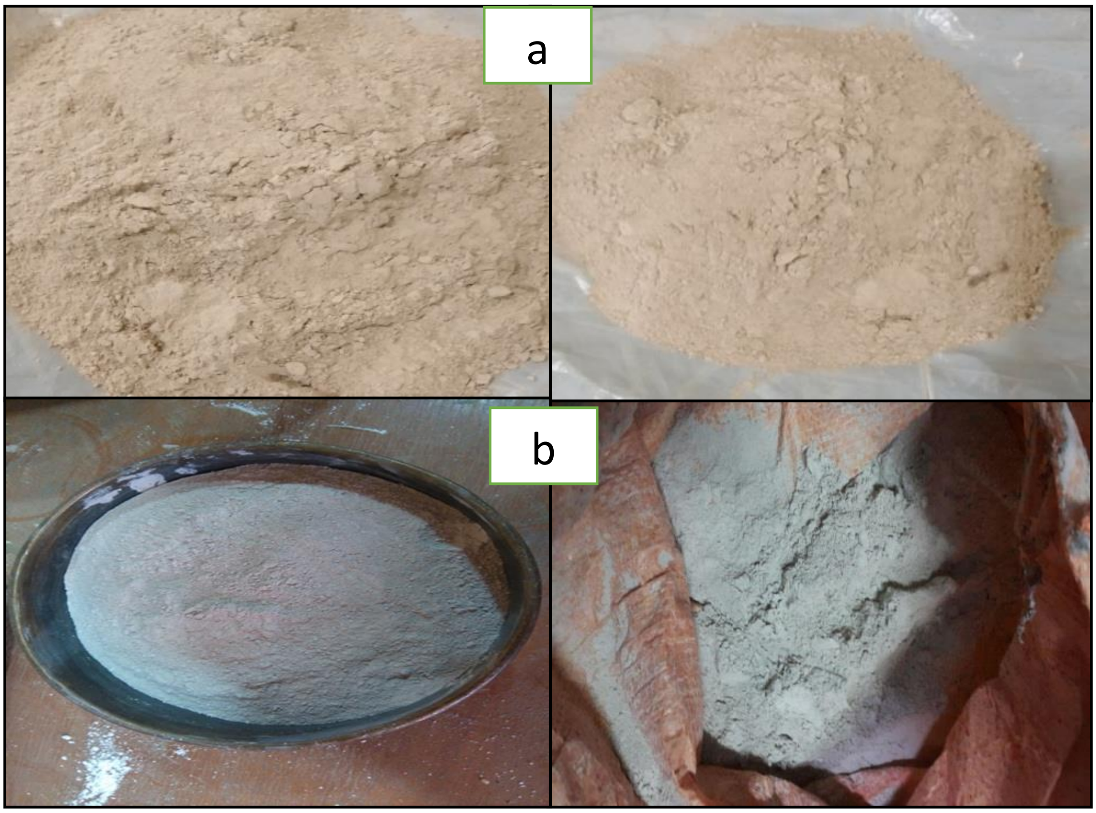

Figure 3.2: Obtained Pozolanic Material (a) Raw Kaolin Clay (b) CKC Powder

3.3.2.1 Chemical Properties of Metakaolin

The chemical properties and oxide composition are other important parameters for the activation of a binder. The oxide composition and loss of ignition (LOI) test results are presented and discussed below in detail. The chemical composition of the Metakaolin or calcined kaolin clay was being studied focusing on similar chemical compositions contained in cement. In general, the main chemical compositions in cement are lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_2O_3). In addition, the miner compounds such as MgO, SO_3, K_2O, Na_2O, and LOI, which also determined. Table (3.3) presents the chemical compositions of the kaolin clay (KC), Metakaolin (MK), and cement (PLC).

It was found that the major constituents of MK were silica oxide (SiO_2) and alumina oxide (Al_2O_3). The results revealed that the percentages of SiO_2 and Al_2O_3 were (54.7 % and 37.4 %), respectively, which are responsible for the pozzolanic reaction. The total percentage of major oxides (SiO_2 + Al_2O_3 + Fe_2O_3) was over 70% for CKC, which was greater than the minimum (70%) as specified in **(ASTM C618, 2005)**, standards for class "N" pozzolans, which is a high-quality pozzolan category. The amount of TiO_2 indicated the presence of anatase or rutile, and the presence of the lower amount of K_2O indicated the presence of a trace of micaceous or K-feldspar mineral. The presence of P_2O_5 and MgO could be attributed to the impurities of aluminosilicate phases. Through calcination, it could be seen that the contents of SiO_2 and Al_2O_3 were increased. Thus, calcining the kaolin at 800 C^o for 2 h resulted in higher SiO_2 and Al_2O_3 than the raw kaolin, as seen in Table 3.3.

Table 3.3: Chemical Compositions and Loss on Ignition (LOI) of Kaolin clay (KC), and Metakaolin (MK)*

Chemical composition (%)	Kaolin clay	Metakaolin
Silicon dioxide (SiO_2)	49.3	54.7
Aluminum trioxide (Al_2O_3)	33.8	37.4
Iron oxide (Fe_2O_3)	1.43	1.72
Calcium oxide (CaO)	0.71	0.84
Magnesium oxide (MgO)	0.57	0.42
Sodium oxide (Na_2O)	0.26	0.37
Potassium oxide (K_2O)	0.41	0.54
Sulfur trioxide (SO_3)	0.19	0.13
Phosphorus pentoxide(P_2O_5)	0.31	0.29
Titanium dioxide (TiO_2)	0.52	0.68
Loss on ignition (LOI)	11.73	2.91

* Chemical tests were conducted in The National Center for Construction Laboratories and Research (NCCLR) in Babylon.

It could further be observed in Table 3.3 that the content of sodium oxide (Na_2O) and potassium oxide (K_2O) was slightly lower in raw kaolin, and the calcination of raw kaolin further increased the content of Na_2O and K_2O. Similar trends were also reported by other researchers **(Shafiq et al., 2015; Tchakouté et al., 2016; Kadhum & Owaid,2020)**. The loss on ignition (LOI) is the weight lost when the material was heated to 1000 °C. Usually, at this temperature, any moisture is dried and any CO_2 present in the material is released. The LOI of the MK was 2.91%. It was less than the prescribed value of 10%. Thus, these results were under the standard of **(ASTM C618, 2005)** for class "N".

3.3.2.2 Physical Properties of Metakaolin

Different physical properties, including specific gravity, grain size distribution, and fineness, were examined. Details of the physical properties of MK and PLC are summarized in Table 3.4. After calcination, MK became much harder, due to the calcination effect and the color changed to off-white. The specific gravity of PLC and MK were 3.12 and 2.59, respectively. Thus, the specific gravity of MK used was lower than that of PLC, as shown in Table 3.4.

Table 3.4: Physical Properties of PLC and MK

Property	Cement	CKC
Specific gravity	3.12	2.59
Fineness (Blaine Method), m^2/kg	314	1640
Median particle size (μm)	16.8	14.3
Color	Grey	Off-White

Due to certain transformations, the specific surface area (SSA) of MK was higher than that of PLC. The SSA of the MK was determined to be 1640 m^2/kg, whereas the PLC was 314 m^2/kg. All the pozzolanic materials possess greater SSA than the PLC. The high specific surface area of the pozzolanic materials prepared for this study was a good presumption that they possess the right quality to potentially be an effective pozzolan. The particle size distribution of MK had a mean diameter (d_{50}) about 14.3 μm.

3.3.3 Nano Calcium Carbonate ($CaCO_3$)

The nano calcium carbonate (NC) used in this study is ultra-fine precipitated calcium carbonate with an average particle diameter of fewer than 100 nanometers. It is of a high degree of purity and in powder form. It contained more than 96% of $CaCO_3$. The nano calcium carbonate (NC) was added to the mixtures as a partial replacement of the weight of cement. Table 3.5 presents the physical and chemical properties of NC taken from the manufacturer. The NC powder is shown in Figure 3.3.

Table 3.5: Properties of Nano Calcium Carbonate ($CaCO_3$)*

Property	Test Results
$CaCO_3$%	≥ 96
Physical form	Powder
Colour	White
Particle size, nm	< 100
Spesific Surface area $m2/g$	≥20
Whiteness %	≥93
Moisture content%	≤0.9
Morphology	Cubic
pH	8.5-9.7
Loss on ignition%	44±1
MgO content %	≤0.8
Alumina+Iron oxide %	≤0.3
The insoluble matter with acid%	≤0.3
Activation rate %	≥95

* Properties of Nano ($CaCO_3$) are obtained from the manufacturer.

Figure 3.3: Nano Calcium Carbonate Powder

3.3.4 Nano Alumina (Al_2O_3)

The nano alumina (AL_2O_3) used in this study is a high-purity, superfine nanoparticle with an alpha phase. Its purity is 99.99% with an average diameter of 80 nm. Table (3.6) shows the properties of NA taken from the manufacturer and Table (3.7) shows the physical properties of PLC,NC, and NA. The nano alumina powder is shown in Figure 3.4.

Table 3.6: Properties of Nano Alumina (Al_2O_3) *

Property	Test Results
Physical form	Powder
Colour	White
Particle size, nm	80
shape	spherical
purity %	99.99
Crystal	alpha

* Properties of Nano (Al_2O_3) are obtained from the

Figure 3.4: Nano Alumina Powder

Table 3.7: Physical Properties of PLC, NC, and NA

Property	Cement	NC	NA
Specific gravity	3.12	2.5	3.1
Fineness (Blaine Method), m^2/kg	314	≥20000	70000
particle size (nm)	16800	< 100	80
Color	Grey	White	White

3.3.5 Fine Aggregate

Three important factors must be taken into consideration when producing self-compacting concrete, which is: the amount of fine aggregate; grading; and the shape of the particle. In this study, the fine aggregate used was the local natural sand brought from the Al-Akhaidher region. The grading of fine aggregate is provided in Table 3.8 and shown in Figure 3.5, while the physical properties of fine aggregate are provided in Table 3.9. Through the results, it was found that the used fine aggregate is located within the third gradient zone, conforms to the Iraqi standards **(IQS 45,1984)**, and has a fineness modulus of (2.52).

