DEVELOPMENT OF MODELS FOR PRODUCING HIGH PERFORMANCE RECYCLED AGGREGATE CONCRETE USING EXTREME VERTICES DESIGN

BY

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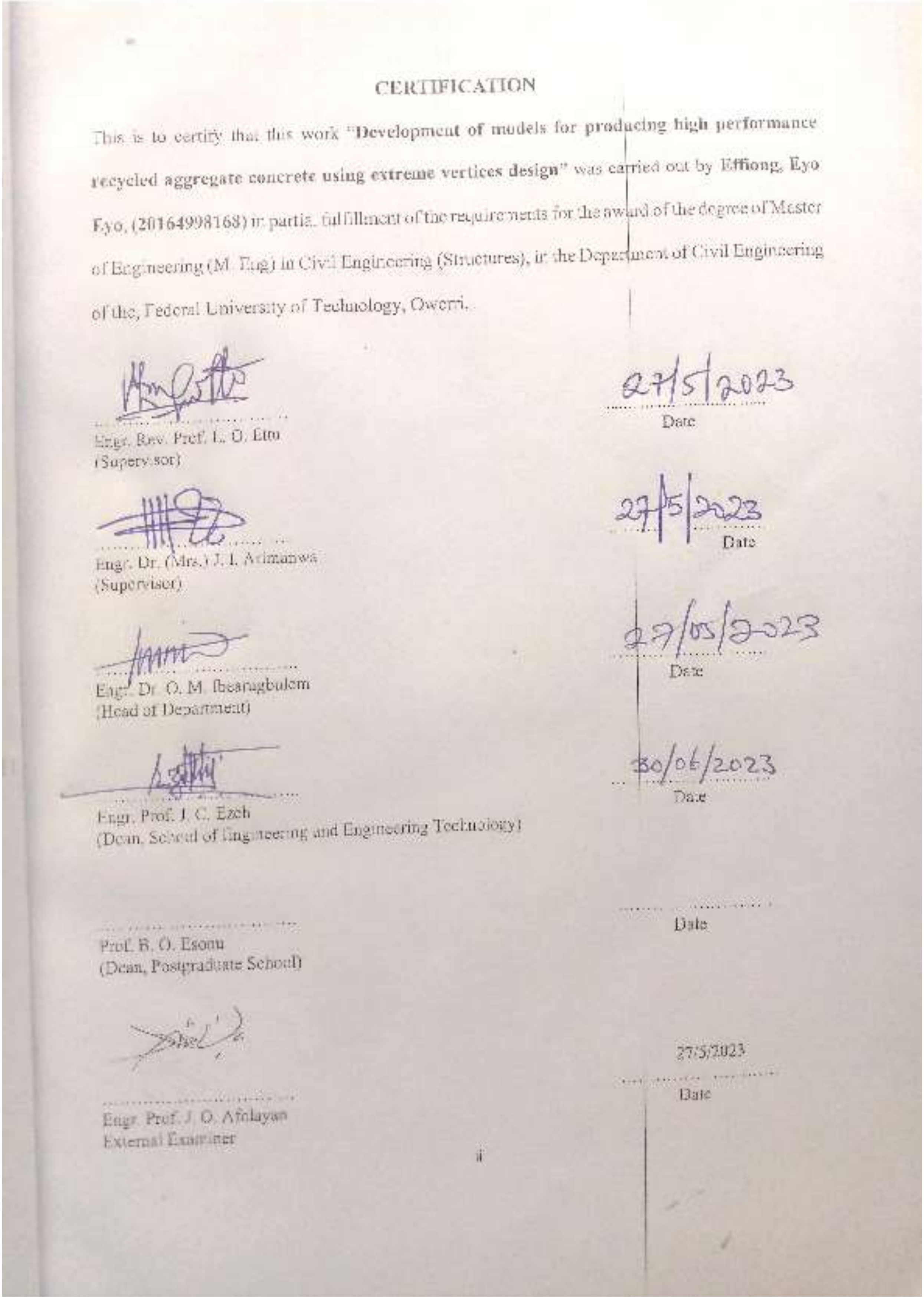

CERTIFICATION

This is to certify that this work "**Development of models for producing high performance recycled aggregate concrete using extreme vertices design**" was carried out by **Effiong, Eyo Eyo**, (20164998168) in partial fulfillment of the requirements for the award of the degree of Master of Engineering (M. Eng) in Civil Engineering (Structures), in the Department of Civil Engineering of the, Federal University of Technology, Owerri.

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DEDICATION

In memory of my late Father Mr. Eyo Effiong Eka.

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ABSTRACT

This research utilizes statistical methods to develop models (prediction equations) for various properties of high-performance recycled aggregate concrete. These models are further applied to obtain optimum combinations of the components of high-performance recycled aggregate concrete which include water, cement, silica fume, High range water reducing admixture (HRWRA), natural coarse aggregate, recycled coarse aggregate, and fine aggregate. The properties of the HPC studied are the slump, 1-day compressive strength, and 28-day compressive strength. Mixture experiment approach was employed in this research. A selected reference mixture gave the guide for the selection of upper and lower bounds of the mixture components in terms of volume fractions. A total of 46 experimental runs were planned for the mixture experiment design. Minitab statistical software was employed in the design and analysis of the experiment. The experiment design was based on the extreme vertices design for mixture experiment. The mixture experiment was modeled on the Scheffe's quadratic polynomial. The numerical optimization procedure based on desirability function methodology was used to obtain the optimum components combinations to simultaneously meet all desired response properties. A confirmation experimental test was carried out using predicted mixture component settings from Minitab's response optimizer, to verify the predictions from the fitted models. A second approach for testing the model was to randomly remove 3 design points from the 46 design points initially used to fit models. New models were fitted using the 43 remaining design points and the models were used to predict the three design points that were randomly removed. The two approaches showed that the developed models had high accuracy because they gave predictions which were close to experimental results, and would have been perfectly accurate in an isolated system, i.e. barring all possible sources of error. Results obtained showed that the range of slump is 80 - 170(mm), the range of 1-day compressive strength is 14.6 – 26.4(MPa) and that of 28-day compressive strength is 36.2 – 57.4(MPa), and that it would be possible to obtain 28-day compressive strength of upto 45MPa with upto 43% replacement of natural coarse aggrgate by recycled coarse aggregate, and a 28-day compressive strength of upto 55MPa is feasible with only 13.3% replacement. The use of recycled aggregates has therefore been recommended for partial replacement in high performance concrete mixes with expected properties similar to results obtained herein.

Key words: Models, High performance concrete, recycled coarse aggregate, High range water reducing admixture, Extreme Vertices.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Concrete is a major construction material for civil engineering works. Today, the rate at which concrete is used is much higher than it was 40 years ago (Mehta and Monteiro, 2006). This assertion is also evident in the rate of infrastructural development in different parts of the world. Large quantity of construction waste is being produced in Nigeria almost on daily basis from demolition and renovation of old and worn-out structures, yet very little demolished concrete is currently recycled or reused in this country. The small quantity which is recovered is mainly reused as unstabilized base or sub-base in highway construction. The rest is dumped or disposed of as fill materials (Akinkurolere et al, 2013).

In Nigeria and most of other developing countries where technological development is still growing, some regions especially large urban areas are already facing problems of obtaining adequate aggregate supplies at reasonable cost due to the distance to the source of the aggregate. The idea of recycling aggregates, become invaluable in such areas.

For reasons of waste reduction and to save energy and cost in the production of natural aggregate, it is important for concrete from demolished structures to be reused for construction of new structures. Concrete debris is typically reclaimed as recycled concrete aggregate (RCA).

By recycling concrete, valuable landfill space and natural resources are preserved. This concept is part of the larger “sustainable construction” philosophy that seeks to minimize waste generation and encourage recycling in order to prevent adverse long-term environmental effects (ACI CRC 18.517, 2019). For effective utilization of waste concrete, it is necessary to use waste concrete as recycled aggregates for new concrete (Jianzhuang et al., 2005).

Though there have been previous researches on recycled aggregates, most have been on the production of conventional concrete. This research shall focus on determining the suitability of recycled aggregates for high-performance concrete (HPC), and the development of prediction models for various properties of HPC made with recycled aggregate, which can be subsequently used to obtain optimal combinations of the mixture components for HPC.

The traditional method of concrete mixture proportioning is usually based on trial and error method, which most times do not give the best setting of components to meet several performance criteria simultaneously. Thus it is relevant to have a method which is not only precise in meeting the required properties for a given concrete mixture proportion, but can also be used to optimize mixture proportions such that the most efficient component setting in terms of the desired response property(s) and cost are obtained. This study shall attempt to use a statistical method which incorporates the idea in scheffe's regression technique to create a model to adequately predict both fresh and harden properties of HPC made with recycled concrete coarse aggregate, and this model shall further be used to optimize the HPC mixture.

1.2 Problem Statement

Although there are instances where recycled aggregates have been successfully used to produce conventional concrete, there have been very little research on the use of recycled aggregates for the production of high-performance concrete. The problem before us is to model the workability and strength properties of HPC made with recycled coarse aggregate such that it would be possible to easily obtain optimum quantity of recycled aggregate as well as other components, to use in the production of such HPC using the models. Therefore, this research shall tackle the problem that is associated with determining the quantity of recycled aggregate that is required to produce a given grade of HPC that meets reasonable quality by creating models that will adequately predict the considered responses or properties of such a

HPC. In these models, each response (resultant concrete property) such as strength and slump, is expressed as an algebraic function of factors (individual component proportions) of which recycled aggregate is one, hence, the models can conveniently be used to predict the approximate amount or proportion of recycled aggregate that will yield an optimum magnitude of each considered response.

1.3 Objectives of study

The main objective of this work is to develop models for producing high-performance recycled aggregate concrete using extreme vertices design.

The specific objectives are to:

i. characterize the materials used in producing HPC.
ii. develop high-performance concrete mix proportions with natural coarse aggregate partially replaced with recycled aggregate.
iii. develop models for predicting the compressive strength and workability of high performance concrete with natural coarse aggregate partially replaced with recycled aggregate.
iv. establish the effect of recycled coarse aggregate on HPC mixes.
v. determine the mix of HPC that gives optimum compressive strength (Optimization of high performance recycled aggregate concrete).

1.4 Significance of study

This work will be of great significance as it will:

i. give prescription on how recycled coarse aggregate can be applied in the production of HPC.
ii. produce a method that is precise and efficient for creating a mix proportion of HPC made with recycled aggregate.

iii. serve as a guide to structural designers who intend to produce concrete of similar properties using similar materials.
iv. serve as a reference for subsequent studies and researches that involve the use of recycled coarse aggregate in the production of HPC.

1.5 Scope of study

This study covers work on recycled aggregate in the production of HPC with a focus on developing models that will predict and optimize the properties of the resulting HPC. The recycled aggregate was obtained from a site of demolished structure along MCC road in Calabar. The method employed in this research is based on studies on physical and mechanical properties of the materials involved and the resulting concrete.

The compressive strength and the workability of fresh concrete were the properties on which comparisons were made by replacing proportions of natural coarse aggregate with recycled coarse aggregates. The targeted compressive strength of high-performance concrete is between 70-90MPa. Properties of aggregates such as aggregate grading, abrasion resistance, water absorbing capacity, density, and apparent specific gravity, were also examined in order to determine the usability of the aggregates, especially the recycled aggregate.

This study does not cover the microstructure properties of high-performance concrete made with recycled aggregate. Frost action on aggregates is not also considered as the environment in which the research is carried out and the outcome is to be applied in is not susceptible to freezing and below freezing temperatures.

CHAPTER TWO

LITERATURE REVIEW

2.1 Concrete as a construction material

In an online article published by Encyclopedia Britannica in June 2021, concrete is defined as "a construction material consisting of a hard, chemically inert particulate substance, known as aggregate (usually sand and gravel), that is bound together by cement and water".

In an article published by the Scientific American in April 1964, Brunauer and Copeland, two eminent scientists in the field of cement and concrete, wrote that "the most widely used construction material is concrete, commonly made by mixing portland cement with sand, crushed rock, and water" (Mehta and Monteiro, 2006).

From the above literatures, it is seen that construction concrete or conventional concrete is a composite material that is basically composed of fine aggregate and coarse aggregate, bonded by the chemical action of cement and water. For the use of concrete as a construction material, its ability to withstand applied forces and loads should be of ought most concern, hence, the strength of concrete is a major property that must be carefully analyzed. However, since the strength of concrete is very seriously affected by its degree of compaction (Neville, 2011), then the property of fresh concrete which allows for easy and good compatibility, becomes even as much important as its strength.

2.1.1. Properties of harden concrete.

1. Strength is "a measure of the amount of stress required to fail a material". "In situations where Engineering materials are to be subjected to stresses, then such materials ability to withstand the applied stresses must be given outmost consideration, because the ability of a material to withstand stresses is proportional to the strength of that material. Depending on how stresses are applied on a material, the stresses may be distinguished as compressive stress, tensile stress, flexural stress, shear stress and torsional stress. A material strength is then defined according to the type of stress that it is being subjected to. From the working stress theory for concrete design, concrete is mostly suitable for bearing compressive loads (i.e., under compressive stress); this is why it is the compressive strength of concrete that is generally specified for Engineering construction purposes" (Mehta and Monteiro, 2006).

The **compressive strength** of concrete is "the strength of concrete under the action of compressive load. Because the strength of concrete depends on the cement hydration process, which is relatively slow, traditionally the specifications and tests for concrete strength are based on specimens cured under standard temperature-humidity conditions for a period of 28 days" (Mehta and Monteiro, 2006). "The concrete cube test is usually performed to determine the compressive strength of a standard concrete cube test specimen, which is expected to represent the potential quality of the structural concrete. The cubes are produced from well-proportioned concrete components. A concrete cylinder test may as well be used" (Neville, 2011). The methods of compression test for the compressive strength of concrete cubes are presented in section **2.2.6.1.**

The **tensile strength** of concrete (i.e. strength of concrete under tensile load) is "very small and generally neglected in normal design practice, so that little dependence is placed on it and steel reinforcing bars are provided to resist all the tensile forces in reinforced concrete members" (Shetty, 2000). Although concrete is not normally designed to resist direct tension, the knowledge of tensile strength is of value in estimating the load under which cracking will develop. "The absence of cracking is of considerable importance in maintaining the continuity of a concrete structure and in many cases in the prevention of corrosion of reinforcement. Cracking problems occur when diagonal tension arising from shearing stresses develops, but the most frequent case of cracking is due to restrained shrinkage and temperature gradients. An appreciation of the tensile strength of concrete helps in understanding the behavior of reinforced concrete even though the actual design calculations do not in many cases explicitly take the tensile strength into account" (Neville, 2011). The direct tension test, flexure test, and the split tensile test are types of tests for strength of concrete in tension.

"In the direct tension test, direct application of a pure tension force, free from eccentricity, is very difficult. Despite some success with the use of lazy-tong grips, it is difficult to avoid secondary stresses such as those induced by grips or by embedded studs. A direct tension test, using bonded end plates, is prescribed by the U.S. Bureau of Reclamation" (Neville, 2011).

In the **flexural strength test**, "a concrete test specimen subjected to flexure will experience tensile stresses at the bottom fiber, and the theoretical maximum tensile stress reached at the bottom fiber of a member subjected to flexure is known as modulus of rupture" (Neville, 2011). The magnitude of the modulus of rupture is a representation of the tensile strength of the concrete.

"The tensile strength of concrete and its flexural strength are of the order of 10 and 15 percent respectively, of the compressive strength", (Mehta and Monteiro, 2006). This implies the poor strength of concrete in tension and flexure.

2. Porosity is the volume of all voids present in harden concrete. "It is a property of concrete that can also affect the strength of the harden concrete. It is known that the strength of concrete is basically a function of the volume of voids in it. The volume of all voids which tend to influence the strength of concrete include: entrapped air, capillary pores, gel pores, and entrained air, if present" (Neville, 2011).

3. Durability according to Mehta and Monteiro, (2006) is defined as the "service life of concrete under given environmental condition". Shetty, (2000) also defined durability as "the ability of concrete to resist weathering action, chemical attack, abrasion, or any other process of deterioration". "Durable concrete will retain its original form, quality, and serviceability when exposed to its environment. Although, the strength of concrete has direct relationship with durability, this is not the case in all situations. Because of the time constraint factor in construction projects, the construction industry needs faster development of strength in concrete so that the projects can be completed in time or before time. This demand is met by the use of very low W/C ratio by high early strength concrete, through the use of increased cement content and reduced water content. The above steps result in higher thermal shrinkage, drying shrinkage, modulus of elasticity and lower creep coefficients. With higher quantity of cement content, the concrete exhibits greater cracking tendencies because of increased thermal and drying shrinkage. Because of the low creep coefficient in such concrete, there will not be much freedom for relaxation of stresses. Therefore, high early strength concretes are more prone to cracking than moderate or low strength concrete" (Shetty, 2000). The appearance of cracks is an indication of failure in serviceability of concrete, which by extension reduces the durability of concrete. "It is known that volume change results in cracks and cracks are responsible for disintegration of concrete. It is also known that permeability is the contributory factor for volume change, and higher W/C ratio is the fundamental cause of high permeability. Therefore, use of higher W/C ratio which results in high permeability leading to volume change, cracks, disintegration, and failure of concrete is a cyclic process in concrete. Hence, for a durable concrete, use of lowest possible W/C ratio is the fundamental requirement to produce dense and impermeable concrete" (Shetty, 2000). The permeability of concrete, which is the ease of flow of liquid through the concrete, has been see to have a great impact on its durability.