Table 3.8: Grading of Fine Aggregate Used Throughout this Work*

Sieve size (mm)	Cumulative Passing by weight (%)	Limits of the Iraqi specification IQS 45 (zone 3)
10	100	100
4.75	100	90-100
2.36	87	85-100
1.18	78	75-100
0.60	64	60-79
0.30	30	12-40
0.15	7	0-10

*Sieve Analysis and sulfate content were Conducted by the Constructional Materials Laboratory at the University of Babylon.

Table 3.9: Physical Properties of Fine Aggregate Used Throughout This Work*

Property	Test Results	Limits of the Iraqi Specification IQS 45
Specific gravity	2.65	--
Absorption (%)	0.94	--
Fineness Modulus	2.52	--
Sulfate content (%)	0.309	≤ 0.50 %
Material finer than 0.075 mm (passing from sieve (75μm)) %	1.81	≤ 5.0 %

*Physical Tests were Conducted by the Constructional Materials Laboratory in the University of Babylon.

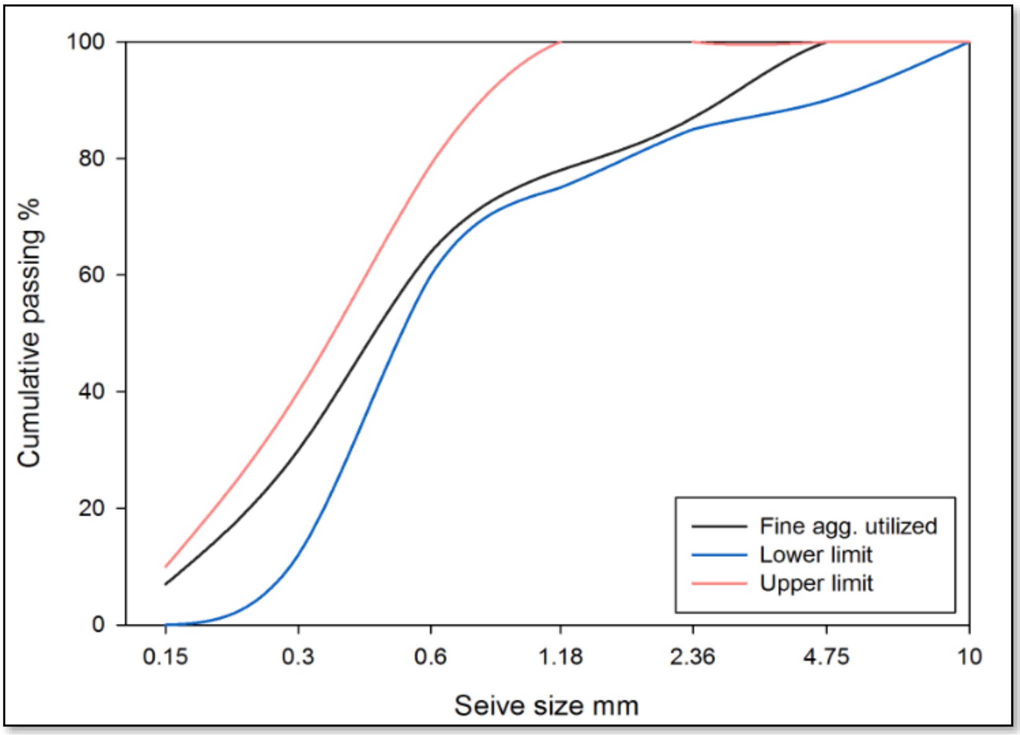

Figure 3.5: Grading of Fine Aggregate

3.3.6 Coarse Aggregate

In this study, the washed gravel from the Al-Nabai'i area with a maximum size of 10 mm was used, as Table 3.10 and Figure 3-6 show the gradation of coarse aggregate. Through the results of the examination, it was found that the coarse aggregate conforms to the Iraqi standard specifications (**IQS 45,1984**). The values (absorption, sulfate content, and specific gravity) of the coarse aggregate are provided in Table 3.11.

Table 3.10: Grading of Coarse Aggregate

Sieve Size (mm)	Cumulative Passing by Weight (%)	Limits of the Iraqi Specification IQS 45
14	100	100
10	100	85 – 100
5	20	0 – 25
2.36	0	0 – 5

Table 3.11: Physical Properties and Sulfate Content of Coarse Aggregate*

Properties	Test Results	Limits of Iraqi Specification IQS 45
Specific Gravity	2.58	-
Sulfate Content SO_3, (%)	0.03	< 0.1%
Absorption, (%)	0.5	_

*Physical tests were conducted in the construction materials laboratory at the University of Babylon.

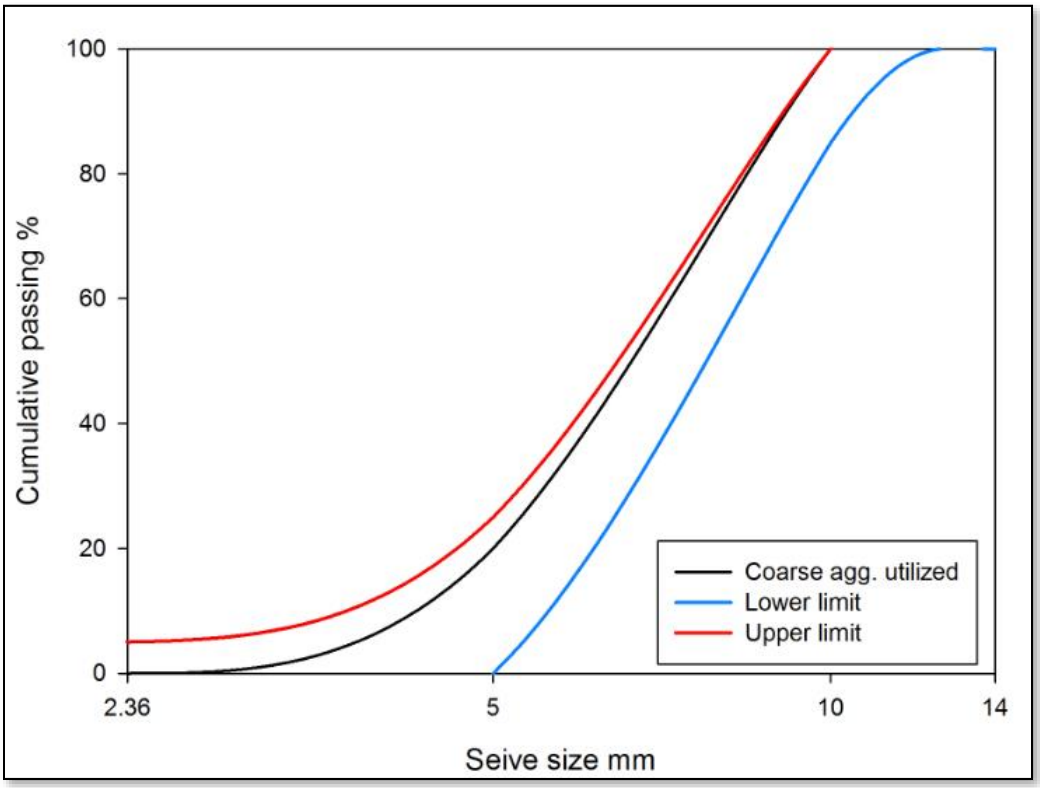

Figure 3.6: Grading of coarse aggregate

3.3.7 Water

The mixing water used for all the mixes was normal tap water from the domestic water supply. So it was clear of residual and organic materials that could have impacted the concrete properties.

3.3.8 High Range Water Reducing Admixture

A modified polycarboxylic ether-based High water reducing agent (HWRA) Superplasticizer (SP), commercially known as Glenium 54, was used to produce the required flowing ability of SCC. Representative experiments must be performed to find the ideal dose of Superplasticizer to fulfill performance requirements. It is produced by BASF Company and conforms to **(ASTM C494,2017)** Type F. Table 3.12 shows its properties.

Table 3.12: Typical Properties of High Range Water Reducing Admixture *

Form	**Viscous liquid**
Commercial name	Glenium 54
Appearance	Whitish to straw-colored Viscous liquid
pH	5-8
Relative density	1.07 gm/cm^3 at 20 ^oC
Chloride content	Nil
Storage	Should be stored in original containers and at above 5 ^oC
Transport	Not classified as dangerous
Alkali content (as NaO_2) equivalent)	0.26%

*According to manufacturer

3.4 Pozzolanic Activity of Materials

According to standard test methods **(ASTM C311, 2005**; **ASTM C1240, 2005),** the strength activity index (SAI) of metakaolin (MK) and nanoparticles (NC and NA), respectively, was determined. The 7 and 28-day compressive strengths of a mortar prepared with a 20% MK substitution for cement are compared to those of a control mortar (100% PC) as per **(ASTM C311, 2005; Saand et al., 2016)**. **(ASTM C618, 2005)** specifies that the mixture with the SCM must have a minimum of 75% of the strength of the control mix (SAI ≥ 75) at 7 days or 28 days. The proportion of NC or NA is 7% of cement (by weight). According to **(Hassan, 2019)**, the standard ASTM C1240 procedure is applicable for nanoparticles, but a lower cement replacement percentage should be used.This study found that the addition of nanoparticles should not be more than 7% of the cement.To meet **(ASTM C1240,2005)** requirements, the compressive strength of the pozzolanic-mortars must be at least 105% of the control mortar (SAI ≥ 105) after 7 days. For testing the pozzolanic activity index, mortar cubes of 50 mm in length are used for this test. Mortar was prepared and tested for compressive strength according to **(ASTM C109, 2009).** The strength activity index was calculated by Equation (3-1):

$$SAI(\%) = \left(\frac{A}{B}\right) \times 100 \qquad (3\text{-}1)$$

A is the average compressive strength of the test mixture cubes, MPa, and B is the average compressive strength of control mix cubes, MPa.

3.5 Concrete Mixture Proportion

To provide a distinguishable observation of the effectiveness of the replacement levels of Metakaolin (MK), nano calcium carbonate (NC), and nano alumina (NA). A total of 15 self-compacting concrete (SCC) mixtures were designed and cast at a water to binder ratio (w/b) of 0.38 and a total binder content of 485 kg/m^3. The superplasticizer dosages were 1.7%, 2%, and 2.3% by mass of cementitious material to fulfill performance requirements of SCC as per **(EFNARC, 2005**). The normal dosage for glenium 54 is between 0.5 and 2.5 liters per 100 kg of cement (cementitious material) as described by Company. All the mixes were designed based on the typical range of SCC mix composition proposed by **(EFNARC, 2005)** standards.

This thesis develops three blend systems as shown in Table 3.13: binary, ternary, and quaternary, in three stages. In the first stage, the control mix was made with only PLC as the binder, while the remaining mixtures incorporated binary blend systems (PLC+CKC, PLC+NC, and PLC+NA) in which PLC was replaced at 30%, 45%, and 60% of CKC, whereas with the NC and NA, it was 3% and 2%, respectively, by weight of cement as shown in Table 3.14. The above contents of nanoparticles for NA and NC are used as optimal values of replacement based on previous studies **(Nazari & Riahi, 2011a; Kadhum & Owaid,2020)**. In the second stage, the ternary blend systems, the replacement ratios for CKC were 30%, 45%, and 60%, with 3% of NC and 2% of NA, respectively, as partial replacement of binder (by weight). In the third phase, for the quaternary systems, the replacement ratios for CKC were 30%, 45%, and 60%, with hybrid nanoparticles 3% of NC and 2% of NA as partial replacements of binder (by weight) as shown in Table 3.15.

Table 3.13: Notation of the Mixes

Mix Notation	Details
Control-PLC	Reference mix of SCC was made with only Portland limestone cement (100%PLC)
30%CKC	The binary blend of SCC was made with (60%PLC+30%CKC)
45%CKC	The binary blend of SCC was made with (55%PLC+45%CKC)
60%CKC	The binary blend of SCC was made with (40%PLC+60%CKC)
3%NC	The binary blend of SCC was made with (97%PLC+3%NC)
2%NA	The binary blend of SCC was made with (98%PLC+2%NA)
30%CKC3%NC	The ternary blend of SCC was made with (67%PLC+30%CKC+3%NC)
45%CKC3%NC	The ternary blend of SCC was made with (52%PLC+45%CKC+3%NC)
60%CKC3%NC	The ternary blend of SCC was made with (37%PLC+60%CKC+3%NC)
30%CKC2%NA	The ternary blend of SCC was made with (68%PLC+30%CKC+2%NA)
45%CKC2%NA	The ternary blend of SCC was made with (53%PLC+45%CKC+2%NA)
60%CKC2%NA	The ternary blend of SCC was made with (38%PLC+60%CKC+2%NA)
30%CKC3%NC2%NA	The quaternary blend of SCC was made with (65%PLC+30%CKC+3%NC+2%NA).
45%CKC3%NC2%NA	The quaternary blend of SCC was made with (50%PLC+45%CKC+3%NC+2%NA).
60%CKC3%NC2%NA	The quaternary blend of SCC was made with (35%PLC+60%CKC+3%NC+2%NA).

3.6 Mixing Procedure and Casting of Specimens

Mixing is a mechanical operation to obtain a uniform mixture of concrete. Mixing procedure and mixing time are more critical in SCC as compared to conventional concrete mixtures. The mixing time for SCC is greater than that of ordinary concrete due to its higher plastic viscosity at a low W/B ratio **(Chopin et al., 2004)**. Also, experience has shown that the time necessary to achieve complete mixing of SCC may be longer than for normal concrete due to reduced frictional forces and to fully activate the superplasticizer. However, with SCC, it is particularly important that the mixer is in good mechanical condition and that it can ensure full and uniform mixing of the solid materials with sufficient shear action to disperse and activate the superplasticizer **(EFNARC,2005)**.

During the mixing time, the mixer should be covered to avoid moisture loss from the fresh concrete. The concrete mixing throughout the study was carried out in a laboratory at 25±2°C temperature and in a concrete horizontal drum laboratory mixer. Before mixing, nano calcium carbonate (NC) and nano alumina (NA) were mixed with cementitious materials including cement or a combination of cement and calcined kaolin clay in dry form for 5 min using an electric mixer in all mixes, including nanoparticles, to obtain the best dispersion and to prevent agglomerations of nanoparticles due to the high surface area of nano-powder, which involves special treatment **(Mohamed,2016)**. To begin the mixing process, coarse and fine aggregates were added to a rotary mixer of $0.1m^3$ capacity. While the mixer was running, one-third of the mixing water was added. The mixer ran for 30 seconds before the cement, pozzolans, nanoparticles, and the remaining water was added. The mixer continued mixing for another 3 minutes before resting. The concrete was left to rest in the mixer with the lid closed for another 3 minutes. After that, the superplasticizer was added to the concrete and mixed for another 3 minutes **(ASTM C192, 2003)**. Then the mixture was produced, tested for fresh properties, and cast.

The mixing process is important for obtaining the requisite workability and homogeneity of SCC mixes. The mixtures were cast as specimens using 50 mm × 50 mm × 50 mm standard cube molds, 100 mm × 100 mm × 100 mm standard cube molds, and 100 mm × 200 mm cylinders. These molds were cleaned and their internal surfaces were oiled to avoid adhesion with the mixture after hardening. Then, the mixtures were being poured into the molds until it's filled without any compaction. Soon after casting, the concrete surfaces are leveled utilizing trowel, and the specimens are covered with nylon sheets to assure a humid air and left in the casting room at 25±2°C for 24 hours until demoulding as seen in Figure 3.7. After that molds were removed, cubes were immersed in the water basin to be tested later at room temperature for the required ages.

Figure 3.7: Mixer, and Cast Samples for (a) Mortars (b) SCCs

3.6.1 SCCs Specimens

The mixtures in this study were cast as specimens to examine SCC property using the molds as followed:

1. (50×50×50) mm cubes to obtain specimens for the compressive strength of mortar to determine the pozzolanic activity test of materials.

2. (100×100×100) mm cubes to obtain specimens for bulk density, compressive strength, ultrasonic pulse velocity (UPV), water absorption, porosity, and sorptivity.
3. (100×200) mm cylinders to obtain specimens for the splitting tensile strength test.

3.6.2 Curing of Specimens:

All SCC specimens must be cured before they are tested, so the specimens should be placed after demoulding in the curing tank according to **(BS1881: Part 111, 1983)**, where the specimens are fully immersed in a water tank and are maintained at a temperature 25±2°C until the specified testing ages, as shown in Figure 3.8.

Figure 3.8: Curing of the SCC specimens

3.7. Fresh Tests on Self-Compacting Concrete

Fresh tests for self-compacting are important tests required to evaluate all the following three properties: filling ability, passing ability, and segregation resistance. However, there is no single test to measure the three characteristics together. In this experimental study, the fresh properties of SCC were measured by slump flow (D (mm) and T_{500} (s)), V-funnel, L-box, and segregation resistance tests. The experimental procedures for the mentioned tests are described below.

3.7.1 Slump Flow and T_{500mm} Tests

The slump-flow and T_{500} time tests to assess the flowability and flow rate of self-compacting concrete in the absence of obstructions. The result is an indication of the self-compacting concrete's filling ability. The T_{500} time is also a measure of the speed of flow and hence the viscosity of the self-compacting concrete. The test equipment and technique as defined in **(EFNARC, 2005)**. Figure (3.9) shows the equipment and the slump flow of the fresh mix. The largest diameter of the flow spread of the SCC and the diameter of the flow spread at right angles to it are measured, and the mean is the slump-flow, expressed to the nearest (10) mm as shown in Equation (3-2).

As for, the slump flow time T_{500mm}, it is the period between the moment the cone leaves the base plate and the SCC first touches the circle of diameter 500 mm, and it is expressed in seconds to the nearest 0.1 seconds.

$$SF = (D1 + D2)/2 \quad (3\text{-}2)$$

Where :