2.1.2. Properties of fresh concrete.

The property of concrete at its early age that is of concern and requires some reasonable attention is its workability. According to ASTM C-125, "workability is defined as the property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity". "The term "manipulate" includes the early-age operations of placing, compacting, and finishing. The effort required to place a concrete mixture is determined largely by the overall work needed to initiate and maintain flow, which depends on the rheological property of the lubricant (the cement paste) and the internal friction between the aggregate particles on the one hand, and the external friction between the concrete and the surface of the formwork on the other.

Consistency, measured by the slump-cone test or Vebe apparatus, is used as a simple index for mobility or flowability of fresh concrete. The effort required to compact concrete is governed by the flow characteristics and the ease with which void reduction can be achieved without destroying the stability under pressure.

Stability is an index for both the water-holding capacity (the opposite of bleeding) and the coarse-aggregate-holding capacity (the opposite of segregation) of a plastic concrete mixture. A qualitative measure of these two characteristics is generally known as ***cohesiveness***. From the above, we see that workability is made up of two main components: Consistency (describes the ease of flow) and Cohesiveness (describes the stability or lack of bleeding and segregation characteristics.)" (Mehta and Monteiro, 2006). Slump test which measures the consistency of fresh concrete is the most widely used test to measure workability. The procedure for carrying out the slump test is presented in section **2.2.6.2**. Other available test for measuring the workability of fresh concrete include: the compacting factor test, the flow test and the vee-bee consistometer test.

For conventional Portland cement concrete, there are some deficiencies on the above discussed properties, (Mehta and Monteiro, 2006); therefore, the need to overcome these deficiencies have necessitated the need for the formulation of special types of concretes meeting these and some other special requirements of concrete for the construction industry. This need is the basis for the study and formulation of high performance concrete.

2.2. High-performance concrete

The American Concrete Institute, (2015), defines high performance concrete as “concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practice”. Shetty, (2000) also defined high performance concrete as “the concrete mixture which possess high workability, high strength, high modulus of elasticity, high density, high dimensional stability, low permeability and resistance to chemical attack”.

Conventionally, products that last longer are called high-performance products. “From laboratory investigations many researchers have reported that properly proportioned and cured mixtures of superplasticized concrete, with 0.4 or less water/cement (w/c) ratio, show a little or no permeability, which is the most desired property for long-term durability of structures exposed to corrosive environments. In fact, superplasticized concrete mixtures made with blended portland cements containing mineral additives exhibit unusually low permeability ratings in the ASTM C 1202, rapid chloride penetration test” (Mehta and Monteiro, 2006).

According to the U.S. Federal High Way Administration (FHWA), high performance Concrete (HPC) is a “concrete that has been designed to be more durable and if necessary, stronger than conventional concrete. HPC mixtures are essentially composed of the same materials as conventional concrete mixtures. But the proportions are designed or engineered to provide the strength and durability needed for the structural and environmental requirements of the project”.

2.2.1. Constituents and production of high-performance concrete

According to Neville (2011), High performance concrete contains the following ingredients: “common, albeit good quality, aggregate; ordinary Portland (Type I) cement (although rapid-hardening Portland (Type III) cement can be used when high early strength is required) at a very high content, 450 to 550 kg/m^3; silica fume, generally 5 to 15 per cent by mass of the total cementitious material; sometimes, other cementitious materials such as fly ash or ground granulated blast furnace slag; and always a superplasticizer. The dosage of the superplasticizer is high: 5 to 15 litres per cubic meter of concrete, depending on the solids content in the superplasticizer, as well as on its nature. Such a dosage allows a reduction in water content of about 45 to 75 kg/m^3 of concrete”.

“In the production of HPC, batching and mixing require particular care. Because of the importance of thorough mixing, using the mixer at less than its rated capacity may be beneficial; a reduction of one-third, or even one-half, may be desirable. A longer mixing time than usual is required to ensure homogeneity of what is usually rather a sticky mix: 90 seconds has been recommended, but even longer periods may be desirable” (Neville 2011).

2.2.2 Properties of high performance concrete

Mehta and Aitcin (1990), suggested the term high-performance concrete (HPC) for concrete mixtures that possess the following three properties: high-workability, high-strength, and high durability.

a) **High-workability:** In his book “Properties of Concrete” Neville, (2011) stated that “the particular proportions of the ingredients of high performance concrete, namely, the very high cement content, the very low water content, and the high dosage of superplasticizer, influence the properties of the fresh concrete in some respects in a manner different from the usual mixes. He observed that slump within the range of 150-200mm could be achieved but that this was relatively dependent on the sequence of feeding the ingredients into the mixer”. Mehta and Monteiro, (2006) reported that the HPC concrete mixes used in the construction of the confederation bridge in Canada could attain a slump of between 185 – 200mm.

b) **High-strength**: In a publication by civil-resources.blogspot.com, 2010, high performance concrete was classified in terms of strength as shown in Table 2.1.

Table 2.1 Strength classification of HPC according to civil-resources.blogspot.com (2010

Compressive strength (MPa)	50	75	100	125	150
High Performance Class	I	II	III	IV	V

Neville (2011), in his book "Properties of concrete" also stated that high performance in terms of strength will be taken as a compressive strength in excess of 80 MPa. Also, Mehta and Monteiro, (2006) reported that the high performance concrete mixes used in the construction of the main piers and T-beams of the confederation bridge in Canada had 1-day strength of 35MPa and 28-day strength of 82MPa. While that used for massive foundation of same construction had a 1-day strength of 9.7MPa and 28-day strength of 50MPa.

c) **High durability**: "A durable concrete will retain its original form, quality, and serviceability when exposed to its intended service environment" (Mehta and Monteiro, 2006). "High-performance concrete implies strength as well as durability; hence high-performance concrete must be durable. Durability in concrete is usually determined by a measure of its permeability, that is the ability of the concrete to resist or allow the ingress of fluids and ions. Properly proportioned and cured mixtures of superplasticized concrete (HPC), with 0.4 or less water/cement ratio, have been found to show little or no permeability, which is the most desired property for long-term durability of structures exposed to corrosive environments. In fact, superplasticized concrete mixtures made with blended Portland cements containing mineral additives exhibit unusually low permeability ratings in the

ASTM C 1202 rapid chloride penetration test" (Mehta and Monteiro, 2006). "The fact that high performance concrete has a particularly dense structure of hydrated cement paste – indeed, this is what imparts high performance – with a discontinuous capillary pore system, means that high performance concrete possesses a high resistance to external attack. This is particularly true with respect to the ingress of chlorides into the concrete. For instance, tests similar to those of ASTM C 1202-10, on 3-month-old cores from columns made with 120 MPa concrete (17 000 psi) have shown a negligible chloride-ion permeability. Even concrete with a water/cement ratio of 0.22, subjected to drying at 105 °C (221 °F), which removes the evaporable water from the hardened cement paste, was found, on subsequent exposure to chloride ions, to have an extremely low permeability to chloride ions" (Neville, 2011).

2.2.3 Properties of aggregate suitable for high performance concrete

"Although common aggregates are used in making high performance concrete, in concretes of very high strength, the strength of the coarse aggregate particles themselves can be critical. In consequence, the strength of the parent rock is of importance, but the bond strength of the aggregate particles can also be a limiting factor. The mineralogical characteristics of coarse aggregate have been found to influence the strength of the resulting concrete, but no simple guidance on the selection of aggregate is available" (Neville, 2011). "The criterion of the strength of aggregate is valid when a high long-term strength of concrete is required. If, however, the desired property of high performance concrete is a high strength at a very early age (say, 40 MPa at 2 days) and a higher strength in the long term is unnecessary, then the strength of the aggregate particles is unimportant. Generally, however, good quality aggregate must be used. To ensure good bond between the coarse aggregate particles and the matrix, these particles should be approximately equi-dimensional. It should be remembered that the shape of crushed particles depends, in addition to the parent rock type and its bedding, also on the method of crushing used, impact crushers generally producing few elongated or flaky particles. Gravel is satisfactory as far as shape is concerned and it can be used in high performance concrete, but the aggregate–matrix bond may be inadequate when the surface texture of the gravel is very smooth. Cleanliness of the aggregate, absence of adhering dust, and uniformity of grading are essential" (Neville, 2011). "Durability of coarse aggregate particles is vital when the concrete containing the given aggregate is likely to be exposed to freezing and thawing" (Neville, 2011).

According to Mehta and Monteiro, (2006), the strength of a concrete mixture can be increased significantly by simply reducing the maximum size of the coarse aggregate because this has a beneficial effect on the strength of the interfacial transition zone. According to Aitcin (1990), the higher the targeted strength, the smaller should be the maximum size of coarse aggregate. "Up to 70 MPa compressive strength concrete can be produced with a good-quality coarse aggregate of 20 to 25 mm maximum size. To produce concrete of 100MPa compressive strength, aggregates with 14 to 20 mm maximum size should be used. Commercial concretes with compressive strengths of over 125 MPa have been produced with 10 to 14 mm maximum size coarse aggregate" (Mehta and Monteiro, 2006).

With regards to the mechanical properties of coarse aggregate to be used in high performance concrete, the aggregate crushing value and aggregate impact value shall not exceed 30%, according to BS 812-part 3-1975, for aggregates to be used in concreting.

"In regard to fine aggregate, fine aggregate should be rounded and uniformly graded, but rather coarse, because the rich mixes used in high performance concrete have a high content of fine particles; a fineness modulus of between 2.8 and 3.2 is sometimes recommended. However, any material with the particle size distribution meeting the ASTM Standard Specification C 39 is adequate for high-strength concrete mixtures" (Neville, 2011). Table

2.2a shows the limit of grading of coarse aggregate used in concreting and Table 2.2b shows the limit of grading of fine aggregate used in concreting in accordance with BS 882:1992

Table 2.2a : Limit of grading of coarse aggregates (BS 882: 1992)

Sieve size (mm)	**Percentage by mass passing test sieves** (%)							
	Nominal size of graded aggregates (mm)			Nominal size of single-sized aggregate (mm)				
	40 to 5	20 to 5	14 to 5	40	20	14	10	5
50	100	-	-	100	-	-	-	-
37.5	90-100	100	-	85-100	100	-	-	-
20	35-70	90-100	100	0-25	85-100	100	-	-
14	25-55	40-80	90-100	-	0-70	85-100	100	-
10	10-40	30-60	50-85	0-5	0-25	0-50	85-100	100
5	0-5	0-10	0-10	-	0-5	0-10	0-25	45-100
2.36	-	-	-	-	-	-	0-5	0-30
NOTE: For coarse recycled 20 mm and 10 mm single-sized aggregates, the percentage by mass passing 4 mm test sieve shall not exceed 5%.								

Table 2.2b: Limit of Grading of Fine Aggregates (BS 882: 1992)

Sieve Size	Percentage by mass passing test sieves (%)			
	Overall Limits	Limits for declared grading		
		C	M	F
10mm	100	-	-	-
5mm	89-100	-	-	-
2.36mm	60-100	60-100	65-100	80-100
1.18mm	30-100	30-90	45-100	70-100
600µm	15-100	15-54	25-80	55-100
300µm	5-70	5-40	5-48	5-70
150µm	0-20	-	-	-

2.2.4. Superplasticizers and Silica Fumes in High-Performance Concrete

According to Mehta and Monteiro, (2006), “Superplasticizers are high range water reducing admixtures” **(HRWRA). “**Water reducing admixture as the name implies are chemicals that are capable of reducing the mixing water of concrete mixture. While a normal water reducing admixture can reduce up to 5% mixing water, high range water reducers can reduce up to 12% mixing water in a concrete mixture. Silica fume also known as microsilica, is an ultrafine powder collected as a byproduct of the silicon and ferrosilicon alloy production and consist of spherical particles with an average particle diameter of 150 nm”.

Neville, (2011) stated that the “effectiveness of superplasticizers is enhanced by the presence of silica fume”. Giving an instance, he explained that in mixes with a slump of 120 mm, a given dosage of a superplasticizer was found to reduce the water demand by 10 kg/$m^3 m^3$in a Portland cement- only concrete. The same dosage maintained the slump when the silica fume content was 10 per cent by mass of cementitious material. “Without the superplasticizer, the water demand due to the inclusion of silica fume in the mix would have risen by 40 kg/m^3”. Therefore, he made the conclusion that “the use of both silica fume and a suitable superplasticizer is beneficial and makes it possible to use low water/cement ratios at a given workability”.

2.2.5 Mix proportion of high-performance concrete

While there exists no standard, or even typical, mix proportions of high performance concrete, it is useful to present information on several successful mixes; this is given in Table 2.3 (Neville, 2011).

Table 2.3 Mix Proportions of Some High-Performance Concretes

Ingredient (kg/m^3)	Mix								
	A	B	C	D	E	F	G	H	I
Portland cement	534	500	315	513	163	228	425	450	460
Silica fume	40	30	36	43	54	46	40	45	
Fly ash	59	-	-	-	-	-	-	-	-
ggbs	-	-	137	-	325	182	-	-	-
Fine aggregate	623	700	745	685	730	800	755	736	780
Coarse aggregate	1069	1100	1130	1080	1100	1110	1045	1118	1080
Total water	139	143	150	139	136	138	175+	143	138
Water/cementitious material ratio	0.22	0.27	0.31	0.25	0.25	0.3	0.38	0.29	0.3
Slump, mm	255	-	-	-	200	220	230	230	110
Cylinder strength (MPa) at age (days)									
1	-	-	-	-	13	19	-	35	36
2	-	-	0	65	0	0	0	-	-
7	-		67	91	72	62	0	68	-
28	-	93	83	119	114	105	95	111	83
56	124	-	-	-	-	-	-	-	-
91	-	107	93	145	126	121	105	-	89
365	-	-	-	-	136	126	-	-	-

The mix proportions and the properties of concrete used for the construction of the confederation bridge in Eastern Canada are given in Table 2.4 (Mehta and Monteiro, 2006). These mixes were design to meet the given properties of the concrete used in the said construction

Table 2.4: Confederation Bridge HPC Mix Proportions and Properties (Mehta and Monteiro, 2006)

Mix proportions, kg/m^3	Class A concrete for main piers and T-beams	Class C Concrete for massive foundation	Abrasion-Resistant Ice shield Concrete
Portland cement	416	285	478
Silica fume	34	22	42
Fly ash, Class F	-	133	60
Fine aggregate	737	744	650
Coarse aggregate	1030	1054	980
Water	153	159	142
Superplasticizer	3	2	6
W/cm	0.34	0.37	0.25
Properties			
Entrained air, %	6.1	7.0	-
Slump, mm	200	185	-
Compressive strength, MPa			
1-day	35	9.7	-
3-days	52	27.4	-
28 days	82	50.0	100
91 days	-	76.0	-
Rapid chloride permeability, Coulombs (AASHTO T277)			
28 days	300	420	-
90 days	-	-	-

SOURCE: Langley, W.S., R. Gilmour, and E. Trompsch, ACI SP-15

2.2.6 Tests on high-performance concrete

"Testing standard compression specimens – 150 by 300 mm cylinders or 150 mm cubes – may present a problem with respect to the capacity of the testing machine; as 80 percent of the capacity should not be exceeded, a capacity of 4 MN may be required. The use of smaller specimens is, therefore, preferable: specifically, 100 by 200 mm cylinders or 100 mm cubes are satisfactory" (Neville, 2011).

For workability test, the conventional slump test suffices. The test procedures in sections 2.2.6.1 and 2.2.6.2 are applicable for testing of high performance concrete.

2.2.6.1 Compression Test

In carrying out compression test on concrete cubes, the cubes were first be prepared in accordance with the relevant standard, before being tested in a compression testing machine also in accordance with the relevant standard.

a. Preparation of cubes in accordance with BS 1881: Part 108: 1983

Apparatus

(a) Mould: 100 x 100 x 100mm

(b) Compacting bar: A compacting bar made out of a steel bar weighing 1.8 kg, 300 mm long and having a ramming face 25 mm square.

(c) Plasterer's steel float.

(d) Sampling tray, 1.2 m x 1.2 m x 50 mm deep made from minimum 1.6 mm thick non-corrodible metal.

(e) Square mouthed shovel, size 2 in accordance with BS 3388.

Preparing the sample

After appropriate batching, the sample was emptied from the container(s) on to the sampling tray. It shall be ensured that no more than a light covering of slurry is left adhering to the container(s). The sample was thoroughly mixed by shoveling it to form a cone on the sampling tray and turning this over with the shovel to form a new cone, the operation being carried out three times. When forming the cones, each shovelful of the material was deposited on the apex of the cone so that the portions which slide down the sides are distributed as evenly as possible and so that the centre of the cone is not displaced. The third cone was flattened by repeated vertical insertion of the shovel across the apex of the cone, lifting the shovel clear of the concrete after each insertion.

Procedure:

Filling the mould: The mould was placed on a rigid horizontal surface or on the vibrating table and filled with concrete in such a way as to remove as much entrapped air as possible (without significantly reducing the amount of entrained air, if present) and to produce full compaction of the concrete with neither excessive segregation nor laitance. For this purpose, by means of the scoop, the concrete is placed in the mould in layers approximately 50 mm deep and each layer is compacted by using either the compacting bar or the vibrator. After the top layer has been compacted, it is leveled and made smooth with the top of the mould, using the plasterer's float, and then the outside of the mould is wiped.

b. Testing of specimen in accordance with BS 1881-116: 1983

Apparatus:

i. Compression testing machine.
ii. Auxiliary platens. When auxiliary platens are used, the top auxiliary platen shall rest on and be aligned with the cube. It shall not be fixed to the upper machine platen.

Preparation of test specimens:

Test specimens were 100 x 100 x 100mm concrete cubes made in accordance with part "**a**" of section **2.2.6.1**, cured and stored appropriately. All cubes were cast in properly assembled moulds. Any projecting fins were removed before cubes were tested.

Procedure:

I. Preparation: Cubes which have not been cured in water or where the surfaces have been allowed to dry were immersed in water for a minimum of 5min. The cubes were removed from the curing or density water tank and tested while they were still wet.
II. Placing the cube in the testing machine: It was ensured that all testing-machine bearing surfaces were wiped clean and that any loose grit or other extraneous material

are removed from the surfaces of the cube which will be in contact with the platens. No packing between the cube and platens was used, and the spacing blocks if used. The cube was carefully centered on the lower platen and ensured that the load will be applied to two opposite cast faces of the cube.

III. Loading: Without shock, the load was applied and increased continuously at a nominal rate within the range 0.2 $N/(mm^2 \cdot s)$ to 0.4 $N/(mm^2 \cdot s)$ until no greater load can be sustained. The maximum load applied to the cube was recorded.

Calculation:

Calculation of cross-sectional area: The cross-sectional area of the cube was calculated from the nominal dimensions, if both lie not more than 1% above or below the nominal cube size, whether the cube is to be tested between the machine platens or auxiliary platens.

Calculation of strength: The compressive strength of each cube was calculated by dividing the maximum load applied to it by the cross-sectional area and the results expressed to the nearest 0.5 N/mm^2.

2.2.6.2 Slump Test

Slump test measures consistency of concrete in that specific batch. It was performed to check the consistency (also known as workability, or fluidity) of freshly made concrete, and therefore the ease with which concrete flows. It was conducted in accordance with BS 1881-102.

Apparatus:

i. Mould. Mould made of metal not readily attacked by cement paste and not thinner than 1.5mm. The interior of the mould shall be smooth and free from projections such as protruding rivets and shall be free from dents. The mould shall be in the form of a hollow frustum of a cone having the following internal dimensions:

Diameter of base: 200 ± 2 mm

Diameter of top: 100 ± 2 mm

Height: 300 ± 2 mm

The base and the top shall be open and parallel to each other and at right angles to the axis of the cone. The mould shall be provided with two handles at two-thirds of the height, and with foot pieces to enable it to be held steady. A mould which can be clamped to a base-plate is acceptable as an alternative if the clamping arrangement can be released without movement of the mould.

ii. Scoop, approximately 100mm wide.
iii. Sampling tray, minimum dimensions900mm× 900mm × 50mm deep, of rigid construction and made from a non-absorbent material not readily attacked by cement paste.
iv. Square mouthed shovel, size 2 in accordance with BS3388.
v. Tamping rod, made out of straight iron or steel bar of circular cross section, 16± 1mm diameter and 600± 5mm long, with both ends hemispherical.
vi. Rule, graduated from 0mm to 300mm at 5mm intervals, the zero point being at one end of the rule.

<u>Preparing the sample for test:</u>

Materials were appropriately batched and emptied from their containers onto the sampling tray. It was ensured that no more than a light covering of slurry is left adhering to the container(s). The sample was thoroughly mixed by shoveling it to form a cone on the sampling tray and turning this over with the shovel to form a new cone, the operation being carried out three times. When forming the cones, each shovelful of the mixing concrete was deposited on the apex of the cone so that the portions which slide down the sides are distributed as evenly as possible and so that the centre of the cone is not displaced. The third cone is flattened by repeated vertical insertion of the shovel across the apex of the cone, lifting the shovel clear of the concrete after each insertion.

Procedure:

It was ensured that the internal surface of the mould is clean and damp but free from superfluous moisture before commencing the test. The mould was placed on a smooth, horizontal, rigid and non-absorbent surface free from vibration and shock and held firmly against the surface below with the funnel, if used, in position at the top whilst it was filled in three layers, each approximately one-third of the height of the mould when tamped. Each layer was tamped with 25 strokes of the tamping rod, the strokes being distributed uniformly over the cross-section of the layer. Each layer was tamped to its full depth, ensuring that the tamping rod does not forcibly strike the surface below when tamping the first layer and just passes through the second and top layers into the layers immediately below. The concrete was heaped above the mould before the top layer is tamped. If necessary, further concrete was added to maintain an excess above the top of the mould throughout the tamping operation. After the top layer has been tamped, the funnel was removed, if fitted, and the concrete was leveled with the top of the mould with a sawing and rolling motion of the tamping rod. With the mould still held down, any concrete which may have fallen onto the surface below or leaked from the lower edge of the mould was cleaned. The mould was removed from the concrete by raising it vertically, slowly and carefully, in 5s to 10s, in such a manner as to impart minimum lateral or torsional movement to the concrete. The entire operation from the start of filling to the removal of the mould was carried out without interruption and was completed within 150s. Immediately after the mould is removed, the slump was measured to the nearest 5mm by using the rule to determine the difference between the height of the mould and of the highest point of the specimen being tested. This measurement was recorded.

2.3 Recycled aggregate (RA) or Recycled concrete aggregate (RCA)

Recycled aggregate (RA) or Recycled concrete aggregate (RCA) are fragments of concrete obtained from demolished concrete structures or road pavements and then resized into usable desired sizes. In this study, the recycled aggregate used are only coarse in nature.

Mehta and Monteiro, (2006), stated that "rubble from demolished concrete building yields fragments in which the aggregate is contaminated with hydrated cement paste, gypsum, and minor quantities of other substances. The size fraction that corresponds to fine aggregate contains large amount of hydrated cement paste and gypsum, and it is unsuitable for making fresh concrete mixture. However, the size fraction that corresponds to coarse aggregate, although coated with cement paste, has been used successfully in several laboratory and field studies".

Neville (2011), also reported that because "RCA consists in part of old mortar, the unit weight (density) of concrete made with RCA is lower than that of concrete made with conventional aggregate. For the same reason, concrete made with RCA has a higher porosity and absorption. The higher absorption of RCA can be exploited if it is saturated before mixing: the absorbed water provides internal curing. In particular, this is so for RCA containing a large amount of brick".

2.3.1 Production of recycled aggregate

The fragment of demolished concrete structures obtained at the site of demolition is usually too coarse and full of impurities and dust. In order to obtain usable aggregate from demolished concrete structures, then, these fragments have to pass through some processes.

These processes that are followed in order to obtain usable aggregate from fragments of demolished concrete structures are discussed in this section.

2.3.1.1 The recycling process

"A recycling plant is quite similar to a plant producing crushed natural aggregate. The closed system illustrated in Figure 2.1 is the layout which is normally recommended for production of recycled aggregate" (Hansen 1985). The open system which is shown in Figure 2.2 has greater capacity, but "the maximum particle size is less well defined and this can lead to large variations in the size of the end product". As clean concrete is not always available, provision must be made in a recycling plant for the extraction of contaminants from the material.

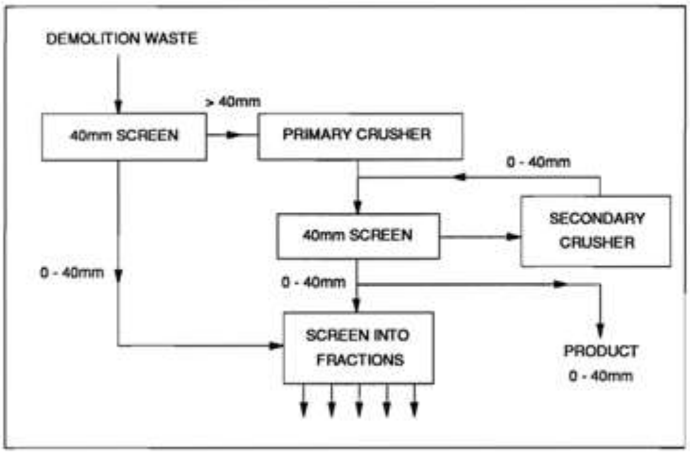


Figure 2.1 Flow chart of a typical closed system recycling plant, set up to produce a grading of 0 - 40mm (after Hansen, 1985)

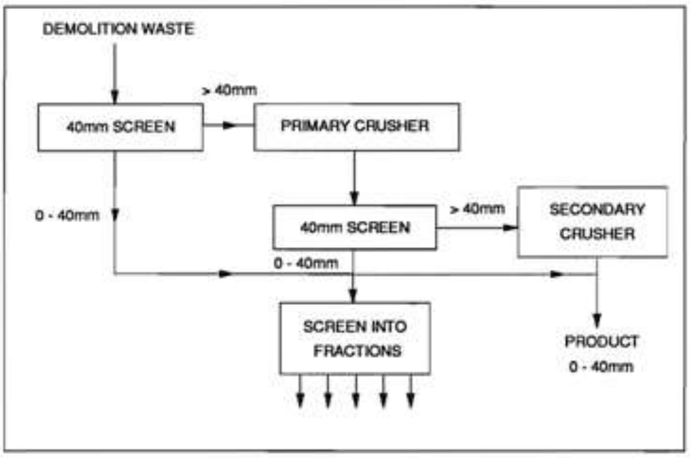


Figure 2.2 Flow chart of a typical open system recycling plant, set up to produce a grading of 0 - 40mm (after Hansen, 1985)

“Recycling plants can be mobile or stationary. Normally, a mobile plant consists of one crusher and some sorting devices. The removal of contaminants and steel is mainly conducted by hand sorting and self-cleaning electromagnets. In some cases, mobile plants can consist of two crushers. The main advantages of a mobile plant are as follows” (Lindsell and Mulheron, 1985):

i. Transport in the vicinity of the site is reduced, particularly if the rubble is produced, recycled and reused on the same site.
ii. Disposal costs are reduced because of less dumping.
iii. The local supply of aggregate is increased and therefore less aggregate needs to be imported into the area.
iv. The recycling plant can be moved relatively easily to another site.

The disadvantages of a mobile recycling plant are as follows:

i. There are limited cleaning facilities in this type of installation and therefore the recycled product is usually of low quality.
ii. The recycling plant can cause high level of dust and noise which will be unacceptable close to residential areas.
iii. This type of plant can only be used if there is a sufficient quantity of rubble on the site to justify the expenses of setting up the recycling plant.

“A stationary recycling plant usually incorporates a large primary crusher working in conjunction with a secondary crusher and also includes various cleaning and sorting devices to produce high quality aggregate. This type of plant normally combines two jaw crushers and is capable of yielding a range of graded products. Self-cleaning electromagnets, sieves and hand sorting are employed to produce a relatively clean and recycled aggregate from a mixed and contaminated input material” (Mulheron, 1988). A typical layout of a stationary recycling plant is shown in Figure 2.3. The main advantages of stationary recycled plants are as follows (Lindsell and Mulheron, 1985):

i. The recycling plant is capable of producing a high quality product.
ii. The efficiency of the plant is better than that of a mobile recycling plant because different recycled products of various grading can be produced.

iii. Disposal costs are reduced because of less dumping.

iv. The local supply of aggregate is increased and therefore less aggregate needs to be imported into the area.

The disadvantages of a stationary recycling plant are as follows:

i. The initial cost of setting up such a plant can be very high.

ii. There is an increase in transport in the vicinity of the recycling plant.

iii. The recycling plant can cause an increase in noise level.

iv. The efficiency of production depends on the local supply of rubble and unfortunately, demolition contractors are rarely able to ensure a constant supply of demolition waste.

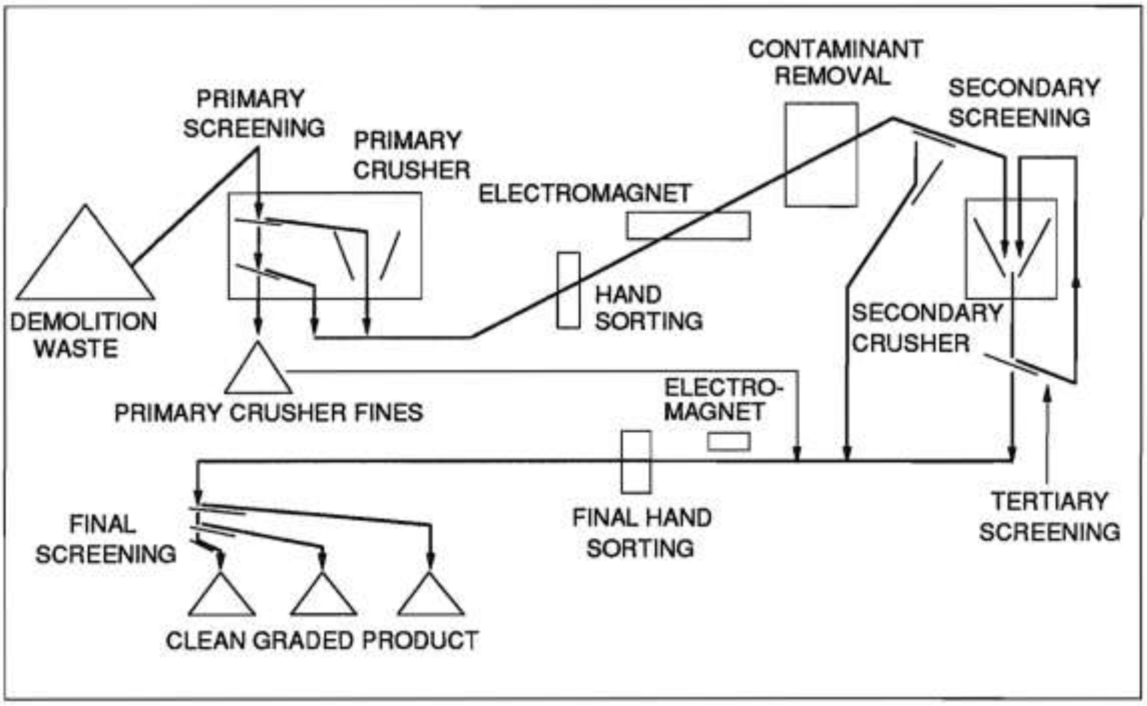


Figure 2.3 Typical layout of a stationary recycling plant (after Lindsell and Mulheron, 1985)

2.3.1.2 Crushers

“The crushers which are used at present for the recycling of rubble were not designed or developed specifically for the purpose. The majority of crushers originate from coal and ore processing or from natural stone crushing plants” (Boesman, 1985). Modifications have been made to these crushers to alter the degree of size reduction and the particle size distribution, to reduce wear and to prevent high levels of dust and noise.

The suitability of three types of crushers for crushing construction waste was investigated by Boesman (1985). They included a jaw crusher, an impact crusher and a cone crusher. “A cone crusher cannot accept materials which is larger than 200mm in size and therefore only jaw and impact crushers should be considered for use as primary crushers” (Boesman, 1985).

“A jaw crusher consists of two plates fixed at an angle – one plate remains stationary while the other plate oscillates back and forth relative to the fixed plate. This action crushes materials passing between the two plates. The degree of particle size reduction depends on the maximum and minimum size of the gap at the base of the plates. An impact crusher breaks the material up by striking it with a high speed rotating impactor which impacts a shearing force on the rubble”.

“The particle size distribution of the output material is affected by the type of crusher used” (Boesman, 1985). In general, the impact crusher has a large reduction factor. “The reduction factor is defined as the ratio of the particle size of the input to the particle size of the output material” (Lindsell and Mulheron, 1985).

“A jaw crusher crushes only a small proportion of the original aggregate particles but an impact crusher crushes mortar and aggregate particles alike and for the same maximum size of particles generates twice the amount of fines. One advantage of the impact crusher is its high efficiency and relatively low sensitivity to material which cannot be crushed e.g. reinforcement. Consequently, impact crushers suffer high wear and tear, which means that maintenance costs are high”.

2.3.1.3 Impurities in recycled aggregate

Recycled aggregates contain impurities or contaminants. Some of the impurities that may be found in recycled aggregates include wood fragments, soil, paint, asphalt, dust, gypsum, chloride etc. Mulheron (1986) found the levels of chloride in natural and recycled aggregates to be below the point of detection. "If recycled aggregate was to be produce from the crushing of a bride deck or a concrete carriageway from a road or an airport, it is expected that the level of soluble chloride might be excessive and consequently, the aggregate produced might not be suitable for aggregate in concrete. Chloride has little significant influence on the properties of plain concrete but in reinforced concrete, the presence of chlorides initiate corrosion of embedded steel" (BRE 1980, 1982).

Other impurities known to cause problems are timber and vegetable matter from soil. "The level of contamination of any recycled aggregate depends on the source of the aggregate and the method of production and control. Wood can be removed in floating operations which are usually only employed by the larger fixed-site recycling plants. Organic matter is considered to be a harmful impurity in aggregate intended for use in concrete (Collis and Fox, 1985). Humus and oil, for example can retard or even prevent the hydration of cement when present even in small quantity" (Sherwood and Roeder, 1965).

Kemi and Nakagawa (1978), tested concrete containing increasing levels of paint, asphalt, gypsum, wood, soil, and plaster. The compressive strength of the most heavily contaminated was 85% that of the control concrete specimens. The building contractors society of Japan (1981), determined the percentage of six contaminants which, when added to crushed concrete to be used as aggregate in new concrete, would cause no more than a 15% reduction in the compressive strength. The maximum percentages by volume were found to be 7% plaster, 5% soil, 4% wood, 3% gypsum, 2% asphalt, and 0.2% paint.

Graf (1973) and Gaede (1957) decided that the allowable level of soluble sulphate in recycled aggregate concrete should be maintained between 0.5% and 1%. “When present in sufficient quantity, sulphate in aggregate reacts with cement compounds if the aggregate is used in concrete manufacture. This results in excessive expansion and ultimately the deterioration of hardened concrete in wet or damp conditions” (Lea, 1970).