SF = Slump Flow, mm

D1 = diameters max, mm

D2= diameters perpendicular, mm

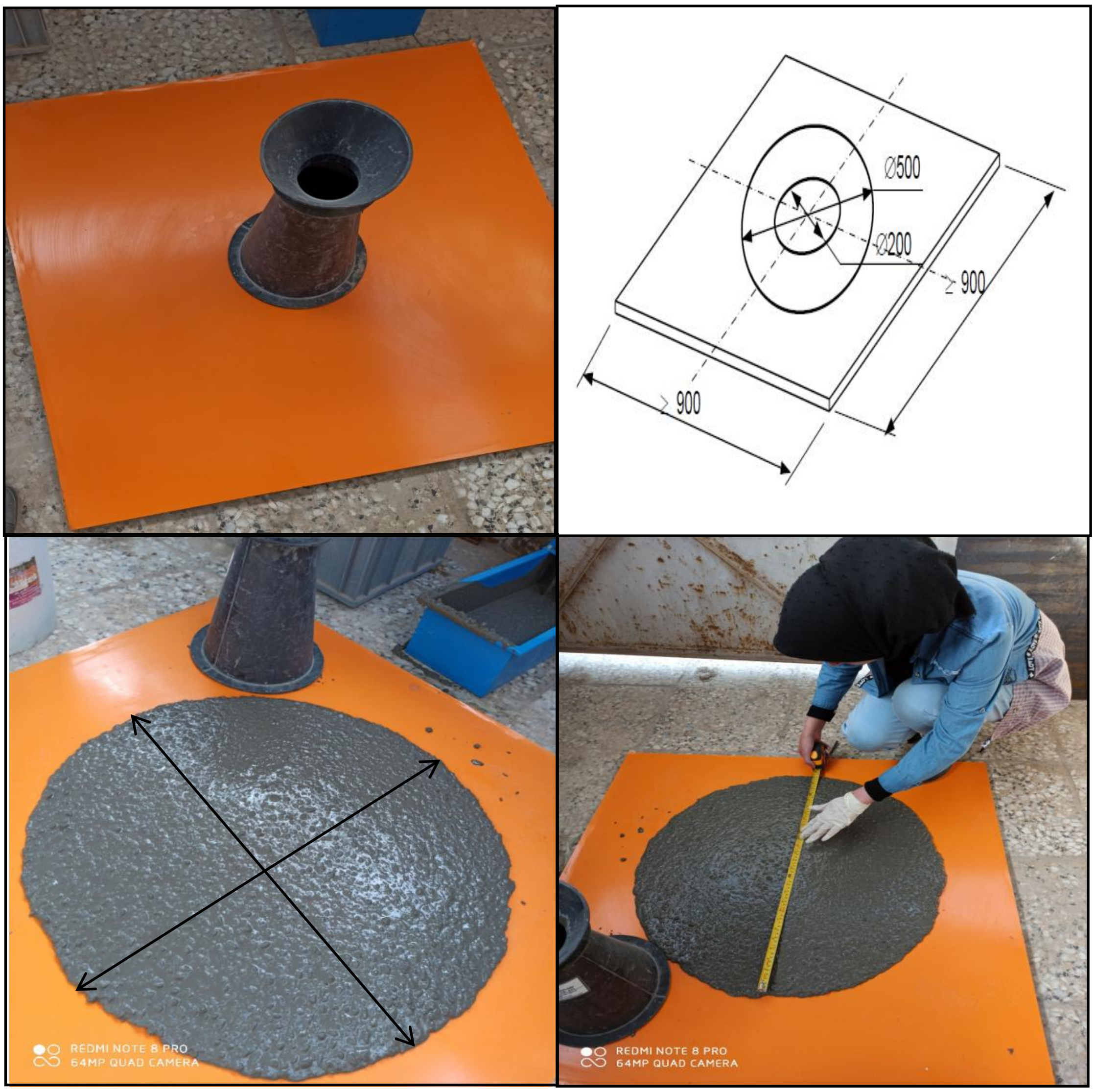

Figure 3.9: Test Equipment and Slump Flow of SCCs

3.7.2 V-Funnel Test

The test used to assess the filling ability and viscosity of SCC is the V-funnel test. Whereas the test procedure and the apparatus used are described in **(EFNARC, 2005; De Schutter, 2005)**. The apparatus of the V-funnel test used in this study is shown in Figure 3.10. The test was conducted by placing the V funnel vertically on a flat, stable surface, with the top opening positioned horizontally. Using a wet sponge or towel, we moisturize the inside of the funnel and remove excess water by opening it. Noting that the inside of the funnel remains "wet”. Then we had closed the gate and place the container under the funnel to retain the concrete to be passed. Then the funnel was filled with SCC without applying any pressure or rodding. Any excess concrete was removed from the top of the funnel using a straight edge. After a waiting period of (10 ± 2) seconds, from filling the funnel, the gate was opened and the time t_v, to the nearest 0,1 s, was measured from the opening of the gate to when it was possible to see vertically through the funnel into the container below for the first time. t_v is the V-funnel flow time.

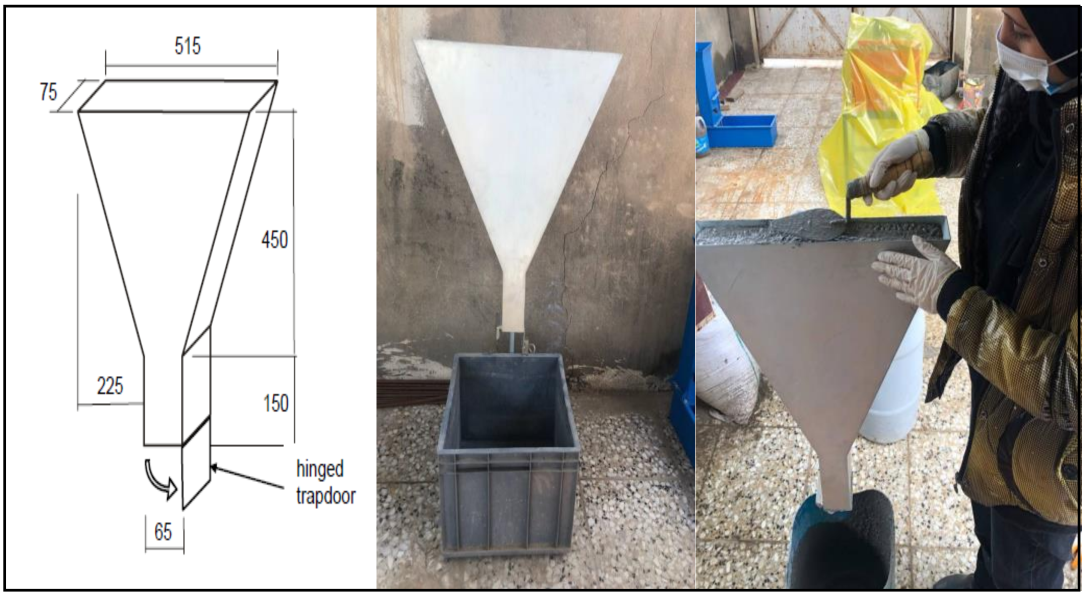

Figure 3.10: V-Funnel Test

3.7.3 L-Box Test

The L-Box test is used to determine the SCC's passing ability to flow without segregation or blockage in the presence of reinforcing obstructions. Two variants exist, the two-bar test and the three-bar test. According to **(EFNARC,2005; De Schutter, 2005)**, the three-bar test was used to predict more congested reinforcement. The L-box test in this study is shown in Figure 3.11. Before the start of the test, the test equipment was cleaned and just moist. First, the L-box was placed centrally in a stable and level position. Then, the vertical part of the L box was filled with fresh SCC and allows the concrete to sit in the vertical section for 1 minute. During this time, concrete will be displayed whether or not it is stable (segregation). Second, we raised the sliding gate and allow the concrete to flow outward into the horizontal section. When concrete stoped moving, we measured the concrete depth directly behind the gate as H1 mm and the concrete depth at the end of the horizontal section as H2 mm using a rule, graduated from (0–300) mm. The passing ability (PA) was calculated by using the Equation (3-3) expressed in dimensionless to the nearest (0.01).

$$PA = H2/H1 \quad (3\text{-}3)$$

Where:

PA= passing ability

H_1= Concrete depth directly behind the gate, mm.

H_2= Concrete depth at the end of the horizontal section, mm.

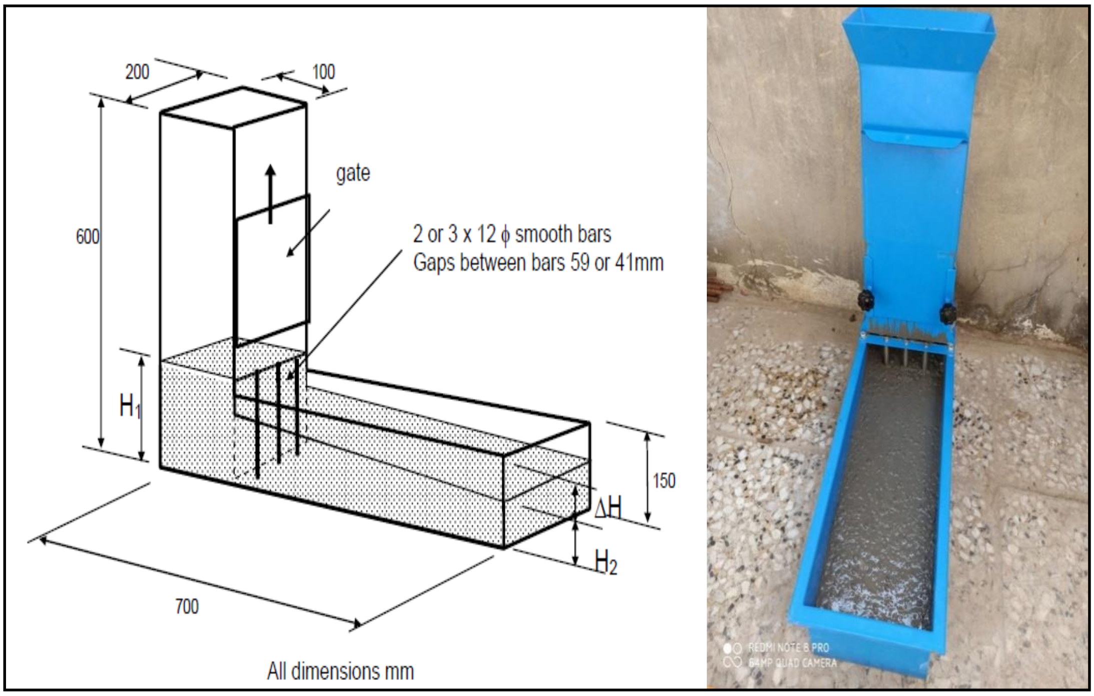

Figure 3.11: L – Box Test

3.7.4 Sieve Segregation Resistance Test

Segregation resistance is the ability of a fresh mix to maintain its original, adequately uniform distribution of constituent materials. This test is used to assess the resistance of SCC to segregation. The test equipment and protocol as defined in **(EFNARC, 2005)**. The test is shown in Figure 3.12. About (10± 0,5) liters of concrete were placed into a container and allowed to stand in a level position without disturbance for (15 ± 0,5) min. The sieve receiver was placed on the weighing machine and its mass (Wp g) was recorded. A sample of (4.8±0.2) kg of concrete was poured from a height of (500 ± 50) mm onto a 5 mm sieve with a diameter of 300 mm, and the actual mass of concrete (WC g) was recorded on the sieve. The concrete was placed in the sieve for (120±5) seconds to allow any laitance or mortar to pass through it while standing on the sieve receiver. The mass of the receiver was recorded with concrete that had passed into it (Wps g). The segregated portion (SR) was calculated from the following Equation (3-4) to the nearest 1%.

$$\mathrm{SR}(\%) = \left(\frac{Wps - Wp}{Wc}\right) \times 100 \qquad (3\text{-}4)$$

Where:

SR: Segregation resistance.