2.3.1.4 Sorting techniques

There are several methods of removing contaminants from demolition debris and they can be separated into two groups, (i) pre-crushing separation and (ii) post-crushing separation.

i. **Pre-crushing separation**

   Pre- crushing separation is to “remove the contaminants and sort rubbles while a structure is being demolished. This type of separation however, can be expensive and time consuming for the demolition contractor and therefore is not normally carried out unless there are definite incentives on a particular demolished site. Most sorting takes place when the rubble reaches the recycling plant. When the waste arrives, it is stockpiled according to its major constituent or the amount of contamination present. The plant operator can therefore deal with very large or undesirable material separately” (Lindsell and Mulheron, 1985). “This initial sorting can help to optimize crushing time because e.g. a large quantity of clean rubble which has accumulated in a stockpile can be crushed in a single continuous crusher run”.

   “At most recycling installations, primary screening is conducted by passing the rubble over a sieve before it reaches the primary crusher. Therefore, material which is already of the required size and which needs no further crushing, bypasses the primary crusher. This fraction is usually screened further to remove soil and other fine contaminants and the remainder is returned at a later stage to the recycling process”.

ii. Post-crushing separation

Post-crushing separation involves the removal contaminants from demolition debris after the material has been crushed. There are two methods of post-crushing separation namely: i. manual or hand sorting, ii. automatic sorting.

i. The simplest method is the manual or hand sorting method which involves removing contaminants by hand from the conveyor belts. The efficiency of this system depends on the concentration of the operator and the speed of the conveyor belt. The main advantage of this method is that the human eye can recognize contaminants which would be difficult to remove by mechanical means, e.g. glass.

ii. Automatic methods of contaminant removal include the following: electromagnetic removal of steel, dry sieving, and wet separation.

a) Electromagnetic removal of steel

“Self-cleaning electromagnets for the removal of steel are commonly employed in recycling plants. Usually, the magnet is located across the conveyor belt between the primary and secondary crushers. The efficiency of the magnet depends on the distance between the magnet and the conveyor belt, the conveyor belt speed, the density of the passing demolition debris and the angle at which the magnet is inclined to the conveyor belt. A magnet works more efficiently when it is positioned directly above and parallel to a slow moving, lightly loaded conveyor belt”. (Lindsell and Mulheron, 1985).

b) Dry sieving

Dry sieving can be used to separate the materials into fractions which can be recombined later to produce well graded aggregate. The main disadvantage of dry sieving methods is the production of large quantities of dust. According to the Building Contractors Society of Japan (BCSJ) (1981), coarse materials can be separated more efficiently by “using inclined screens vibrating at low frequencies and large amplitudes, while horizontal screens vibrating at high frequencies and small amplitudes are more effective for separating fine material”.

c) **Wet separation**

“Low density contaminants can be removed from demolition debris using an aquamator” (Lindsell and Mulheron, 1985). “This method of separation is conducted by placing the material in a tank full of water. The water in the tank is circulated at a fast rate and currents are set up by water jets. Wood and other lightweight impurities which float in water are removed by combs which move from one end of the tank to the other. This cleaning technique is normally restricted to materials of particle size greater than 10mm because of the excessive quantity of sludge which would be produced if material from a smaller fraction was added to the tank”.

2.3.2 Previous works on use of recycled aggregate in concrete production

Cardoso, et al (2016), concluded that the performance of most recycled aggregate is comparable to that of natural aggregate and can be used in unbounded pavement layers or in other applications requiring compaction.

Also in a report presented by Cement Concrete & Aggregates Australia, (2008), titled “use of recycled aggregate in concrete production” it was reported that there is a clear indication of increasing trend and incentive for the greater use of manufactured and recycled aggregates in construction. It also stated that there are however, limitations to the use of such materials, but the report focused on known benefits and limitations of a range of manufactured and recycled aggregates. Reporting further, it stated that "In terms of performance, many countries are focusing on recycled concrete aggregates (RCA) which is proven to be practical for non-structural concretes and to a limited extent for some structural-grade concrete. However, the processing and quality control cost associated with their use plus the premium paid for mix design adjustment to achieve the same strength grade as concrete with natural aggregates can vary considerably. In summary, the report stated that "In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities which have the potential to be used in construction. Air-cooled blast furnace slag (BFS) and manufactured sand are two good examples of concrete aggregates. Work is continuing to obtain performance data and appropriate specifications for manufactured sand. In other construction applications such as pavement, road base and subbase, there is limited information on the performance of each material as assessment appeared to be based on field trials, especially those by road authorities. In all cases, the availability and consistency of supply are prerequisite for the use of manufactured and recycled aggregates in the various applications".

Also in an article titled "Using Recycled Aggregates from Construction and Demolition Waste in Unbound Layers of Pavements" published on www.mdpi.com, Pourkhorshidi et al, (2020), wrote that "One of the main groups of recycled materials which has attracted much attention since the end of the last century is construction and demolition waste aggregates (CDW)". Writing further, they explained that "The number of completed and on-going studies on the possible use of CDWs has increased in recent years and this gives evidence of the diffuse concern on the sustainability of the construction sectors. In many cases CDW have been proven to perform as well as natural aggregates and in some cases, the residual binding properties have contributed to the development of mechanical properties in time. The use of CDWs in pavements is more likely one of their best applications as their adoption can be calibrated on the basis of their actual laboratory and field assessed characteristics. In most of the cases their constituents are natural aggregates, and this is usually positive for their use as unbound layers". In further writing, they opined that "Once the waste materials have been treated at the recycling plant and the CDW aggregates can return on the market as recycled construction material, their use in pavement layers does not differ from that of natural aggregates. The construction steps are the same and the same machinery can be used for the delivery, laying, grading and compaction of the layers. This is valid for both unbound and bound materials, including the possible application for bituminous layers".

In conclusion, they wrote that the "use of CDWs in the construction of pavements has proven to be a viable solution to exploit their residual positive properties. The recycling processes and the correct classification and selection of the raw waste materials is of great importance in the quality of the final product, i.e. of the constructed layers. Minor additional caution should be used when their use is foreseen in foundation or base layers".

After a thorough review of some 163 literatures, Simoes dos reis et al, (2021), wrote in their publication titled "Current Applications of Recycled Aggregates from Construction and Demolition: A Review" that "Environmental concerns about construction and demolition waste (CDW) generation and accumulation rise every year, which has reinforced the need to reuse it as recycled aggregate for construction industries, because the sector has a great potential to absorb most of the CDW generation". Concluding the report, they identified seven main applications for recycled aggregates obtained from CDW to include: "sand production, pavement/road construction, ready mix concrete, concrete blocks, cement, ceramics/bricks, and low-cost adsorbent for wastewater treatment. They discovered from the data found in the literature survey that recycled aggregates from CDW can be successfully used to produce construction materials with quality comparable to those produced with natural aggregates and constitute an environmentally friendly approach for a future construction and demolition waste management strategy”.

The also identified three main issues for future actions and studies related to the recycling of CDW in new construction materials to include:

(i) “the development of standardized tests to orient specific regulations for using RA from CDW in new materials”

(ii) “investigating the environmental risks associated with the use of RA from CDW as well as ways to potentialize its application in high added-value sectors, such as ceramics and pollutant adsorbents”

(iii) “looking deeper at aspects related to political strategies to boost the confidence and acceptance of materials derived from CDW by professionals and society”

In the final analysis, they mentioned that “the more knowledge about the capabilities of using recycled aggregates, the better one can arrive at solutions to overcome the current challenges”.

Also Silva and de Brito, (2015), in a conference paper presented at Latin-American and European Conference on Sustainable Buildings and Communities (EURO-ELECS 2015) At: Guimarães, Portugal, while attempting to discuss the characterization of recycled aggregates from construction and demolition wastes, mentioned that Silva et al. (2014e) proposed a performance-based classification for recycled aggregates based on their water absorption, oven-dried density and resistance to fragmentation. These classifications are as presented in Table 2.5.

Table 2.5 Performance based classification of recycled aggregates (Silva et al., 2014e)

Aggregate class		A			B			C		D
	I	II	III	I	II	III	I	II	III	
Minimum oven dried Density kg/m^3	2600	2500	2400	2300	2200	2100	2000	1900	1800	
Maximum water Limit absorption (%)	1.5	2.5	3.5	5	6.5	8.5	10.5	13	15	No
Maximum LA abrasion mass loss (%)		40			45			50		

Silva and de Brito, (2015), in the conclusion of their conference paper presentation, mentioned that “to ensure that good quality recycled aggregates are manufactured, the quality control process must start during construction or demolition activities”. Therefore, “by applying a selective demolition method, waste materials will then be separated and stored properly, which, besides facilitating the task of recycling plant operatives, will also minimize contamination levels of future recycled aggregate”. They stated further that; “as various studies have demonstrated while using a selective demolition approach, significant economic and environmental benefits may be guaranteed”. In the final analysis, they concluded that “the use of materials from processed construction and demolition wastes, results in dramatic reduction of the use of natural resources as well as the amount of waste sent to landfills”.

2.3.3 Use of recycled aggregate in concrete production (recycled aggregate concrete RAC)

“As a result of the ever increasing need for construction in today’s modern society leading to increase in demand for and decrease in supply of natural aggregate, it may be useful to find new sources of aggregate for the production of concrete. Simultaneously, as more structures are being constructed, increasing number of weak and not useful concrete buildings are being demolished and the difficulty of disposing of the rubble has prompted an interest in the possibility of using crushed concrete as aggregate in new concrete” (Nixon, 1978).

2.3.3.1 Mix design for recycled aggregate concrete

In principle, the mix design of recycled aggregate concrete is not different from that of conventional concrete and the same mix design procedures can be used. In practice, slight modifications are required. Hansen (1985) concluded that for the Department of Environment (DoE) mix design, written by Teycheene, Franklin and Erntroy in 1982, the following modifications would be necessary when using recycled aggregate. This design method will be referred to hereafter as the DoE mix design.

a) “When designing a concrete mix using recycled aggregate of variable quality, a higher standard deviation should be employed in order to determine a target mean strength on the basis of a required characteristic strength”

b) “When coarse recycled aggregate is used with natural sand, it may be assumed at the design stage that the free water/cement ratio required for a certain compressive strength will be the same for recycled aggregate concrete as for conventional concrete. If trial mixes show that the compressive strength is lower than required, an adjustment of the water/cement ratio should be made”.

c) “For a recycled aggregate mix to attain the same slum, the free water content will need to be approximately 10 litres/m^3m^3 higher than for conventional concrete”

d) “If the free water content of a recycled aggregate concrete is increased, the cement content will also need to be higher to maintain the same water/cement ratio”.

e) “Trial mixes should be made to obtain the required workability and the most suitable water/cement ratio”.

2.3.3.2. Workability of recycled aggregate concrete

Ravindrarajah (1985), found when recycled aggregate was used as the coarse fraction and natural sand as the fines in a concrete mix that an increase in free water of 8% was needed to achieve the same workability as that of natural aggregate concrete. Hansen and Narud (1983) reported needing 5% higher free water content than for normal mixes. Similarly, Mulheron and O'Mahony (1988), found when crushed concrete aggregate was used as the coarse fraction that the mixes were slightly harsher and less workable than the conventional aggregate mixes.

Frondistou-Yannas (1977) and Buck (1976) both reported that there appear to be little difference in workability when recycled aggregate was used as the coarse fraction with natural sand, but Buck (1976) noticed that the slum was lower if recycled aggregate was used for both coarse and fine fractions. Hansen and Marga (1988) agreed with this and stated that an increase in free water content of 14% was required when the total aggregate content in a mix consisted of recycled aggregate. An unusual result was reported by Yamato et al (1988) who found that workability was increased considerably when recycled aggregate was used. It is thought that this result was specific to his research and the type of aggregate used.

2.3.3.3 Strength of recycled aggregate concrete

The strength of recycled aggregate concrete shall be considered in terms of compressive strength, tensile strength, flexural strength, as well as its young's modulus, shrinkage and creep. These are discussed in this section.

a) Compressive strength

Hansen (1985) stated that "the compressive, tensile, and flexural strength of recycled aggregate concrete could be equal to or higher than that of conventional concrete if the same or a lower water/cement ratio was used. In practice however, the strength of recycled aggregate concrete is often found to be lower”. Frondistou-Yannas (1977) reported a 4% to 14% drop in compressive strength whereas, Kemi and Nakagawa (1978), Ravindrerajah (1985), Yamato et al (1988), Mulhedron and O’Mahony (1988), Nishibayashi and Yamura (1988), and Kasai (1985) all reported a reduction between 14 and 32%. Nixon (1978) found in a series of tests that the compressive strength of the original concrete, from which the recycled aggregate was obtained, did not appear to affect the compressive strength of the recycled aggregate concrete very much. Kashino and Takahashi (1988) noted when less than 30% of natural aggregate in a concrete mix was replaced by recycled aggregate that there appeared to be no change in compressive strength. Wesche and Schulz (1982) compiled earlier results obtained by Buck (1977), Malhotra (1978), and Frondistou-Yannas (1977). An apparent correlation was found between compressive strengths of conventional and recycled aggregate concretes. Recycled concretes consistently had 10% lower compressive strength than control concretes made with conventional aggregate.

More recently, in their works, Limbachiya et al. (2004), the compressive strength test on standard 100 mm cubes up to one year after initial curing in water at 20 °C and in air at 20°C/ 55% RH showed that up to 30% recycled coarse aggregates has no effect on the strength of recycled aggregate concrete, but thereafter, a gradual reduction with increasing RCA content occurs. Kou et al. (2004) also reported that as the recycled aggregate content increased from 0% to 100%, the compressive strength decreased accordingly. However, the reduction in strength can be either compensated by a decrease in the w/c ratio or with the use of fly ash as an additional cementitious material. They also reported that for example, if a concrete strength of 66 MPa is needed, the concrete could have a water-cement (w/c) ratio of 0.45 without fly ash and a recycled aggregate content of about 6%. Alternatively, the recycled aggregate content could be increased from 6 to 33% by adding fly ash as 25% by weight of cement. If a higher recycled aggregate content is preferred (that is 50%), the water-cement ratio could be reduced from 0.45 to 0.4 but no additional fly ash would be required.

Akinkurolere (2008) reported that at 90 days it appears that replacement with recycled aggregates up to 60% does not have much adverse effect on the compressive strength of recycled aggregate concrete. In addition, at this dose, the rate of increase in strength of recycled aggregate concrete was higher than natural aggregate concrete. This might be due to angular shape and rough texture of recycled aggregates which might have provided better bonding and interlocking between the cement paste and the recycled aggregates themselves compared with those of natural aggregates. Another major reason for this trend might be the absorbent nature of the recycled aggregates which absorbed some of the water during mixing and caused a reduction in the actual water-cement ratio of the recycled aggregate concrete mixes.

b) Tensile strength

BCSJ (1977), Mukai et al. (1978) and Ravindrarajah and Tam (1985) concluded in their works that indirect tensile strength of recycled aggregate concrete made with coarse recycled aggregate and natural sand is not significantly different from that of conventional concrete. However, when both coarse and fine recycled aggregates were used as replacements, the tensile strength of recycled aggregate concretes was up to 20 % lower than that of conventional concrete. Gerardu and Hendriks (1985) reported at most a 10 % lower indirect tensile strength for recycled aggregate concrete made with coarse recycled aggregate and natural sand compared with conventional control concretes made with virgin materials. If the sand is also replaced with crushed concrete fines, the reduction is at most 20%.

Kou et al. (2004) also reported that similar to the results of the compressive strength, the tensile splitting strength decreased with an increase in the recycled aggregate content. The

90-day tensile strength of concrete prepared with 100% recycled aggregates for three different mixes, was 12%, 10% and 9% lower than that of the conventional concrete. Also, when fly ash was incorporated as an additional cementitious material, the splitting tensile strength of the concrete mixtures prepared with 100% recycled aggregates increased by 3%, 6%, and 8%, respectively. The increase in the tensile splitting strength with fly ash could be attributed to the pozzolanic reaction of fly ash and the possible reduction in porosity as a result of the densification effect of the fine fly ash particles.

Akinkurolere (2008) also reported that there is a sharp reduction in rate of tensile strength development. It was noted through the study that at early ages, where there is a higher percentage of recycled aggregates, there was also a higher tensile strength compared to other mixes containing recycled aggregates. Also, for concrete containing high proportions of recycled aggregates the failure of the specimens occurred along the recycled aggregates having been the weakest point.

c) Flexural strength

"The rate of development of strength at early ages was similar to that of the compressive strength, but greatly reduced at later ages" (Akinkurolere, 2008). This increase in strength at early ages and decrease at later ages may be attributed to the rough–textured recycled aggregates. According to Mehta (2006), a "stronger physical bond between the rough-textured aggregate and the cement paste is responsible for the increased tensile strength at early ages. However, at later ages when chemical interaction between the aggregates and the paste begins to take effect, the effects of the surface texture may not be as important".

BCSJ (1977) found that the flexural strength of recycled aggregate concrete is somewhere between 1/5 and 1/8 of its compressive strength, similar to what is the case for conventional concrete, but no experimental data was presented. Meanwhile, Ravindrarajah and Tam (1985) found no significant difference in flexural strength of conventional concrete and recycled aggregate concrete made with coarse recycled aggregate and natural sand. Lastly, Katz (2003) concluded in his work that the ratio of the flexural and the splitting strengths to the compressive strength is in the range of 16–23% and 9–13%, respectively. These values are about 10–15% lower compared to the recommendations of ACI 363R.

d) Young’s modulus

Kemi and Nakagawa (1978), Ravindrerajah (1985), Yamato et al (1988), Mulhedron and O’Mahony (1988), Nishibayashi and Yamura (1988), and Kasai (1985), quoted values of young’s modulus. They noted a reduction of 15 - 40% in the young’s modulus of recycled aggregate concrete, which was attributed to the large amount of weak, old, mortar attached to the aggregate. Kasai (1985), reported a 10 - 20% reduction in young’s modulus for concrete made with coarse recycled aggregate and natural sand. The lower Young’s modulus of recycled aggregate concrete in general is explained by Frondistous-Yonnas (1977). Recycled aggregate normally has a lower modulus than natural aggregate. As the modulus of concrete is dependent on the modulus of the aggregate present, the lower modulus of recycled aggregate concrete is not surprising. (O’Mahony, 1990).

e) Shrinkage and creep

Helmuth and Turk (1967) reported that the drying shrinkage of cement paste increases linearly with its porosity. Therefore, if the porosity of the paste could be reduced, e.g. by decreasing the water/cement ratio, the shrinkage of cement paste will also be reduced. Mulheron (1986), noted an increase in shrinkage of 58%-95% more than control concrete depending on whether crushed concrete or demolition debris was used in the recycled aggregate concrete; demolition debris giving the worst result. Shrinkage of concrete also depends on the Young’s modulus of the aggregate present and it is likely that the low modulus of the mortar on the recycled material would cause an increase in shrinkage.

Mulhedron (1986) found a 40%-100% increase in creep for concrete made using coarse recycled aggregate and natural sand. Ravindrarajah (1985) and Hansen (1985) also observed higher creep than for conventional aggregate concrete. Nishibayashi and Yamura (1988) also found the creep of recycled aggregate concrete made with coarse recycled aggregate and natural sand to be 50% higher than that of conventional aggregate concrete. The presence of aggregate in concrete restrains the volume change of the cement paste and therefore reduces creep. However, if the aggregate in concrete has a low modulus, e.g. recycled aggregate, then its ability to reduce creep is lower.

2.4 Advantages and disadvantages of the use of recycled aggregate in concrete production

In a publication on the blog ‘happoh.com’, titled “Recycled Aggregate Concrete: Applications, Advantages & Disadvantages in Construction”, the Advantages and disadvantages of the use of recycled aggregate in concrete are given thus:

Advantages of use of recycled aggregate in concrete production:

The following are the advantages of using recycled aggregate in concrete production

i. “Using recycled aggregate in concrete production reduces the amount of virgin aggregates to be created, hence less evacuation of natural resources”.

ii. “While being crushed into smaller particles a large amount of carbon dioxide is absorbed. This reduces the amount of CO_2 is the atmosphere”.

iii. “Cost saving – there is a significant reduction in construction costs if RAC is used”.

iv. “Conserves landfill space, reduces the need for new landfills and hence saving more costs”

v. “Creates more employment opportunities in the recycling industry”.

Disadvantages of use of recycled aggregate in concrete production

The disadvantages of using recycled aggregate in concrete production include:

i. “The quality of concrete is relatively reduced”.

ii. “There is increase in water absorption capacity ranging from 3% to 9%”

iii. “There is a decrease in compressive strength of concrete (10-30%)”

iv. “Using recycled aggregate will reduces workability of concrete”.

v. “There is no specifications and guidelines on mix designs for RAC”.

vi. “Less durability of RAC, however few papers have shown an improvement in the durability by mixing it with special materials like fly ash”.

2.5 Mixture experiment

“A mixture is the end product substance or material obtained by mixing or combining or blending two or more ingredients or components in varying proportions. The quality characteristics of the end product are recorded for each blend to see if the quality changes or varies from one blend to the next. Usually, mixtures are made to obtain products with some predetermined properties; these properties are the responses from a systematic combination of the mixture components. In order to obtain such predetermined properties or responses from a particular mixture, then there must be a systematic preparation and combination of the components that make up the mixture. **Mixture experiment** therefore is an experiment in which an experimenter varies the proportion of two or more ingredients of a mixture to obtain different blends of the mixtures and then studies the effects of the variation of the ingredients with a view of obtaining the best component settings or a better performance for one or more response properties of the mixture" (Cornell, 2011). "The characterizing feature of mixture experiments is that the values taken by the mixture components represent proportionate amounts in the mixture rather than unconstrained amounts. Thus, the property under investigation depends on the proportions of the mixture components, but not on the amount of the mixture. Hence, the component proportions may not change independently of each other" (Brown, 2014). Some examples of mixture experiments include:

1. "Recording flavor, color, and overall acceptance of a fruit punch blended from watermelon, pineapple, and orange juices".
2. "Measuring the efficacy and durability of a pesticide formed by mixing several chemicals".
3. "Improving brightness and durability of railroad flares, which are the products of blending proportions of magnesium, sodium nitrate, strontium nitrate, and binder" (Cornell, 2011).

2.5.1 Design of mixture experiments

"Mixture experiment design or mixture design is an aspect of the response surface methodology in which the mixture under investigation is made up of several components. Response surface methodology (RSM) consists of a set of statistical methods that can be used to develop improve, or optimize products" (Simon, 1996). "Mixture designs are useful because many product designs and development activities in industrial situations involve formulation of mixtures. In these situations, the response is a function of the proportions of the different ingredients in the mixture" (Minitab support, 2018). This relationship between the response and the mixture ingredients or components can be represented in mathematical terms as a model, which could be developed by some rigorous statistical methods; this process is known as modeling.

A typical example of mixture experiment is in concrete production. Concrete is a mixture of several components of which the basic ones are water, Portland cement, fine and coarse aggregates. Various chemical and mineral admixtures, as well as other materials such as fibers, also may be added. “From mixture experiment approach, for a given set of concrete materials, the proportions of the components directly influence both fresh and hardened properties of the concrete mixture” (Simon, 1996).

“Statistical mixture methodology is a type of response surface experiment in which the variables are the components of a mixture and the responses are a function of the proportion of the mixture”. Simon et al. (1997) used the statistical mixture method for optimizing concrete mixture proportions in high performance concrete. Muthukumar et al. (2004) and Barbuta et al. (2008) also used this approach to optimize polymer concrete mixtures. Akalin et al. (2010) conducted a series of experiments in which a statistical mixture design approach was used to optimize an eight-component self-consolidating high strength concrete mixture subject to several performance constraints.

Practical mixture design involves complex statistical methods and is therefore tedious to undertake manually, it is better done using a computer program.

“Basically, a certain number of experimental runs are usually planned for. The minimum number of experimental runs is usually estimated based on the number of components to be used in the mixture, then, upper and lower bounds of the components of the mixture are set based on experience or review of previous experiments on that particular type of mixture. With these upper and lower bounds of component proportions, a computer program can be used to generate the number of design points at which experiments could be conducted; these are the possible experimental runs. Once the total number of design points is generated, it is left for the mixture experimenter to decide whether to use all of the design points or select a sub-set of the total design points to run experiments. It is usually necessary to select a sub-set of the total design points at which experiments would be conducted because the initial design could contain very many design points and it may not be feasible to conduct experiments at all the design points given the ever present economic and time constraints. The minimum number of experimental runs always serves as the basis for selecting the number of sub-set experimental runs. For simple illustration and clear understanding, mixture experiment designs are usually hypothetically described and studied using the simplex”.

2.5.1.1. Processes involved in mixture experiment modeling

Modeling means to develop or postulate and equation that relates the response(s) to the mixture component to represent the response surface. These postulated equations are the **models,** and they can be used to predict the responses at certain values of mixture components.

“The first step in developing a mixture experiment model is to select a model on which the modeling shall be based. It is common to model a mixture experiment on the linear or quadratic Scheff´e mixture model. The next step is to choose a design at whose points we may collect observations to which the equation can be fitted (or, the coefficients in the regression equation can be estimated). The basic types of designs available for use are the simplex-lattice and simplex centroid designs, as introduced by Scheff´e. There is also the extreme vertices design which arises as a result of setting constraints on mixture components. The choice of a design basically depends on the type of mixture and the number of components in the mixture. Finally, the adequacy of the model is tested. This final step is to ensure that our fitted equation is a prediction tool with which we can feel comfortable” (Cornell, 2011).

2.5.1.2 Model formulation (Scheffé’s method)

“Scheffé (1958), proposed a comprehensive methodology for the treatment of mixture experiment problems. This methodology is based on the formulation of a functional relationship between the investigated properties of the mixture and the mixture components. This relationship is presented in the form of a statistical model”.

As mentioned earlier, Scheffé’s method was developed for the analysis of mixture experiments, therefore, since concrete is a mixture of different components, the method can find adequate application in concrete production.

In mixture experiments the response of interest y is dependent on the proportions of the q mixture components x_i, $i = 1 \ldots q$, such that:

$$\sum_{i=1}^{q} x_i = 1, x_i \geq 0 \tag{2.1}$$

by reparameterization of standard polynomials of degree m, for q components by using equation 2.

A standard polynomial is given by:

$$y = \beta_0^* + \beta_1^* \beta_1^* x_1 + \beta_2^* \beta_2^* x_2 + \ldots + \beta_q^* \beta_q^* x_q + \varepsilon \tag{2.2}$$

Where

$\beta_i^* \beta_i^*$ are constant terms

x_i are the independent variables or mixture components (in mixture experiments), and

ε is the random error term.

From equation 2.1, $x_1 + x_2 + x_3 \ldots x_q = 1$

By replacing $\beta_0^* \beta_0^*$ with $\beta_0^* \beta_0^*(x_1 + x_2 + x_3 \ldots x_q)$, Equation 2.2 can be rewritten to obtain equation 2.3

$$y = \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_q x_q + \varepsilon \tag{2.3}$$

Equation (2.4) is known as the Scheffés linear mixture polynomial or first degree polynomial and can be written in the form:

$$E\{y\} = \sum_{i=1}^{q} \beta_i x_i \qquad (2.4)$$

Similarly, the quadratic polynomial or second degree polynomial can be written as:

$$E\{y\} = \sum_{i=1}^{q} \beta_i x_i + \sum_{i<j}^{q} \beta_{ij} x_i x_j \qquad (2.5)$$

Where,

$x_i x_j$ are interaction terms.

Equation (2.5) is called the Scheffé quadratic mixture polynomial. There are other higher degree polynomials like the special cubic, full cubic etc, which can also be obtained in similar manner. Low-degree polynomial equations are more conveniently handled than higher degree equations because the lower degree polynomials contain a fewer number of terms and therefore require fewer observed response values in order to estimate the parameters (the β's) in the equation. "On occasions when a very complicated system is being studied, experimenters may feel the need to use a third-degree equation or some special form of a cubic or third-degree equation (especially when even a transformation of the data values does not simplify the system). Most of the time; mixture experimenters would always try to be successful making use of at most the second degree or quadratic polynomial" (Cornell, 2011).

2.5.1.3 The Simplex

"A simplex is a hypothetical illustration of the design space of a mixture experiment" (Minitab support, 2017). "The blending of mixture components is assumed to take place within this space such that each point within the space is considered a distinct blend from another point. In its simplest form, it is a regular triangle (L-simplex). There are basically two types of simplex designs in mixture experiment, the simplex lattice and simplex centroid designs. These two design space take up the form of a regular triangle i.e. the L-simplex. In the L-simplex, each component may take up any value between 0 and 1, indicating that a component may be present at its maximum setting, 1, or may not be present at all, 0, in the mixture. But if in a mixture, it is necessary to include all the components that make up the mixture, then, upper and lower bounds must be set on all or some of the components". "The presence of upper and lower bounds constrains the design space of the experiment into a sub-portion of the simplex. In this case, the design space is no longer an L-simplex, but an extreme vertices design" (Cornell, 2011). The extreme vertices design is the ideal mixture design in mixture experiment that involves concrete production, because all the ingredients that make up concrete must be present in adequate proportion. The blending of mixture component is usually represented by a triangular coordinate system.

2.5.1.2 Triangular coordinate system

"Triangular coordinate systems allow you to visualize the relationships between the components in a three-component mixture. In a mixture, the components are restricted by one another in that the components must add up to the total amount or whole. If the components of a three-component mixture are x_1, x_2, and x_3, then, the triangular coordinate systems in this section show the minimum of the x_1, x_2, and x_3 components as 0, with the maximums at 1.

The illustrations in figs.2.4a – 2.4f show the general layout of a triangular coordinate system. The components in mixture experiments are referred to in terms of their proportion to the whole, with the whole as 1. The vertices of the triangle represent pure mixtures (also called single-component blends). In pure mixtures, the proportion of one component is 1 and the rest are 0. Figure 2.4a indicates points at the vertices of the triangle, indicating pure mixtures only, Figures 2.4b – 2.4d indicate points along the edges of the triangle representing blends where one of the components is absent, and Figures 2.4e and 2.4f illustrate the different points on the triangular coordinate system”. (Minitab support, 2017).

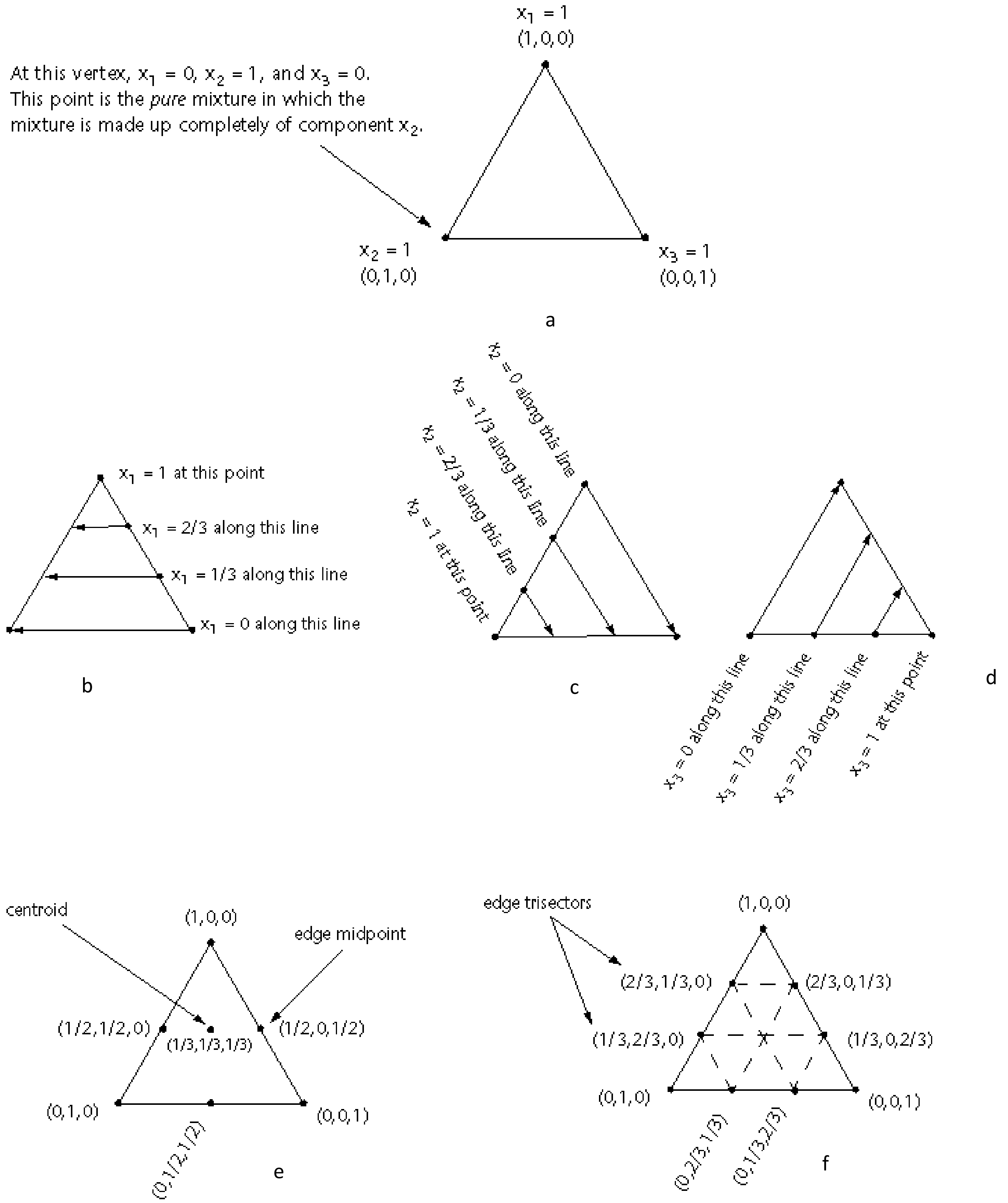


Figure 2.4 Triangular coordinate system

Each location on the triangles in Figure 2.4b – Figure 2.4f represents a different blend of the mixture. For example,

1. i. “edge midpoints are two-blend mixtures in which one component makes up 1/2 and a second component makes up 1/2 of the mixture”.
2. ii. “edge trisectors are two-blend mixtures in which one component makes up 1/3 and another component makes up 2/3 of the mixture. These points divide the triangle edge into 3 equal parts”.
3. iii. “the center point (or centroid) is the complete mixture in which all components are present in equal proportions (1/3, 1/3, 1/3). Complete mixtures are on the interior of the design space and are mixtures in which all of the components are simultaneously present” (Minitab support, 2018)

“As a simple (hypothetical) example of a mixture experiment, consider concrete as a mixture of three components: water (x_1), cement (x_2), and aggregate (x_3), where each x_i represents the volume fraction of a component. Assume the coarse-to-fine aggregate ratio is held constant. The volume fractions of the components sum to one, and the region defined by this constraint is the regular triangle (or simplex) shown in Figure 2.5. The axis for each component x_i extends from the vertex it labels ($x_i = 1$) to the midpoint of the opposite side of the triangle ($x_i = 0$). The vertex represents the pure component. For example, the vertex labeled x_1 is the pure water mixture with $x_1 = 1$, $x_2 = 0$, and $x_3 = 0$, or (1, 0, 0). The midpoint the edges indicate blends which contain two components in equal proportion. The point where the three axes intersect, with coordinates (1/3, 1/3, 1/3), is called the centroid, it indicates a blend which contain each of the three components in equal proportion” (Simon, 1996).