Wps: mass of the receiver and concrete, g.

Wp: Mass of the receiver, g.

Wc: actual mass of concrete, g.

Figure 3.12: Sieve Segregation Resistance Test

3.8 Hardened Tests on Self-Compacting Concrete

The hardened specimens of various SCCs in this study were tested for bulk density, compressive strength, splitting tensile strength, and ultrasonic pulse velocity (UPV). These tests are described below in detail.

3.8.1 Bulk Density

The mechanical properties of concrete are highly influenced by its density. A denser concrete generally provides higher strength, durability, and resistance to permeability due to the lower amount of voids and porosity.The self-weight of any structure is completely dependent on the unit weight (bulk density) of the ingredient materials. Thus, it is a considerable parameter for mortar or concrete. Bulk density is the mass of a unit volume of hardened concrete expressed in kilograms per cubic meter. The bulk density of hardened SCC at the ages of 7 and 28 days was determined from Equation (3-5) and according to (**BS 1881: Part 114, 1983).** The average results of three cube specimens with dimensions of (100×100×100) mm as shown in Figure 3.13, were reported for each mixture and age.

Density = $\frac{m}{v}$ (3-5)

Where

m: The mass of the specimen in the air (in kg).

V: The volume of the specimen calculated from its dimensions(m^3)

Figure 3.13: Weights of Cubes for Bulk Density Test

3.8.2 Compressive Strength

Compressive strength has been an established measure that represents one of the most important mechanical properties of concrete, which could provide an overall image of the quality of concrete. The compressive strength test was carried out according to **(BS1881: Part 116, 1983)**. For each mixture and age, the average results of compressive strength of three cube specimens with dimensions (100×100×100) mm were calculated at 3, 7, 28,56, and 90-days age. The test involves recording the maximum applied load at failure, by using a compression machine with a load capacity of 1900 kN, by increasing the load continuously at a nominal rate of 0.2 N/(mm^{2}s) to 0.4 N/(mm^{2}s) until no greater load can be sustained (see Figure 3.14). The compressive strength was calculated by dividing the maximum load by the cross-sectional area of the specimen through Equation (3-6).

$$Fc = \frac{P}{A} \tag{3-6}$$

Where:

Fc = compressive strength (MPa).

P = the maximum applied load (N).

A = cross-sectional area of the specimen (mm^2).

Figure 3.14: Compressive Strength Test

3.8.3 Splitting Tensile Strength

Tensile strength is an important property of concrete because concrete structures are highly vulnerable to tensile cracking due to various kinds of effects and the applied loading itself. The tensile strength of the concrete was measured indirectly using the tensile splitting strength test, as direct tensile tests are difficult to conduct on concrete specimens. The splitting tensile strength was applied following the procedure outlined in **(ASTM C496, 2004)**. For each mixture and age, the average results of splitting tensile strength of three-cylinder specimens with dimensions of (100 mm × 200) mm were calculated at 7, 28, and 90 days of curing. Two thin bearing strips of plywood (3.2 mm thick) were placed between the specimen and both the testing machine's upper and lower bearing blocks. The test involves recording the maximum applied load at failure, by using the testing machine with a load capacity of 1900 kN, at a constant rate within the range (0.7 to 1.4 MPa/min) until the failure occurs (see Figure 3.15). The splitting tensile strength (T) of the specimen is calculated by the following Equation (3-7):

$$T = \frac{2P}{\pi d l} \qquad (3\text{-}7)$$

Where:

T: Splitting tensile strength, (MPa).

p: Maximum applied load indicated by the testing machine, (N).

d: Cylinder diameter, (mm).

l: Cylinder length, (mm).

Figure 3.15: Splitting Tensile Strength Test

3.8.4 Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity test (UPV) method is a non-destructive method, as the technique uses compressional waves, resulting in no damage to the concrete element being tested. The pulses are introduced into the cube specimens by a piezoelectric transducer, and a similar transducer acts as a receiver to monitor the surface vibration caused by the arrival of the pulse, as shown in Figure (3.16). The nominal frequency of the transducers used for testing concrete cubes was 50 kHz, and the transmission time was measured in microseconds, with an accuracy of 0.1 μs. An ultrasonic pulse velocity test was carried out according to **(ASTM C597, 2002)**, using (100×100×100) mm cubes.

A portable ultrasonic non-destructive digital indicating tester (PUNDIT) was used for determining the UPV test. Before using the PUNDIT, the transducers were zeroed by placing them face-to-face with water-soluble coupling gel. The end surfaces of the samples were polished and greased to provide good coupling between the transducer faces. During testing, the transducers were coupled firmly to the specimen ends, and the transit time was recorded. The ultrasonic pulse velocity was determined from measured transit time (T) and path length (L) and averaged based on the results of three specimens for each mixture and age. The pulse velocity was calculated using the following Formula (3–8):

$$V = \frac{L}{T} \qquad (3\text{-}8)$$

Where:

V= pulse velocity ,(m/s) .

L= distance between transducers,(m) .

T= effective transmit time, (s).

Figure 3.16: Ultrasonic Pulse Velocity Test

3.9 Tests for Durability Performance of Self-Compacting Concrete

The durability performance of any material is one of the key parameters for applying the material in practice. In this study, three durability tests, such as water absorption, porosity, and sorptivity, were quantified. Existing test methods for the mentioned tests of the SCC are further described below.

3.9.1 Water Absorption

The water absorption test of the concrete specimens was conducted by **(ASTM C642, 2013)** to test the voids in hardened concrete and determine the increase in resistance towards water penetration in concrete. Three (100×100×100) mm cube specimens at each age and a mixture of SCC were tested at the ages of 28 and 90 days (after initial curing for 28 days) **(Siddique& Kadri,2011)**, and the average values were recorded. Cube specimens were dried in an oven for no less than 24 hours at 110 ± 5 ^{O}C to a constant weight (A) until two values agreed closely or the difference between any two successive values was less than 0.5% of the lowest value obtained, as shown in Figure 3.17.

Then, the specimens were immersed in tap water for not less than 48 hours and until two successive measurements of the mass of the surface-dried samples at intervals of 24 hours indicated constant mass or until the increase in mass was less than 0.5% of the heavier mass, which defines the saturation stage. After the desired immersion period had passed, the specimens were taken out and surfaces were wiped with a wet cloth quickly, then the saturated surface dried (SSD) specimen was weighed (B) immediately. As a result of this test, the total volume of penetrable pores was determined. The percentage of water absorption (WA) was calculated using the following Equation (3-9) and averaged based on the results of three specimens.

$$\text{Water Absorption } (\%) = \frac{(B - A)}{A} \times 100 \qquad (3\text{-}9)$$

Where:

A = mass of oven-dried sample in air, g.

B = mass of surface -dry sample in the air after immersion, g.

Figure 3.17: Oven-Dried and Weights of cubes for Water Absorption Test

3.9.2 Porosity

The total porosity of the different SCC mixes was evaluated in this study. Three cubes (100 × 100 × 100) mm were prepared for porosity testing for each mixture and age. This method was used to measure the porosity of concrete according to **(ASTM C642, 2013)**. Samples were tested at the ages of 28 and 90 days (after initial curing for 28 days). Cube specimens were dried in an oven for no less than 24 hours at 110 ± 5 ^{O}C to a constant weight (A) until two values agreed closely or the difference between any two successive values was less than 0.5% of the lowest value obtained. Then, the specimens were immersed in tap water for not less than 48 hours and until two successive measurements of the mass of the surface-dried samples at intervals of 24 hours indicated constant mass or until the increase in mass was less than 0.5% of the heavier mass. When the immersion period was completed, the samples were taken out, and the surfaces were wiped with a damp cloth. The saturated surface dry (SSD) mass of specimens after immersion was determined (C). Finally, the specimens were immersed and weighted in water to determine their apparent mass (D), as shown in Figure 3.18. The porosity (P) of the concrete was calculated according to Equation (3–10) and averaged based on the results of three specimens.

$$\text{Porosity}(\%) = \frac{C - A}{C - D} \times 100 \qquad (3\text{-}10)$$

Where:

A = mass of oven-dried sample in air,g.

C =mass of surface-dry sample in the air after immersion, g.

D= Apparent mass of sample in water after immersion, g.