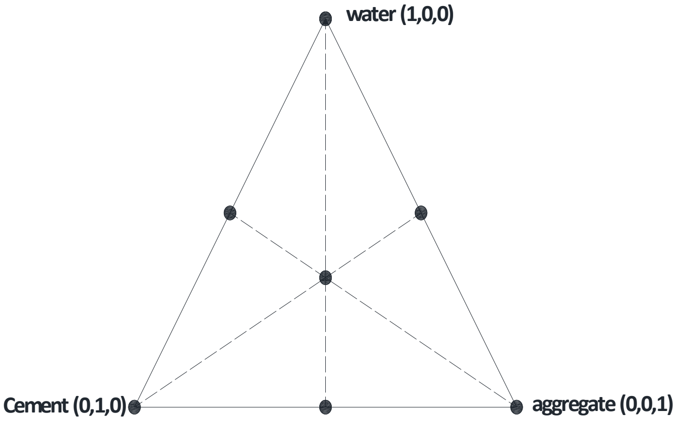


Figure 2.5 Simplex region for three-component mixture experiment

Figure 2.5 serves only as an illustration, since much of this region would not represent either feasible or workable concrete mixtures.

2.5.1.3 Simplex centroid and simplex lattice

“These designs both have their design points arranged in a uniform (lattice) manner over an L-simplex. An L-simplex is similar to and has sides parallel to the triangle shown in Fig. 2.4(a). In addition to the lattice arrangement of a simplex lattice design, the simplex centroid design incorporates centre points into the simplex, this allows for a broader coverage of the design space. Fig. 2.4(a) illustrates a simplex lattice design, while Fig. 2.4(e) illustrates a simplex centroid design. If the design points are not arranged over an L-simplex, but take up only a sub-portion of the L-simplex, then the design is an extreme vertices design”. (Minitab support, 2017).

2.5.1.4. Overview of extreme vertices design

“These are mixture designs that cover only a sub-portion or smaller space within the simplex. These designs must be used when your chosen design space is not an L-simplex. The presence of both lower and upper bound constraints on the components often create this condition. In some designs, feasible or workable mixtures do not exist over the entire region of a simplex; hence, the design space has to be restricted to the region where feasible mixtures are likely to exist” (Simon, 1996). For example, if it is needed to determine the proportions of flour, milk, baking powder, eggs, and oil in a pancake mix that would produce an optimal product based on taste. Because previous experimentation suggests that a mix that does not contain all of the ingredients, or has too much baking powder will not meet the taste requirements, then the design shall be constrained by setting lower bounds and upper bounds. The goal of an extreme vertices design is to choose design points that adequately cover the design space. The illustration in Figure 2.6 shows the extreme vertices for two three-component designs with both upper and lower constraints:

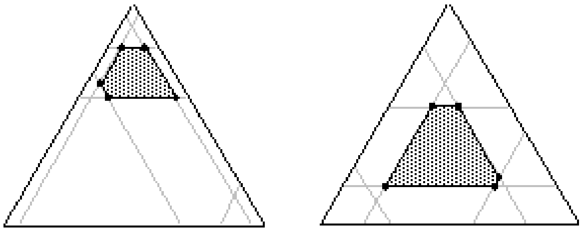


Figure 2.6 Extreme vertices for two three-component designs with both upper and lower constraints (Minitab support, 2017).

Another example of a possible sub-region for three-component mixture experiment is shown in Figure 2.7. It is an experiment to produce a conventional concrete. The experiment is defined by the following volume fraction constraints for the mixture components:

$$0.15 \leq x_1 \leq 0.25$$

$$0.10 \leq x_2 \leq 0.20$$

$$0.60 \leq x_3 \leq 0.70$$

(Where x_1 = water, x_2 = cement, x_3 = aggregate)

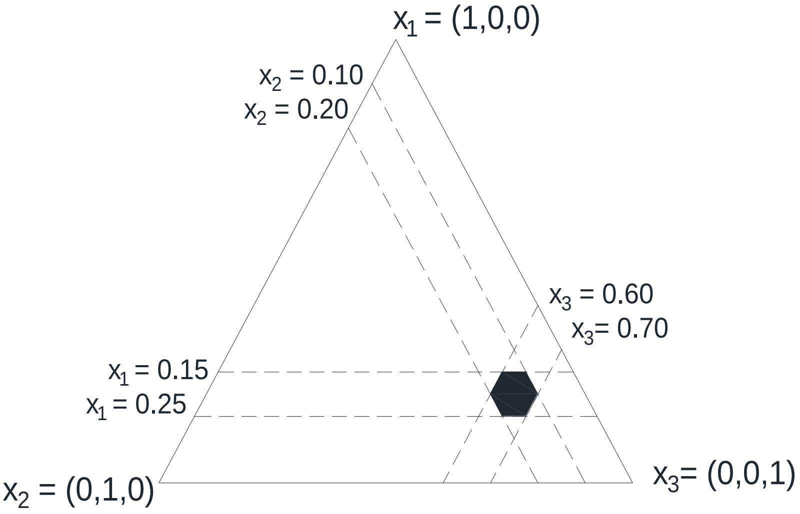


Figure 2.7 Sub-region for a three- component constrained design (Simon 1996).

In Figure 2.6, the light gray lines represent the lower and upper bound constraints on the components. The dark gray area represents the design space. While in Figure 2.7, the broken lines represent lower and upper bound constraints on the components and the dark region represent the design space. The points are placed at the extreme vertices of design space. This type of design is suitable for a mixture experiment involving concrete production, because it is not possible to get a workable concrete mixture over the entire region of the simplex

2.5.1.5 Minimum number of experimental runs in a mixture experiment

"The polynomial selected to represent the response surface of a mixture experiment could be of high or low degree. However, as stated earlier, mixture experimenters would try to be successful with at most the second-degree model, because lower degree polynomials contain a fewer number of terms and therefore require fewer observed response values in order to estimate the constant parameters. Hence, when considering the degree of polynomial to use, the minimum number of experimental runs convenient to undertake should also be put into consideration". Cornell, (2011) stated that the number of terms in the *{q, m}* polynomials is a function of *m*, the degree of the equation, as well as the number of components *q* in the mixture. For a *{q, 1}* polynomial, i.e. first degree polynomial, the number of terms in the polynomial is *q*, for a *{q, 2}* polynomial, i.e. second degree polynomial, the number of terms in the polynomial shall be obtained from Equation 2.6. (Cornell and Harrison, 1997).

$$N_E = q + \frac{q!}{2!(q-2)!} \tag{2.6}$$

Where, N_E = minimum number of experimental runs

q = number of components

There are as many constant terms to be estimated in a *{q, m}* polynomial as there are number of terms in the polynomial of a mixture experiment (Scheffe, 1956) thus, in order to estimate these constant terms, there must be at least as many experimental runs as there are number of constants terms. For example, for a second degree or quadratic polynomial, with seven mixture components, i.e. a *{7, 2}* polynomial, the number of terms in the polynomial and by implication, the minimum number of experimental runs from Equation 2.6 would be:

$$N_E = 7 + \frac{7!}{2!(7-2)!} = 7 + 21 = 28$$

2.5.2 Analysis of mixture experiment

The analysis of mixture experiment is done using least squares technique and analysis of variance (ANOVA). These involve complex statistical methods; therefore, the analysis of mixture experiment is best done using a computer program, especially for mixture components more than three. The analysis of mixture experiments usually culminates in developing a model that can be used to study the effects of each component on the mixture and/or predict new values of responses.

2.5.2.1 Least squares method

The least square method seeks to minimize the sum of squared error terms in regression analysis. If this is achieved, then much credence can be given to the fitted regression line. A model that is fitted by the least squares method has to comply with the least squares model assumptions in order to be deemed valid.

The least squares model assumptions for multiple linear regressions are as follows:

i. "The mean of the response, E(Y), at each set of values of the predictors, (x_1, x_2,…), is a **Linear function** of the predictors".

ii. "The errors, ε, are **Independent"**.

iii. "The errors, ε, at each set of values of the predictors, (x_1, x_2,…), are **Normally distributed"**.

iv. "The errors, ε, at each set of values of the predictors, (x_1, x_2,…), have **Equal variances"** (denoted σ^2).

As can be observed, these assumptions evolve mostly around the error terms. "The residuals i.e. the difference between the observed values and fitted values ($e_i = y_i - \hat{y}_i$), are the best estimates of error", therefore, the assumptions can be checked by assessing residual plots (Pardoe et al, 2019).

2.5.2.2 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) consists of calculations that provide information about levels of variability within a regression model and form a basis for test of significance.

The significance test in regression analysis is a method of determining what terms to retain or remove from the final model.

Usually, in a regression model such as for mixture experiments, not all the terms in the model are relevant, hence, it is necessary to identify a model that is most appropriate and fits the data well. This is done by reducing the model until only significant terms are left in the model (Pardoe et al, 2019).

2.5.2.3 Model reduction and model identification

According to Pardoe et al, (2019), Usually not all the terms in a mixture experiment model is significant to be included in the model. Therefore, an appropriate model where only significant terms are present should be identified. "Even though the experiment design used permits the estimation of quadratic models, sometimes, linear models only may provide a better fit". Model identification can be achieved by doing a model reduction. To reduce the model in order to obtain a model with only significant terms, ANOVA is used to perform a sequential F-test. The F-test or F-statistics is used to carry out a hypothesis test on the coefficients of the model terms.

"The null hypothesis "H_0" is that the coefficient of a model term is equal to zero ($H_0 = \beta_i = 0$) and should be removed from the model. The alternate hypothesis "H_A" is that the coefficient of the model term is not equal to zero ($H_A = \beta_i \neq 0$) and can be included in the model.

In multiple linear regression, the sources of variability in the model could be the linear, quadratic or higher order terms present in the model, therefore, The F-statistic is calculated for each type of model, and the highest order model with significant terms normally would be chosen. Significance is judged by determining if the probability that the F-statistic calculated from the data exceeds a theoretical value. The probability (p-value) decreases as the value of the F-statistic increases. If this probability is less than 0.05 (typically, although other levels of significance could be used), the terms are significant and their inclusion improves the model, otherwise, they are removed from the model. Hence, for a p-value less than 0.05 (used in this research) the null hypothesis should be rejected for the alternate hypothesis. The value 0.05 is the significance level; it denotes the probability of rejecting the null hypothesis. It is usually denoted as α-alpha" (Minitab StatGuide, 2017).

"A lack-of-fit test is also carried out in ANOVA. It is calculated from the pure error in the experiment which arises from having duplicate experimental runs. The lack-of-fit-test assesses the fit of the model. If the p-value is less than the selected α-level, evidence exists that the model does not accurately fit the data. It may be necessary to change the model or effect data transformation to more accurately model the data" (Pardoe et al, 2019).

Other summary statistics which could also be used to assess the goodness of models in ANOVA include: R-squared (R^2), Adjusted R-squared, Predicted R^2, and Prediction sum of squares (PRESS).

R-squared (R^2): "This is called the coefficient of determination for the model. It represents the proportion of variation in the response data that is explained by the predictors in the model. It is calculated as the ratio of the sums of squares for regression over the total sums of squares. It describes how close the fitted values are to the predicted values".

R^2 (Predicted): "This indicates how well the model predicts responses for new observations".

R^2 (Adjusted): "This is a modified R^2 that has been adjusted for the number of terms in the model. If unnecessary terms are included in the model, R^2 can be artificially high. Unlike R^2, adjusted R^2 may get smaller when you add terms to the model".

Prediction error sum of squares (PRESS): "This assesses the model's predictive ability. In general, the smaller the prediction sum of squares (PRESS) value, the better the model's predictive ability. PRESS is used to calculate the predicted R^2". (Minitab StatGuide, 2017)

"These model summary statistics can give information about the accuracy of the chosen model, but it is better to assess the accuracy of the model by assessing residual plots" (Minitab StatGuid, 2017).

2.5.2.5 Assessing model assumptions (model validation)

In addition to model summary statistics including lack of fit, residual plots which assess model assumptions are also used to assess and validate models, and are probably the most reliable way of model validation. The processes involved in using residual plots, according to Pardoe et al, (2019). are as follows:

a) "create a scatterplot with the residuals, "e", on the vertical axis and the fitted values, ŷ, on the horizontal axis and visual assess whether:

1. the (vertical) average of the residuals remains close to 0 as we scan the plot from left to right (this affirms the linearity condition);
2. the (vertical) spread of the residuals remains approximately constant as we scan the plot from left to right (this affirms the equal variance condition);
3. there are no excessively outlying points"

b) "if the data observations were collected over time (or space) create a scatter plot with the residuals, "e", on the vertical axis and the time (or space) sequence on the horizontal axis and visual assess whether there is no systematic non-random pattern" (this affirms the independent errors condition).

c) create a histogram, and/or normal probability plot of the residuals, "e" to check for approximate normality (the normality condition). (Of these plots, the normal probability plot is generally the most effective).

On assessment of the model as enumerated above, if any of the conditions is determined to be substantially violated, then there would be a need for a transformation of either the response or predictor variables to some other model functions. The log function, the square root, and the power function are some functions into which these variables can be transformed. Good enough, the data obtained and used in analysis in this research did not need any such transformations (Pardoe et al, 2019).

2.5.3 Effects of mixture components on the predicted responses

"The effect of component "i" on the response is the change in the value of the response resulting from a change in the proportion of component "i" while holding constant the relative proportions of the other components" (Cornell, 2011).

"The effect of mixture components on the mixture can be studied using the contour plots and the response trace plots. Contour plots are used to identify conditions that give maximum (or minimum) response. Because contour plots can only show three components at a time (the others components are set at fixed conditions), several plots must be examined when there are more than three components" (Simon, 1996).

Response trace plots (also called a component effects plot) show how each component affects the response relative to a reference blend (usually the centroid of the simplex for an unconstrained design or the cenroid of the constrained space for a constrained design). If the design contains process or amount variables they must be held at a fixed level. "When changing the proportion of a component in a mixture to determine its effect on a response, you must make offsetting changes in the other mixture components because the sum of the proportions must always be one. The changes in the component whose effect you are evaluating along with the offsetting changes in the other components can be thought of as a direction through the experimental region. There are two commonly used trace directions along which the estimated responses are calculated: Cox's direction and Piepel's direction. When the design is not constrained and the reference point lies at the centroid of the unconstrained experimental region, both Cox's directions and Piepel's directions are the axes of the simplex.

“When the design is constrained, the default reference mixture point lies at the centroid of the constrained experimental region that is different from the centroid of the unconstrained experimental region. In this case, Cox's direction is defined in the original design space, whereas, Piepel's direction is defined in the L-pseudocomponent space” (Minitab help, 2017).

“Trace plots have been widely used in mixture design method to assess the effects of mixture components on the measured responses” (Myers and Montgomery, 2008). In general, a trace plot can be drawn in the Cox direction as introduced by Cox (1971), which is an imaginary line projected from the reference mixture (usually centroid) to the vertex x_i=1 Smith, (2005). It reveals how the response changes with the variation of each component from its low to high setting in the design region, while keeping all others in the same relative ratio at a specified reference mixture, usually the centroid (Ley and Hussein, 2013).

The following points are kept in mind while interpreting the response trace plot:

i. “All components are interpreted relative to the reference blend”.

ii. “Components with the greatest effect on the response will have the steepest response traces”.

iii. “Components with larger ranges (upper bound - lower bound) will have longer response traces; components with smaller ranges will have shorter response traces”.

iv. “The total effect of a component depends on both the range of the component and the steepness of its response trace. The total effect is defined as the difference in the response between the effect direction point at which the component is at its upper bound and the effect direction point at which the component is at its lower bound”.

v. “Components with approximately horizontal response traces, with respect to the reference blend, have virtually no effect on the response”.

vi. “Components with similar response traces will have similar effects on the response”. (Minitab StatGuide, 2017)

However, Cornell, (2011) stated that When the mixture component proportions are restricted by lower and upper bounds of the form $0 \leq Li \leq xi \leq Ui \leq 1$, the ranges $Ri = Ui - Li$, $i = 1, 2, . . . , q$, are seldom equal or even close to being equal to each other (as is the case in this work), we cannot be assured of reliable estimates of the effects of the individual components. Furthermore, he stated that more often than not, the centroid of the constrained region is different from the centroid of the simplex, so the directions dictated by the component axes may not be the best directions for measuring the component effects.

2.5.4 Response optimization

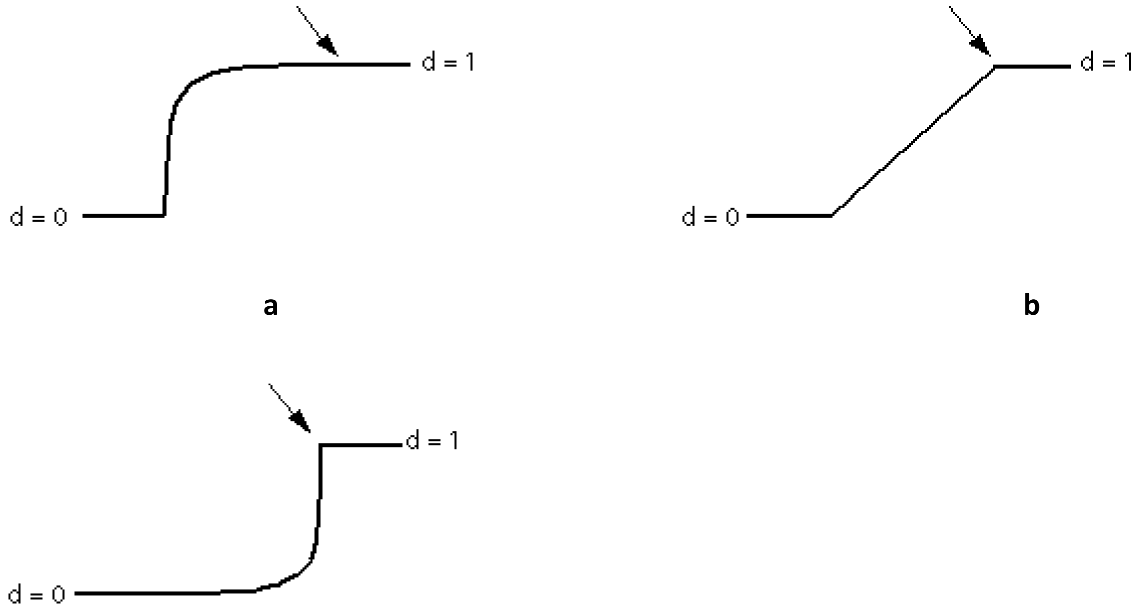
“Once an appropriate model is established for a mixture experiment, it is possible to find a setting for input variables that can jointly optimize any response obtained from the model” (Cornell, 2011). It is also possible to obtain a setting for input variable that can jointly optimize a combination of two or more responses. Optimization involves: obtaining concrete mixes with fresh and harden properties meeting some predetermined specifications at the most considerate cost. It could involve getting a mix that will maximize strength or minimize chloride penetration.

Optimization may be performed using mathematical (numerical) approach.

“Mathematical or numerical optimization involves defining an objective function (called desirability or score function) that reflects the levels of each response in terms of minimum (zero) to maximum (one) desirability. For a set target, the desirability of the response is zero below the set target and one at the set target and above. It is an approach that is useful in optimizing multiple responses” (Simon, 1996). “An approach to optimization involves transforming each of the response values using a specific desirability function. The individual and composite desirability are used to assess how well a combination of input variables satisfies the goals that have been defined for the responses. Individual desirability (d) evaluates how the settings optimize a single response; composite desirability (D) evaluates how the settings optimize a set of responses overall. Desirability has a range of zero to one. One represents the ideal case; zero indicates that one or more responses are outside their acceptable limits. The weight defines the shape of the desirability function for each response. For each response, a weight (from 0.1 to 10) can be selected to emphasize or de-emphasize the target”. A weight

i. “less than one (minimum is 0.1) places less emphasis on the target”
ii. “equal to one places equal importance on the target and the bounds”
iii. “greater than one (maximum is 10) places more emphasis on the target”

Figures 2.8a – 2.8c illustrate the different weight changes and Figures 2.8d – 2.8f illustrate how the desirability functions change with different response goals (i.e. minimize, target, or maximize) (Minitab StatGuide, 2017).



a

b

c

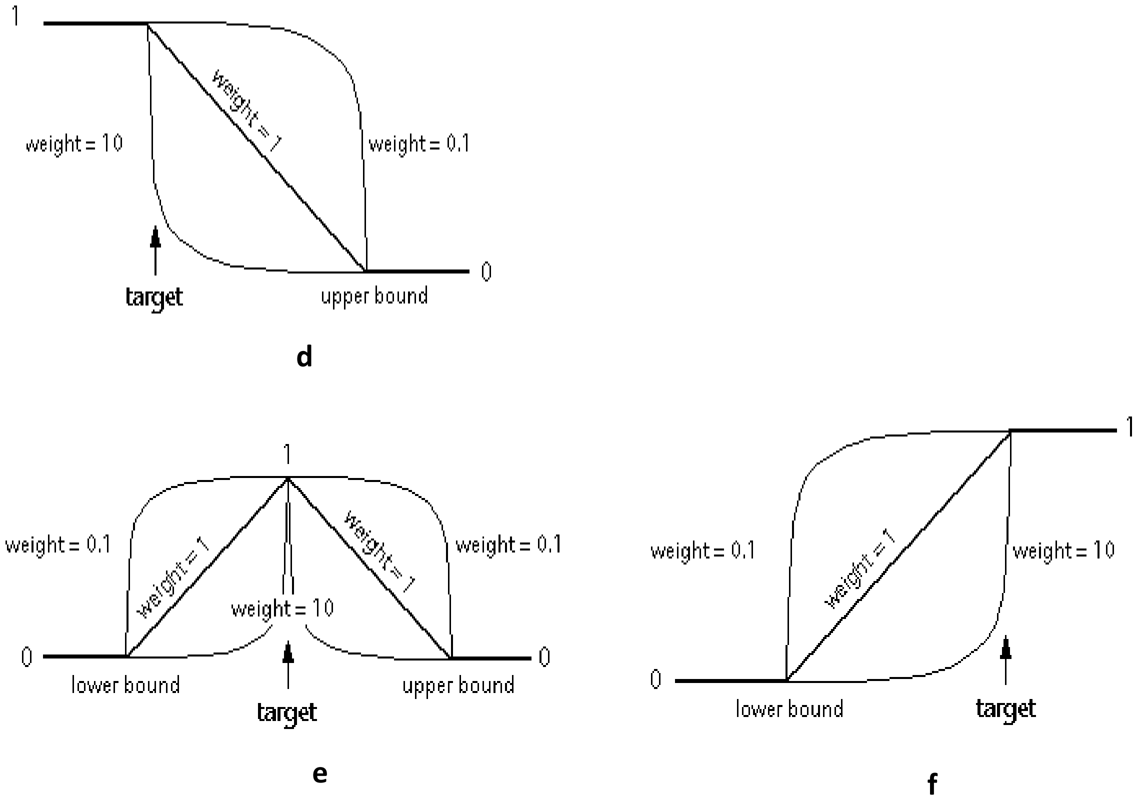
Figures. 2.8 (a-c) desirability functions for different goals

A weight less than one (minimum is 0.1) places less emphasis on the target. A response value far from the target may have a high desirability, Figure 2.8a.

A weight equal to one; places equal emphasis on the target and the bounds. The desirability for a response increases linearly, Figure 2.8b.

A weight greater than one (maximum is 10) places more emphasis on the target. A response value must be very close to the target to have a high desirability, Figure 2.8c.

The illustrations below summarize the desirability functions:



Figures 2.8 (d-f) weights of different desirability functions

i. When the goal is to minimize the response

Below the target the response desirability is one; above the upper bound it is zero, Figure 2.8d.

ii. When the goal is to target the response,

Below the lower bound the response desirability is zero; at the target it is one; above the upper bound it is zero, Figure 2.8e.

iii. When the goal is to maximize the response,

Below the lower bound the response desirability is zero; above the target it is one, Figure 2.8f (Minitab support, 2017).

2.6 Computer program in mixture experiment design and analysis

As stated earlier, mixture experiment design and analysis are best performed using a computer program. This is because of the complex nature of the statistical methods and techniques involved in this design and analysis. In this work, Minitab 17 was chosen as a suitable computer program for the design and analysis of mixture experiment. Minitab is capable of handling the design and analysis as well as the modeling and optimization of mixture experiments. In addition to these utility options, Minitab could also generate plots on mixture experiments, which are used to further assess the models developed from the analysis of mixture experiments, in order to establish their validity. Minitab statistical software comes with a user friendly interface which is easy to use and manipulate to obtain results with high degree accuracy. On Minitab worksheet window, data from “created mixture experiment” design and observed data from experiments are stored for analysis. On Minitab session window, results from all statistical analysis are displayed. The mixture experiment menu is found in the stat menu on the toolbar, under design of experiments (DOE). In the mixture experiment menu, Minitab offers several functions for mixture experiments, including:

“Create Mixture Design”: used to generate settings for simplex centroid, simplex lattice, and extreme vertices designs.

“Define Custom Mixture” Design: used to create a mixture design from data that is already in the worksheet.

“Select Optimal Design”: used to select a subset of design points, augment a design, or evaluate a design.

“Simplex Design Plot”: used to draw a simplex design plot.

“Analyze Mixture Design”: used to fit data from any Scheffe mixture design.

“Contour/Surface Plots”: used to draw a contour plot and a three-dimensional response surface plot.

"Response Trace Plot": used to draw a response trace plot.

"Response Optimizer": used to calculate a numerical optimal solution and draws an interactive plot to help identify the combination of factor settings that jointly optimize a set of responses. Overlaid Contour Plot: used to draw a contour plot for multiple responses (Minitab StatGuide, 2017).

Mixture experiments design and analysis is just one of several statistical functions that Minitab is capable of handling. Minitab 17 belongs to Minitab, Inc and has the registered trademark Minitab®.

2.7 Summary of review

From the literatures reviewed, it may be concluded that there are instances where recycled aggregates have successfully been applied in the production of conventional concrete, however, there have been no research on the application of recycled aggregates in the production of high-performance concrete. Therefore, this research seeks to breach this gap and provide prescriptions on how recycled aggregate could be applied in the production of high-performance concrete by developing models for producing optimized mixes of high performance concrete made with recycled aggregate.

CHAPTER THREE

MATERIALS AND METHODS

3.1: Materials

The materials used in this work are: Water, cement, silica fume, high range water reducing admixture (HRWRA) or superplasticizer, natural coarse aggregate, recycled coarse aggregate, and fine aggregate.

Water

Potable water obtained from the strength of materials laboratory at the Cross River State University of Technology, was used for all concrete works including curing.

Cement

UNICEM brand of ordinary Portland cement (Type II) obtained from a local supplier was used for all concrete casting.

Silica fume

Silica fume in powdered form; was obtained from a local supplier of assorted concreting materials, having a specific gravity of 2.2.

High range water reducing admixture (HRWRA)

The high range water reducing admixture (superplasticizer) used for this work is called Conplast SP430. Conplast SP430 is a chloride free, superplasticising admixture based on selected sulphonated napthalene polymers. It is supplied as a brown solution which instantly disperses in water. More information on this chemical is given in appendix B.

Natural coarse aggregate

The natural aggregate used in this work is granite of intrusive igneous rock origin, with a maximum particle size of 20mm.

Recycled coarse aggregate

The recycled coarse aggregate was obtained from a demolished concrete structure site in Calabar metropolis. It was free from impurities and dust, and was manually crushed to approximate maximum particle sizes in the range of 20mm – 25mm.

Fine aggregate

The fine aggregate is river sand obtained from the Cross River, through local suppliers.

Preliminary tests were conducted on the aggregates used in this work as shown in section 3.2.1, with reference to appropriate standards, to determine their suitability for the work.

3.2 Methods

The materials used in this work were first characterized in accordance with relevant standards, to determine their physical and mechanical properties and ascertain their usefulness for the work. The characterization of materials is also herein referred to as preliminary tests. The mixture experiment method, an aspect of the response surface methodology was utilized for experiment design and analysis. The extreme vertices design was specifically used to design mixture experiments, and ANOVA and least square techniques were employed in the analysis of mixture experiment. All processes in mixture experiment design and analysis were done using MINITAB.

3.2.1 Characterization of materials (preliminary tests)

The following preliminary tests were carried out on samples to determine their physical properties and suitability for the proposed study: sieve analysis on fine and coarse aggregates, specific gravity test (on cement, silica fume, fine, natural, and coarse aggregates), moisture absorption test (on natural and recycled coarse aggregates), aggregate crushing test, and aggregate impact test (on natural and recycled coarse aggregates).

a) **Sieve analysis:** Sieve analysis was performed on natural coarse aggregate and the recycled coarse aggregate as well as the fine aggregate in accordance with BS 1377: Part 2: (1990) to determine the particle size distribution or grading of the aggregates and compare them to appropriate standards for structural concrete production.

Sieve analysis test according to BS 1377: Part 2: 1990

Apparatus:

i. BS standard sieves- 37.5, 25.0, 13.2, 9.5, 6.3, 4.75 (mm), for coarse aggregates, 3.35, 2.36, 1.18 (mm), 600, 425, 300, 212, 150, 75 (µm), for fine aggregate.
ii. A balance readable and accurate to 0.5g
iii. A balance readable and accurate to 0.01g
iv. Sample dividers
v. Oven
vi. Evaporating dishes- 6no, 150µm diameter
vii. 6 metal trays
viii. A scoop
ix. Mechanical sieve shaker.

Procedure:

i. The sub sample to be classified was oven-dried to obtain a constant dry mass, and weigh to 0.1% of the total mass (m_1).
ii. The maximum size test sieve corresponding to the maximum size of material present was fitted and arranged in a descending order till the collector.

iii. The set of sieves with the material in the first sieve was covered and placed on the mechanical shaker and the sieve shaker allowed vibrating for 15 to 20 min.

iv. After which the mass retained on each sieve and collector was weighed and recorded (m_2).

If any of the test sieves became overloaded, the material was sieved in parts and the mass retained recorded.

Calculations:

i. The percentage retained on each sieve was calculated thus:

$$\% \text{ retained} = \frac{m_2}{m_1} \times 100\%. \qquad (3.1)$$

ii. The cumulative percentages retained on each sieve was also calculated and reported.

iii. Percentage passing each sieve shall be calculated:

% passing = 100 – (cumu. % retained)

A gradation curve of percentage passing against sieve sizes shall be plotted on the standard BS graph for sieve analysis.

b) Specific gravity: The specific gravity of all aggregates was determined in accordance with BS 1377: Part 2: 1990: 8.3 using the pycnometer bottle or glass vessel method.

Specific gravity test according to BS 1377: Part 2: 1990

Apparatus

i. A glass vessel or pyknometer 1 litre in capacity, fitted with a metal conical screw top with an approximately 6mm diameter hole at its apex.

ii. A mechanical shaker

iii. A balance readable and accurate to 0.5g *iv.* A thermometer to cover the temperature range of 0^{o}c to 50^{o}c, readable and accurate to 1^{o}c.

Procedure:

i. A sample weighing 200g for fine aggregate and 400g in the case of coarse aggregate was obtained.

ii. The glass vessel and its conical screw top was dried and weighed to the nearest 0.2g (m_1).

iii. The 200g or 400g of aggregate as the case may be was introduced directly into the glass vessel. The glass vessel, conical top, and content were weighed to the nearest 0.2g (m_2).

iv. Approximately 500ml 0f water at a temperature within $\pm\pm$ 2^{o}c of the average room temperature during the test was added to the aggregate in the glass vessel. In the case of coarse aggregate, the glass vessel and content were set aside for at least 4hrs. At the end of the period, the glass vessel and content was weighed to the nearest 0.2g (m_3).

v. The glass vessel was then emptied and approximately 500ml of water was poured into it and weighed together with conical screw top to the nearest 0.2g (m_4).

CALCULATIONS:

$$\text{Specific gravity (GS)} = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \qquad (3.2)$$

Where m_1 = mass of glass vessel + top (g)

m_2 = mass of glass vessel + top + soil (g)

m_3 = mass of glass vessel + top + sample + water (g)

m_4 = mass of glass vessel + top + water (g).

c) **Moisture Absorption Test:** The moisture absorption of an aggregate is defined as the mass of water absorbed into the capillary pores of the saturated surface dry aggregate as a percentage of the dry mass of the aggregate. This test was done in accordance with BS 812: part 2 to determine the absorption capacity of aggregates. It was useful for batching water adjustment.

Apparatus:

i. A container of sufficient size to contain sample covered with water.

ii. A ventilated oven thermostatically controlled to maintain a temperature of 105° ± 5°C.

iii. Watertight tray.

iv. A balance readable and accurate to 0.2g.

Procedure:

i. 1000g of oven dried sample was obtained (m_1).

ii. The sample was placed in a container and water added to the container to ensure that the test sample is completely immersed.

iii. The test portion was kept immersed in water for 24hrs.

iv. After 24hrs, the water was drained carefully and the sample transferred into the watertight tray.

v. The sample in the tray was exposed to a gentle current of warm air to evaporate surface moisture, and stirred at frequent intervals to ensure uniform drying until no free surface moisture can be seen.

vi. The saturated and surface dry test portion was then weighed (m_2).

Calculations:

$$w = \frac{m_2 - m_1}{m_1} \text{ x } 100\% \qquad (3.3)$$

Where

w = water absorption

m_1 = mass of oven dried sample

m_2 = mass of saturated surface dry sample

d) **Aggregate Crushing Test:** The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. With aggregate of an aggregate crushing value higher than 30 the result may be anomalous. This test was performed in accordance with BS 812: part 3 to assess the compressive strength of coarse aggregates (Natural and Recycled).

Apparatus:

i. An open ended steel cylinder of nominal 150 mm internal diameter with plunger and base-plate.
ii. A straight metal tamping rod of circular cross section, 16 mm diameter and 450 mm to 600 mm long. One end shall be rounded.
iii. A balance of at least 3 kg capacity and accurate to 1 g.
iv. BS test sieves of sizes 14.0 mm, 10.0 mm and 2.36 mm.
v. A compression testing machine capable of applying a force of 400 kN and which can be operated to give a uniform rate of loading so that this force is reached in 10 min. The machine shall comply with the requirements of BS 1610 for a made A or a grade B machine. The machine may be used with or without a spherical seating.

Preparation of test sample:

The sample for the standard consisted of aggregate passing the 14.0 mm BS test sieve and retained on the 10.0 mm BS test sieve, and was thoroughly separated on these sieves before testing. The quantity of aggregate sieved out was sufficient for two tests. The aggregate was tested in a surface-dry condition. The quantity of aggregate for one test was such that the depth of the material in the cylinder was 100 mm after tamping. The appropriate quantity was found conveniently by filling the cylindrical measure in three layers of approximately equal depth, each layer being tamped 25 times from a height of approximately 50 mm above the surface of the aggregate with the rounded end of the tamping rod and finally leveled off, using the tamping rod as a straight edge. The mass of material comprising the test sample was determined (mass m_1).