Figure 3.18: Oven-Dried and Buoyancy Balance to Check the Porosity

3.9.3 Sorptivity

The sorptivity was done to assess the resistance of water movement through the concrete by capillary suction. The lower the value of sorptivity, the higher the resistance of concrete to water absorption. The sorptivity (capillary water absorption) measurements were evaluated according to **(ASTM C1585, 2004).** For each mixture and age, a set of three (100×100×100) mm cubes were selected for testing to evaluate sorptivity coefficients at ages 28 and 90 days (after initial curing for 28 days). After the specimens were removed from the water, they were placed in an oven at 50±2 °C for 3 days until they reached constant weight, and then allowed to cool to the ambient temperature in a sealed container before starting the absorption procedure. Only one surface of the concrete specimen was allowed to be in contact with water, with the depth of water (1 to 3) mm above the base of the specimen. The opposite surface was exposed to air, and the other four surfaces were sealed with epoxy resin, ensuring the unidirectional flow of water through the concrete specimen. Before the specimens were located in the water, their initial weights were measured to the nearest 0.01g. Then, the specimens were rested on a special tray used for this test to allow free access of water to the surface, and they were covered with a plastic sheet and kept in the conditioning room to avoid moisture loss, as seen in Figure 3.19. Immediately after the immersion of the cube surface into the water, the water absorption was measured (specimens were removed from the tray and the weights were recorded) at intervals of 1, 5, 10, 30, 60, 120, 180, 240, 300, and 360 min, for initial absorption properties. After that, the measurements are taken once a day for up to 3 days, followed by 3 measurements at least 24 h apart during days 4 to 7; the final measurements are taken at least 24 h after the measurement on day 7 for secondary absorption properties. This longer duration allows water to permeate into the core of the specimen through capillary action. During the test, water was re-filled into the tray to maintain a water depth of 3 mm. The calculated absorption value at each time is plotted against the square root of time. The sorptivity was determined by the slope of the best fit line to these data. The sorptivity was computed by using the following Equation 3-11 and averaged based on the results of three specimens.

$$S = \frac{I}{\sqrt{t}} \qquad (3\text{-}11)$$

where:

S = Sorptivity in ($mm/min^{0.5}$), I=m_t /ad .

I= absorption(mm)

m_t = the change in specimen mass in grams, at the time *t* .

a= the exposed area of the specimen, in mm^2.

d= density of water (used 0.001 g/mm^3)

t = time elapsed in (min)

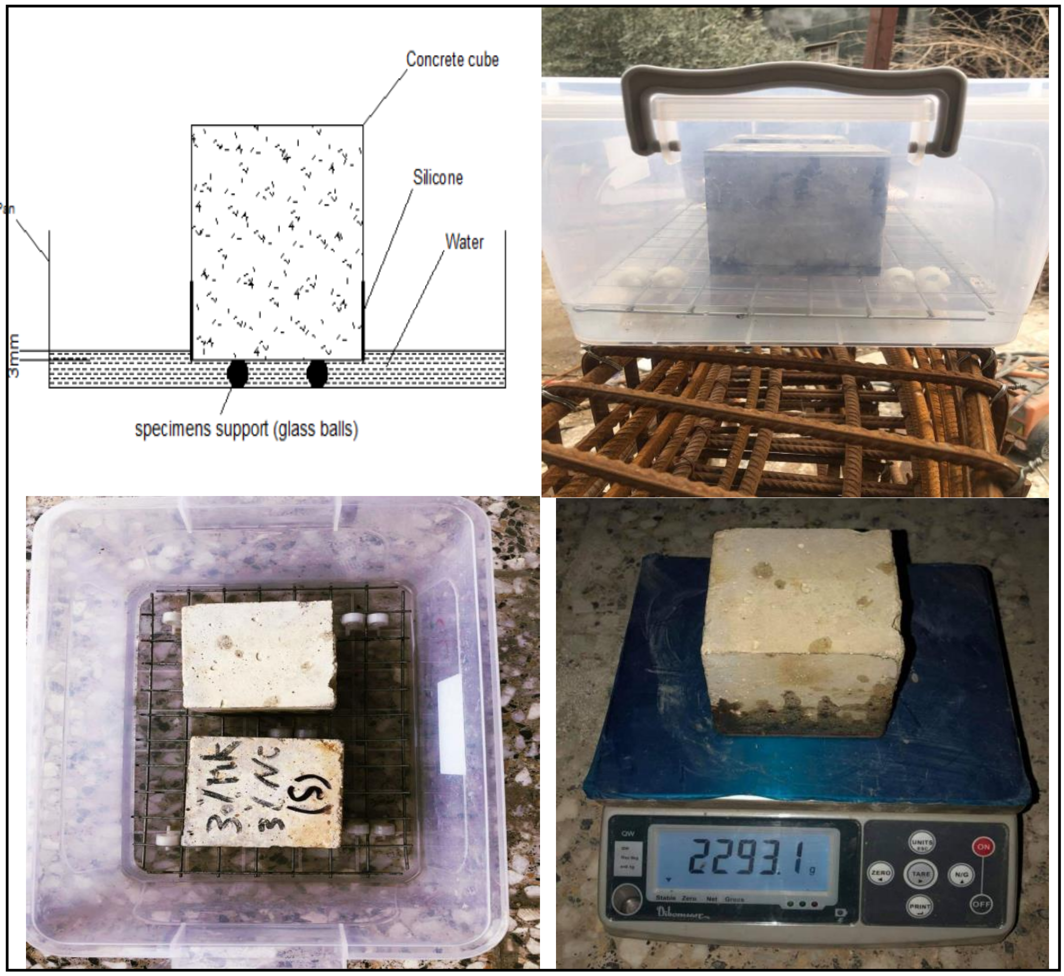

Figure 3.19: Sorptivity Test

3.10 Statistical Evaluation of Experimental Test Results of Compressive Strength of Self-Compacting Concrete

There are a few studies on modeling and prediction of the compressive strength, and the variations in the compressive strength with the ultrasonic pulse velocity test (UPV) of the SCC utilizing low carbon binders.So SCC with (Metakaolin (MK), nano calcium carbonate (NC), and nano alumina (NA)) as partial replacements of cement in binary, ternary, and quaternary blends, was undertaken in this study for the first time.

3.10.1 Multiple Regression Analysis (MRA)

The general MRA equation for this study is given below, with the dependent variable (compressive strength) being a linear function of more than one independent variable. To find the best fit to the data in this study, the following multiple linear regression Equation (3-12) is used:

$$Y = a + b_1X_1 + b_2X_2 + \ldots\ldots\ldots\ldots + b_iX_i \quad (3\text{-}12)$$

Where:

Y: dependent variable
a: constant
$b_1,\ldots, b_i$: coefficients
$X_1,..,X_n$: Independent variables (t,PLC, CKC, NC , NA and SP), but (FA, CA, and W/B) are constant for all SCC mixtures.

CHAPTER FIVE

CONCLUSIONS & RECOMMENDATION

Chapter Five

Conclusions and Recommendations

5.1 Introduction

This study aimed to produce self-compacting concrete using environmentally friendly cementitious materials by blending PLC with different proportions of CKC and hybrid nanoparticles. Thus, this chapter provides the overall conclusions of these research findings and proposes recommendations for further study.

5.2 Conclusion

Based on the results of the experimental work and statistical modeling, the following conclusions have been drawn:

1. The nano alumina (NA) showed the highest pozzolanic activity among other materials.
2. Self-compacting concrete (SCC) could be successfully produced with binary, ternary, and quaternary binder combinations.
3. In the ternary and quaternary blends of mixtures the slump flow decreased further while T_{500} and V funnel increased more compared to the binary and reference mixtures.
4. The L-Box height ratio value diminished as the partial replacement of cement was increased by the CKC and by adding nanoparticles (in the binary blends). This effect increased more with the ternary and quaternary mixtures, and there was no tendency for blockage.
5. Ternary and quaternary blend mixtures had higher segregation resistance than their corresponding control and binary binder mixes of similar

proportions. where the segregation percentage decreased further in these blend mixes. All SCC mixes were stable without the risk of segregation or bleeding.

6. The addition of CKC, NC, and NA decreased the bulk density. The bulk density decreased further in ternary and quaternary mixes. Thus, CKC and nanoparticles could be used in concrete as lighter materials than cement.

7. Compressive strength generally decreased with the increase in CKC content (30,45, and 60%) in binary blended and enhanced with 3% NC and 2% NA (early and long term) in comparison with the control-PLC mixture at all ages.

8. It could be concluded that the mix (30%CKC3%NC2%NA) exhibited the highest compressive strength at all ages.

9. Splitting tensile strength (STS) of SCC mixes followed a similar pattern to that of compressive strength, but the increase was at a lower rate compared to that obtained in compressive strength.

10. The STS of quaternary blends were observed to be better than the STS of other blends, and the mix (30%CKC3%NC2%NA) revealed the maximum splitting tensile strength.

11. The results of UPV demonstrated a similar trend to the compressive strength results, but at a decreasing rate for all the SCC mixes.

12. The UPV values for quaternary mixes were higher than those for the control mixture, binary and ternary blend mixes at the same replacement levels of CKC. The mix (30%CKC3%NC2%NA) exhibited the highest UPV.

13. The SCCs were found to have good to excellent quality.

14. The water absorption (WA), porosity and sorptivity values declined with an increase in the curing period for all blended SCC mixes.

15. The high replacement ratios of CKC (30, 45, and 60%) led to an increase in water absorption, porosity and sorptivity.

16. The replacement of cement by 3%NC and 2% NA could effectively reduce water absorption, porosity and sorptivity.

17. The quaternary blended system exhibited the lowest water absorption, porosity and sorptivity at all ages. The mix (30%CKC3%NC2%NA) was the best due to the lower absorption rates, porosity and sorptivity at all ages.

18. The water absorption (WA) and porosity of SCCs was found to be less than 5% and 15% at all curing ages, respectively, so all SCCs could be categorized as "high quality".

19. All mixtures had a low sorptivity value that was below 0.1 mm/min^{5}.

20. The statistical model developed provides an excellent prediction for the compressive strength, and there was no statistically significant difference between the experimental and predicted strength values.

21. The equation that determined the relationship between the experimental and predicted values of the compressive strength for SCCs cured for various periods revealed an excellent level of agreement between the predicted and experimental readings.

22. The correlation between the compressive strength (Fc) and UPV at various ages was obtained and indicated an excellent exponential relationship between the compressive strength and UPV.

Finally, based on the main findings from this study, the utilization of calcined kaolin clay (CKC) and nanoparticles (NC and NA) as cement replacement could provide a low-carbon binder for producing and developing SCCs for different construction and structures, thereby reducing the cement demand, which would contribute to reducing the emission of greenhouse gases from the globe.

5.3 Recommendations for Future Studies

Several related aspects were not investigated in the present study. Thus, the following research opportunities can be investigated in the future:

- The development of SCCs was studied using calcined kaolin clay material. Thus, a similar investigation can be done using other materials, such as fly ash, zeolite, and so on.
- Different nanoparticles like nano-silica, nano- iron oxide and nano-clay may be used instead of nano-$CaCO_3$ and nano-Al_2O_3 in replacing cement for producing SCCs by using calcined kaolin clay.
- Several other properties of SCCs can be investigated in further study, including the elastic modulus, flexural tensile strength, autoclave expansion, corrosion resistance, carbonation, drying shrinkage, sulfate attack, acid resistance, and so on.
- Study the effects of elevated curing conditions and steam curing conditions on the hydration of cement paste and the performance of SCCs containing CKC, NC, and NA in binary, ternary, and quaternary blended binders.
- Study of the microstructure properties of SCCs at different ages using SEM, XRD, and BET techniques. However, there is a need to investigate these at all ages.

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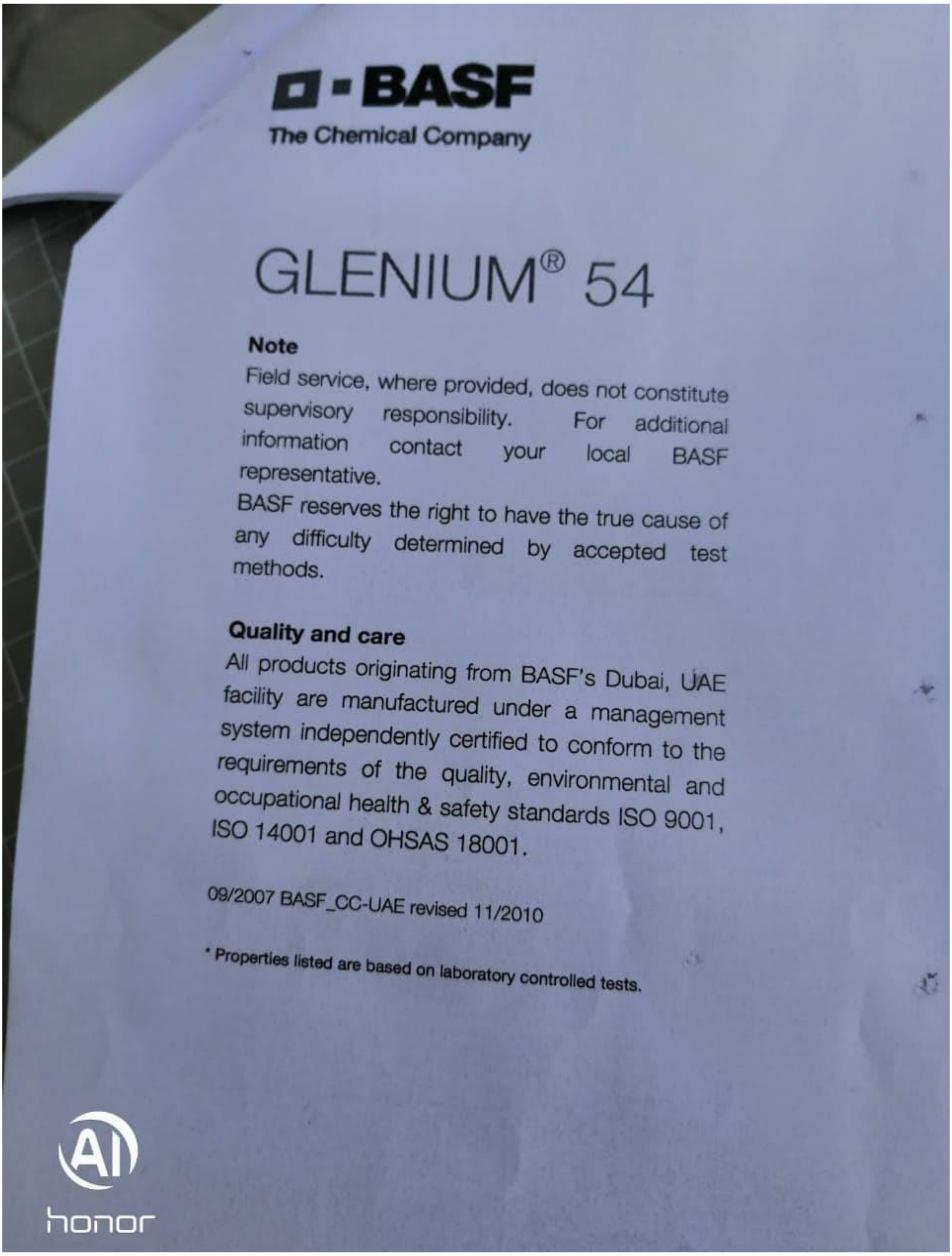
Appendix

Appendix

Material Datasheets

1- Datasheet of Superplasticiser Provided by the Manufacturer.



BASF
The Chemical Company

GLENIUM® 54

Note

Field service, where provided, does not constitute supervisory responsibility. For additional information contact your local BASF representative.

BASF reserves the right to have the true cause of any difficulty determined by accepted test methods.

Quality and care

All products originating from BASF's Dubai, UAE facility are manufactured under a management system independently certified to conform to the requirements of the quality, environmental and occupational health & safety standards ISO 9001, ISO 14001 and OHSAS 18001.

09/2007 BASF_CC-UAE revised 11/2010

* Properties listed are based on laboratory controlled tests.

BASF
The Chemical Company

GLENIUM® 54

Packaging
GLENIUM® 54 is available in 208 litre drums and in bulk tanks upon request.

*Typical properties

Form	Whitish to straw coloured liquid
Relative density	1.07
pH	5-8

Effect on hardened concrete properties
- increased early and ultimate compressive strengths
- increased flexural strength
- higher E modulus
- improved adhesion to reinforcing and stressing steel
- better resistance to carbonation
- lower permeability
- better resistance to aggressive atmospheric conditions
- reduced shrinkage and creep
- increased durability

Compatibility of GLENIUM® 54
GLENIUM® 54 must not be used in conjunction with any other admixture unless prior approval is received form BASF Technical Services.

GLENIUM® 54 is suitable for mixes containing:
- microsilica
- pulverised fuel ash
- ground granulated blast furnace slag cement

Dosage
The normal dosage for GLENIUM® 54 is between 0.5 and 2.5 litres per 100 kg of cement (cementitious material). Dosages outside this range are permissible subject to trial mixes.

Directions for use
GLENIUM® 54 is a ready to use admixture that is added to the concrete at the time of batching.

The maximum effect is achieved when the GLENIUM® 54 is added after the addition of 50 to 70 % of the water. GLENIUM® 54 must not be added to the dry materials.

Thorough mixing is essential and a minimum mixing cycle, after the addition of the GLENIUM® 54, of 60 seconds for forced action mixers is recommended.

Storage
GLENIUM® 54 should be stored in original containers and at above 5 Centigrade. If frozen gradually thaw and agitate until completely reconstituted.

Failure to comply with the recommended storage conditions may result in premature deterioration of the product or packaging. For specific storage advice consult BASF's Technical Services Department.

Safety precautions
GLENIUM® 54 contains no hazardous substances requiring labelling. For further information refer to the Material Safety Data Sheet.

AI honor

2- Datasheet of Nano-$CaCO_3$ Provided by the Manufacturer.

ZOUPING ZHIJIN NEW MATERIAL TECHNOLOGY CO., LTD.

Nano CaCO3 Powder Calcium Carbonate(less than 100nm)

Appearance	White powder
Density	2.5
Size	Less than 100nm
Specific area	>=20
Whiteness	>=93
PH	8.5-9.7
Moisture content	<=0.9
Loss on ignition	44±1
Residue on sieve	<=0.02
$CaCO_3$ content	>=96.0
MgO content	<=0.8
Alumina+Iron oxide	<=0.3
Insoluble matter with acid	<=0.3
Activation rate	>=95
DOP absorbed dose	35-55

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AI QUAD CAMERA

3- Datasheet of Nano-Al_2O_3 Provided by the Manufacturer

HONGWUNEWMATERIAL

Spherical A-Phase Nano Al2O3 Powders

X 25 gm

Size: 80nm

Purity :99.99%

Shape: Spherical

Color: white Powder

Application for α-phase nano al2o3 powders:

1 α-phase nano al2o3 slurry crystal phase stability, high hardness, good dimensional stability, can be widely used in a variety of plastics, rubber, ceramics, refractories and other products reinforcement toughening.

2. Specially to improve dense ceramics, finish, and thermal fatigue resistance, fracture toughness, creep resistance and wear resistance of polymer products is particularly significant.

3. Since the α-phase high performance nano-alumina slurry is far-infrared emitting material, as a far-infrared emission and thermal insulation materials are used in chemical fiber products and high-pressure sodium lamps.

4. In addition, α-phase al2o3 powders high resistivity, with good insulation properties, can be applied to the main parts of YGA laser crystal and the integrated circuit substrate.

Hongwu International Group Ltd-China

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AI QUAD CAMERA

4- Datasheet of epoxy resin by the Company

Quickmast 105

Resin based injection crack repair system

Description

Quickmast 105 is a two component, low viscosity epoxy resin system for crack injection applications in concrete, masonry, and brickwork.

Applications

- For injection of cracks in all types of structural concrete elements, masonry, and brickwork.
- Suitable for injecting cracks widths from 0.2 - 10 mm.

Advantages

- Excellent bond strength to concrete, brickwork, and masonry.
- Low viscosity epoxy resin, formulated to allow cracks penetration down to 0.2 mm.
- Can be used in damp or dry conditions.
- Low creep.
- Non-shrink.
- Exhibit good chemical resistance.

Standards

Quickmast 105 is suitable for use in contact with potable water when tested in accordance to BS 6920.

Method of Use

Depending on crack width, depth, location, and thickness of the structural element that needs to be injected, many injection techniques requiring different injection tools and equipment may be used. The method of injection given in this Technical Data Sheet is based on most common situation. For more details, DCP Technical Department should be consulted for assessments and advise.

Substrate Preparation

The surface of the cracks should be cleaned from dust, oil, plaster, grease, curing compound and corrosion deposits. All cracks to be repaired should be cleaned with compressed air. This should be carried out after drilling of injection holes.

Injection Holes Drilling & Fixing

Holes are drilled to install mechanical packers. Always try to allocate steel re-bars and conduit before drilling.

Technical Properties:

Compressive strength: BS 6319, Part 2:1983	≥ 70 MPa @ 7 days @ 25°C
Flexural strength: ASTM C580	≥ 50 MPa @ 7 days
Tensile strength: BS 6319, Part 7:1985	≥ 25 MPa
Pot life:	50 - 70 min @ 25°C
Density:	1.1 ± 0.05
Viscosity:	3 - 5 poise @ 25°C 1 - 2 poise @ 35°C
Minimum application temperature:	5°C
VOC:	< 20 g/ltr

Using high quality rotary hummer drill, and depending on packer diameter used, a suitable drill pit used, usually 13 mm or 16 mm diameter mechanical packers are used.

The angle which drilling should be is 45°C or less to the surface and toward the crack. Depth of the drill holes intersecting the crack should be somewhat close to middle of structure, if possible.

Holes greater than 45 cm are not required even if the concrete being repaired is more than 90 cm thick. Holes should always be staggered from one side of the cracks to the other.

Spacing: distance between drilled holes usually varies from approximately 15 – 50 cm according to width of the cracks (30 cm is commonly used). Yet the wider the cracks, the further apart are drill holes.

Note:
If concrete thickness 15 cm or less, do not attempt angle drilling. Also to minimize concrete spalling, packers will be set into the face of the crack.

Fixing of Injection Mechanical Packers (Nipples)

Packers shall be placed in drill holes so that top of the rubber sleeve is below concrete surface. Tight the packer with wrench as much as you can.

Quickmast 105

Mix a small quantity of epoxy adhesive using Quickmast GPS (Fast set).

The mix adhesive should be applied on the cracks between the injection packers to seal the cracks at a thickness of 2 – 3 mm and at least 20 – 30 mm extending from both sides of the cracks.

Mixed Quickmast GPS has pot life = 10 – 15 minutes and 30 minutes cure time at 25°C.

Injection process can commence 2 hours after applying Quickmast GPS.

Injection

Mix Quickmast 105, resin and hardener using mechanical slow speed drill when using single component injection pump. When using 2 components pump, the pump should be charged at 4:1 ratio (by volume), which is equivalent to the pre-packed proportion of the base and hardener components.

Load the mixed resin and charge the pump, hose and gun Begin injection at point of highest resistance to ensure good penetration and minimal loss of materials.

The injection is usually starts at the lowest point on vertical crack and at the narrowest area on horizontal surface.

Injection process will continue until the mixed resins (Quickmast 105) travelled to next packer. Disconnect and move to next packer.

After completing two packers, return to first packer and inject again. Continue with this fashion until crack is completely filled.

Cleaning

- Resins must be cleaned up immediately before it sets.
- Packers must be removed within 24 - 48 hours and patched with appropriate epoxy mortar using Quickmast 341C.
- Electrical grinder can be used to remove excess cured resin that flowed out the cracks.

Packaging

Quickmast 105 is available in 1.5 and 5 litre packs.

Thicknesses and Size Limitations

Quickmast 105 is suitable for injecting cracks widths from 0.2 - 10 mm.

Storage

Quickmast 105 has a shelf life of 12 months from date of manufacture if stored at a temperature of 25°C.

If these conditions are exceeded, DCP Technical Department should be contacted for advise.

Cautions

Health and Safety

Consult the appropriate Material Safety Data Sheet prior to using Quickmast 105.

Fire

Quickmast 105, Quickmast GPS & Quickmast 341C are nonflammable.

More from Don Construction Products

A wide range of construction chemical products are manufactured by DCP which include:

- Concrete admixtures.
- Surface treatments
- Grouts and anchors.
- Concrete repair.
- Flooring systems.
- Protective coatings.
- Sealants.
- Waterproofing.
- Adhesives.
- Tile adhesives and grouts.
- Building products.
- Structural strengthening.

الخلاصة

مع التركيز الحالي على التنمية المستدامة في مجال الهندسة المدنية، من الضروري تطوير مواد البناء والتشييد بتكاليف معقولة وتأثيرات بيئية منخفضة من أجل تقليل انبعاثات ثاني أكسيد الكربون (CO_2) من صناعة الأسمنت. تدرس هذه الأطروحة تأثير استخدام الميتاكاوؤلين (MK)، ويسمى ايظا طين الكاولين المحروق(CKC) والمواد النانوية (كربونات الكالسيوم النانوية (NC)، والنانو ألومينا (NA))كبدائل جزئية للإسمنت (PLC) على استدامة خرسانة الرص الذاتي(SCC) وتحسين خصائصها الهيكلية. حيث تم تصميم خمسة عشر نوعًا مختلفًا من الخلطات الخرسانية لإنتاج خرسانة الرص الذاتي، مع استخدام نسبة الماء إلى الخليط (w/b = 0.38)، مع محتوى الاسمنت 485 كجم / م ^{3}.

في هذا البحث تم تطوير ثلاثة أنظمة من الخلطات الخرسانية، هما نظام الخلطات الثنائية والثلاثية والرباعية. تم قياس الخواص الطرية للخرسانة بواسطة اجراء فحوصات مختلفة مثل قطر انسياب الهطول (D) ملم، زمن الوصول لقطر 500 ملم (T_{500mm})، القمع على شكل حرف V، الصندوق على شكل حرفL، وكذلك اختبار مقاومة الانعزال. بينما تم اجراء اختبارات الكثافة الظاهرية، مقاومة الانضغاط، مقاومة الشد، وكذلك اختبار الموجات فوق الصوتية (UPV) لغرض تقييم أداء هذا النوع من الخرسانة في الخواص المتصلبة بأعمار مختلفة. إلى جانب ذلك، تم تقييم أداء الديمومة للخلطات الثنائية والثلاثية والرباعية من خلال اجراء الفحوصات مثل امتصاص الماء، والمسامية، والامتصاصية.

حيث ان النتائج اظهرت أنه عند استخدام الميتاكاوؤلين (MK) والنانو كربونات الكالسيوم(NC) والنانو الومينا (NA)في الخلطات الثنائية والثلاثية والرباعية قللت من الخصائص الطرية وكانت اختبارات انسياب الهطول وزمن الانسياب والانعزال جيدة بما يكفي لإنتاج خرسانة الرص الذاتي وكذلك كانت نسبة المار في فحص الصندوق على شكل L قد تراوحت من 0.791 الى 0.982 مع عدم وجود ميل للانسداد. لذا، فإن جميع الخلطات الخرسانية تفي بالخصائص في الحالة الطارية للخرسانة.

هنالك تحسن كبير ، في نتائج اختبار الخصائص المتصلبة وأداء الديمومة لخرسانة الرص الذاتي في نظام الخلط الرباعي .حيث الخلطات الهجينة المكونة من 3% من النانو كربونات الكالسيوم (NC) و 2% من النانو الومينا (NA)مع الميتاكاوؤلين (MK)في الخلطات الرباعية أعطت أكثر فائدة من استخدامها كمادة واحدة مع الميتاكاوؤلين (MK). من جهة أخرى في عمر 90 يومًا اظهرت الخلطة الخرسانية الحاوية على نسبة استبدال 30 % من الميتاكاوؤلين (MK) و3 %

نانو كربونات الكالسيوم (NC)و2% نانو الومينا (NA) أعلى مقاومة للانضغاط والشد، وفحص الموجات فوق الصوتية(UPV) حيث تصل إلى 61.8 ميجا باسكال، 4.61 ميجا باسكال، و 4905 م/ثانية على التوالي. كذلك اظهرت أفضل خصائص للديمومة نتيجة انخفاض امتصاص الماء والمسامية والامتصاصية للنماذج الخرسانية والتي بلغت (2.98%، 7.82%، 0.031 ملم / دقيقة $^{0.5}$) بعمر 90 يومًا، على التوالي. تم تطوير نموذج للتنبؤ بمقاومة الانضغاط بمتغيرات مختلفة، حيث بلغ معامل التحديد (R^2) 86.2% للنموذج العام مما يدل على وجود علاقة جيدة جدا ونموذج أفضل يناسب البيانات المختبرية. حققت هذه الدراسة أهدافها من خلال إنتاج خرسانة ذاتية الرص من دمج (MK) والجسيمات النانوية (NA،NC) التي يمكن أن تسهم في الحد من الطلب على الاسمنت، وانخفاض معدل انبعاث غاز ثاني اوكسيد الكربون، وجعل خرسانة الرص الذاتي ذات ديمومة عالية وصديقة للبيئة.

جمهورية العــراق
وزارة التعليم العالـــي والبحث العلمي
جامعة بـــابـــل/ كلـــية الهندسة
قسم الهندسة المدنية

تقييم أداء خرسانة الرص الذاتي المصنعة من الميتاكاوؤلين والمواد النانوية

رسالـــــة

مقدمة الى كلية الهندســة / جامعة بابـــــــــــــل

كجزء من متطلبات الحصول على درجة الماجستيـــر في الهندسة / الهندسة المدنية / المواد الإنشائية

من قبل

رويده كريم خومان جبار

بإشراف

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