Test procedure:

The cylinder of the test apparatus was put in position on the base plate, and the test sample was added in thirds, each third being subjected to 25 strokes from the tamping rod distributed evenly over the surface of the layer and dropping from a height approximately 50 mm above the surface of the aggregate. The surface of the aggregate was carefully leveled and the plunger was inserted so that it rests horizontally on this surface, care was taken to ensure that the plunger does not jam in the cylinder. The apparatus was placed with the test sample and plunger in position, between the platens of the testing machine and was loaded at a uniform rate as possible so that the required force is reached in 10 min. The required force was 400kN. The load was then released and the crushed material was removed by holding the cylinder over a clean tray and hammering on the outside with a suitable rubber mallet until the sample particles were sufficiently disturbed to enable the mass of the sample to fall freely on to the tray. Fine particles adhering to the inside of the cylinder was transferred to the baseplate and the underside of the plunger to the tray by means of a stiff bristle brush. The whole of the sample on the tray was sieved on the 2.36 mm BS test sieve until no further significant amount passes in 1 min; the fraction passing the sieve was weighed (mass m_2). Care was taken in all of these operations to avoid loss of the fines. The whole procedure was repeated, starting from the beginning of the test procedure using a second sample of the same mass as the first sample.

Calculations:

The ratio of the mass of fines formed to the total mass of the sample in each test shall be expressed as a percentage, the result being recorded to the first decimal place:

$$\text{Percentage fines} = \frac{m_1}{m_2} \times 100\% \qquad (3.4)$$

Where:

m_1 is the mass of surface-dry sample (g);

m_2 is the mass of the fraction passing the 2.36 mm BS test sieve (g).

e) **Aggregate Impact Test:** The aggregate impact value gives a relative measure of the resistance of an aggregate to sudden shock or impact, which in some aggregates differs from its resistance to a slowly applied compressive load (aggregate crushing value). With aggregate of aggregate impact value higher than 30 the result may be anomalous. This test was performed in accordance with BS 812: part 3.

Apparatus:

I. An impact testing machine of the general form described below and complying with the following.

(a) Total mass not more than 60 kg nor less than 45kg.

The machine shall have a circular metal base weighing between 22 kg and 30 kg, with a plane lower surface of not less than 300 mm diameter, and shall be supported on a level and plane concrete or stone block or floor at least 450 mm thick. The machine shall be prevented from rocking either by fixing it to the block or floor or by supporting it on a level and plane metal plate cast into the surface of the block or floor.

(b) A cylindrical steel cup having an internal diameter of 102 mm and an internal depth of 50 mm. The walls shall be not less than 6 mm thick and the inner surfaces shall be case hardened. The cup shall be rigidly fastened at the centre of the base and be easily removed for emptying.

(c) A metal hammer weighing 13.5 kg to 14.0 kg the lower end of which shall be cylindrical in shape, 100.0 mm diameter and 50 mm long, with a 1.5 mm chamfer at the lower edge, and case hardened. The hammer shall slide freely between vertical guides so arranged that the lower (cylindrical) part of the hammer is above and concentric with the cup.

(d) Means for raising the hammer and allowing it to fall freely between the vertical guides from a height of 380 f 5 mm on to the test sample in the cup, and means for adjusting the height of fall within 5 mm.

(e) Means for supporting the hammer whilst fastening or removing the cup.

i. BS test sieves of aperture sizes 14.0 mm, 10.0 mm and 2.36 mm.

ii. A cylindrical metal measure of sufficient rigidity to retain its form under rough usage and with an internal diameter of 75 + 1 mm and an internal depth of 50 & 1 mm.

iii. A straight metal tamping rod of circular cross section. 10 mm diameter, 230 mm long, rounded at one end.

iv. A balance of capacity not less than 500 g, and accurate to 0.1 g.

<u>Preparation of the test sample:</u>

The sample for the standard test consisted of aggregate passing a 14.0 mm BS test sieve and retained on a 10.0 mm BS test sieve and was thoroughly separated on these sieves before testing. The quantity of aggregate sieved out was sufficient for two tests. The aggregate was tested in a surface-dry condition. The measure was filled about one third full with the aggregate by means of a scoop, the aggregate being discharged from a height not exceeding

50 mm above the top of the container. The aggregate was then tamp with 25 blows of the rounded end of the tamping rod, each blow being given by allowing the tamping rod to fall freely from a height of about 50 mm above the surface of the aggregate and the blows being evenly distributed over the surface. A further similar quantity of aggregate was added in the same manner and a further tamping of 25 blows given. The measure was finally filled to overflowing, tamp 25 times and the surplus aggregate was removed by rolling the tamping rod across, and in contact with the top of the container, any aggregate which impedes its progress was removed by hand and aggregate being added to fill any obvious depressions. The net mass of aggregate in the measure was recorded (mass m_1) and the same mass used for the second test.

Test procedure:

The impact machine is rested, without wedging or packing, upon the level plate, block or floor, so that it is rigid and the hammer guide columns are vertical.

The cup is fixed firmly in position on the base of the machine and the whole of the test sample is placed in it and compact by a single tamping of 25 strokes of the tamping rod as above.

The height of the hammer is adjusted so that its lower face is 380 + 5 mm above the upper surface of the aggregate in the cup and then allowed to fall freely on to the aggregate. The test sample was subjected to a total of 15 such blows, each being delivered at an interval of not less than 1s. No adjustment for hammer height was required after the first blow.

The crushed aggregate was then removed by holding the cup over a clean tray and hammering on the outside with a suitable rubber mallet until the sample particles are sufficiently disturbed to enable the mass of the sample to fall freely on to the tray. Fine particles adhering to the inside of the cup and the underside of the hammer was transferred to the tray by means of a stiff bristle brush. The whole of the sample in the tray for the standard test, on the 2.36 mm BS test sieve was sieved until no further significant amount passes in 1 min. The fractions passing and retained on the sieve was weighed to an accuracy of 0.1 g (mass B and mass C respectively), and if the total mass $m_2 + m_3$ is less than the initial mass (mass m_1) by more than 1 g, the result was discarded and a fresh test made. The whole procedure was repeated starting from the beginning of the test procedure using a second sample of the same mass as the first sample.

Calculations:

The ratio of the mass of fines formed to the total sample mass in each test is expressed as a percentage, the result being recorded to the first decimal place.

Where:

$$\text{Percentage fines} = \frac{m_2}{m_1} \times 100\% \qquad (3.5)$$

m_2 is the mass of fraction passing the sieve for separating the fines (g).

3.2.2 Development of high-performance concrete mix proportions with natural coarse aggregate partially replaced with recycled aggregate.

HPC mix proportions containing recycled aggregate in partial amount of coarse aggregate were developed using MINITAB 17, based on extreme vertices design. 46 mix proportions were developed as described in section 3.2.3.

The recycled aggregate concrete studied was prepared with the partial replacement method, i.e. only a proportion of the natural coarse aggregate in the HPC mixes were replaced with recycled coarse aggregate, as against an alternate method of replacing the whole natural coarse aggregate with recycled coarse aggregate. This method of replacement was considered for this study from the background that recycled coarse aggregate may not always be readily available in such a quantity as to always consider a total replacement, even if the study should show that recycled aggregate are very suitable for HPC production. This is because recycled aggregates are only available when there is a demolition of an existing concrete structure, and even though the rate of demolition has increased in recent times, the quantity of coarse aggregate that could be obtained from demolished concrete structures alone cannot meet the demand for coarse aggregate needed for construction of new concrete structures. Hence, a partial replacement method was considered more feasible for this work. However, it is recommended that independent studies may be carried out on the total replacement of natural coarse aggregate with recycled coarse aggregate in a HPC mixture, in order to determine its feasibility in practical terms, or perhaps for academic purposes.

3.2.3 Development of models for predicting the compressive strengths and workability of HPC with natural coarse aggregate partially replaced by recycled coarse aggregate.

The development of models began with the design of mixture experiment, after which data obtained from the experimental results of the designed mixture experiments were analyzed. But before these, the type of model on which the response surface would be modeled after was determined. The methods used to develop models of interest in this work are described in this section.

3.2.3.1 Model type selection

The properties of HPC containing recycled aggregates were modeled on the Scheffe’s second degree or quadratic polynomial. For a seven component mixture, the Scheffe’s second degree polynomial yields an equation with 28 model terms, implying that there are 28 model coefficients in the equation as seen in Equation 3.15. The choice of the Scheffe’s second degree model is based on the need to have a model that is less complicated and at the same time provide a reliable model for the studied response surface.

3.2.3.2 Design of mixture experiment

Minitab was used to design and analyze the seven component mixture experiment. First, the upper and lower bounds of the proportions of the seven components (in terms of volume fraction) were defined. This was done by selecting a reference mixture of HPC, which served as a guide to obtaining the maximum and minimum levels of the proportion of the mixture components or the volume fraction ranges of the mixture components. This reference HPC mix was the mix proportion of concrete used in the construction of main piers and T-beams of the Confederation Bridge in Canada (see Table 2.3). Using the properties and specifications of materials used in this work, the batching weights of the different components in the reference mixture was converted to volume fractions, and these volume fractions gave the guide to selecting the upper and lower bounds of volume fractions of components. Table 4.1(a) shows the proportions of the reference mixture components, per cubic meter of concrete. Weight proportions were converted to volume fraction proportions using Equations 3.6 – 3.9.

$$v_i = \frac{m_i}{\rho_i} \tag{3.6}$$

But,

$$\rho_i = s.g_i \; x \; \rho_w \tag{3.7}$$

Therefore,

$$v_i = \frac{m_i}{s.g_i \; x \; \rho_w} \tag{3.8}$$

Then,

$$v.f_i = \frac{v_i}{V_T} \tag{3.9}$$

Where,

v_i = volume of component, m_i = mass of component, ρ_i = density of component, ρ_w = density of water, $s.g_i$ = specific gravity of component, $v.f_i$ = volume fraction of component, and

V_T = total volume of mixture.

In relation to this work, if the natural coarse aggregate used in the reference mixture in Table 4.1(a), were replaced completely with recycled coarse aggregate, then the proportion of the component would be as given in Table 4.1(b), considering that the specific gravity of the coarse aggregate has been reduced.

The volume factions of HPC components in Table 4.1(c) were guide to selecting the volume fractions of mixture components used in this work.

Table 4.1(c) shows the volume fractions of mixture components without recycled coarse aggregate, while Table 4.1(d) shows the volume fractions of mixture components with recycled coarse aggregate (i.e. natural coarse aggregate partially replaced with recycled coarse aggregate).

The Constraint $0.4 \leq\leq E + F \leq\leq 0.44$ was imposed on the design so that the sum of volume fractions of natural coarse aggregate and recycled coarse aggregate was never less than 0.4 or more than 0.44 as for the normal HPC mix(i.e. without recycle coarse aggregate). Also, to improve consolidation, the paste fraction of concrete (water, cement, silica fume, and HRWRA), were constrained to stay between 50% and 65% of total mixture (Kosmatka et al., 2003). However, as could be observed in Table 3.3, Minitab adjusted the bounds of components in order to accommodate the specified constraints.

The volume fraction ranges for both natural and recycled coarse aggregates were so selected in Table 4.2b in order to obtain an alternate random selection of both components proportion in all concrete mixes, so as to achieve partial replacements in high and low percentages.

The volume fraction ranges for mixture components given in Table 4.1d were imputed into Minitab, and Minitab used these data to generate a set of candidate design points based on extreme vertices design. The entire design parameter as obtained from Minitab is shown in Table 4.1e.

3.2.3.3 Selection of optimal design

The initial design consisted of eighty-one (81) design points i.e. 81 possible experimental runs, however, due to economic and time constrains, it was not feasible to undertake 81 experimental runs, therefore, a sub-set of design points were selected. Points were selected using distance based optimality to ensure that the selected design points are spread uniformly over the design space. 46 points were selected, keeping in mind that there should be a minimum of 28 design points (section 2.5.1.5) at which to conduct experiments to determine the model coefficients, since there are 28 model coefficients (constants) in the second degree polynomial used to model the response surface. In addition to the 28 distinct mixes needed to estimate the model coefficients, 10 distinct mixes were added to check the adequacy of the model and 8 mixes from the augmented design were replicated (5 mixes replicated once and 1 other thrice) giving a total of 46 mixes, Table 4.1f.

The volume fractions were converted to weight for batching using the specific gravities of the individual components obtained from laboratory testing or from the material supplier.

Equations 3.11 – 3.15 were used for the conversion.

$$s.g_i = \frac{\rho_i}{\rho_w} \quad (3.10)$$

But,

$$m_i = \rho_i \times v_i \quad (3.11)$$

Therefore,

$$m_i = s.g_i \times \rho_w \times v_i \quad (3.12)$$

But

$$v.f_i = \frac{v_i}{V} \tag{3.13}$$

Then equation 3.12 becomes

$$m_i = s.g_i \times \rho_w \times v.f_i \times V_T \tag{3.14}$$

Where,

v_i = volume of component, m_i = mass of component, ρ_i = density of component

ρ_w = density of water, $s.g_i$ = specific gravity of component, $v.f_i$ = volume fraction of component, and V_T = total volume of mixture = 0.9489m^3.

Table 4.1g shows the mix proportion of each of the 46 experimental runs in (kg/m^3), but the HRWRA component is in litres/m^3.

3.2.3.4 Specimen fabrication and testing

The recycled coarse aggregate was observed to have a moisture absorption value of 4.6%, while the natural coarse aggregates had no absorption value, also, the fine aggregates were known to have an absorption value of 1%. Therefore, the recycled coarse aggregates were soaked in water for at least 30minutes and then placed in the open air in order to bring its moisture condition to saturated surface dry (SSD) state.

Forty-six (46) batches of concrete each of approximate volume 0.0032m^3 were prepared manually in a mixing pan with nominal capacity of 0.1m^3. Fine, coarse aggregates (natural and recycled), cement and silica fume are first mixed for 30 seconds; the mixing water was added to the HRWRA first for best effect of HRWRA before being added to the entire mixture. Thorough mixing was done for the next 60 – 90 seconds. Slump was measured immediately after mixing following BS 1881-102. Each batch included sufficient concrete for two slump tests, and six 100mm cubes. After casting, the cubes were left in the mould for 24 hours and then transferred into a curing tank after demoulding, however, three cubes for each mix were crushed after 24 hours using a universal testing machine to determine the one-day strength. The remaining three cubes for a particular mix were crushed after 28 days of curing and their compressive strength determined.

3.2.3.5 Analysis of the mixture experiment using Minitab

After obtaining data for slump, 1-day strength, and 28-day strength, the data were imputed into the experiment design sheet of Minitab and was analyzed using the "Analyze mixture design" function of Minitab. Minitab used the principle of ANOVA and least squares technique to fit models for each of the measured responses as discussed in section 2.5.2.

3.2.3.6 Model reduction, identification, and validation

The Scheffe's quadratic polynomial for the seven component mixture of this work is given in equation 3.15.

$$y = \beta_1 x_1+\beta_2 x_2+\beta_3 x_3+\beta_4 x_4+\beta_5 x_5+\beta_6 x_6+\beta_7 x_7+\beta_{12} x_1 x_2+\ldots+\beta_{67} x_6 x_7+e \tag{3.15}$$

Where: β terms are constants

x terms are the mixture components proportions and

e is the random error.

$x_i x_j$ are interaction terms.

The model contained 28 terms as discussed in section 3.2.3.2**,** and an appropriate model where only significant terms are present was identified through model reduction. To reduce the model in order to obtain a model with only significant terms, ANOVA was used to perform a sequential F-test. The F-test or F-statistics was used to carry out a hypothesis test on the coefficients of the model terms. The null hypothesis "H_0" is that the coefficient of a model term is equal to zero (H_0: $\beta_i = 0$) and should be removed from the model. The alternate hypothesis is that the coefficient of the model term is not equal to zero (H_A: $\beta_i \neq\neq 0$) and can be included in the model.

The null hypothesis was tested for each term in the model, and terms that were not significant or whose coefficients equal zero (i.e. $\beta_i = 0$) were removed from the model. Significance was judged by determining if the probability that the F-statistic calculated from the data exceeds a theoretical value. The probability (p-value) decreases as the value of the F-statistic increases. If this probability is less than 0.05 (typically, although other levels of significance could be used), the terms are significant and their inclusion improves the model, otherwise, they are removed from the model (Simon, 1996).

Hence, for a p-value less than 0.05 (used in this research) the null hypothesis (i.e. $H_0 = \beta_i = 0$) was rejected for the alternate hypothesis (i.e. $H_A == \beta_i \neq\neq 0$). The value 0.05 is the significance level; it denotes the probability of rejecting the null hypothesis. It is usually denoted by alpha (α).

Validating the model involves assessing residual plots and model statistics like the coefficient of determination (R^2), adjusted R^2, predicted R^2 and lack-of-fit. The coefficient of determination (R^2), adjusted R^2, and predicted R^2 assess the goodness of fit of a model, and high values indicate a good model. The lack-of-fit-test is used to assess how well the model fits the data. If the p-value for lack-of-fit is less than the selected significance level (α = 0.05), evidence exists that the model does not accurately fit the data. But if the lack-of-fit p-value exceeds the significance level (α = 0.05), then there is no evidence that the model does not adequately explain the data. These model statistics, together can give a clue to the validity of a model; however, it is more reliable to use residual plots in validating models. Hence, goodness of fit of models was determined by assessing residual plots and discussed in section 2.5.2.5.

3.2.4 The effect of recycled coarse aggregate on HPC mixes

The effect of recycled coarse aggregate was studied using the Cox response trace plots for each response property. The trace plots were plot by Minitab, and the trace direction of a particular component indicates how the components affect the mixture. The trace plots were interpreted relative to a reference mixture which is the centroid of the design points.

3.2.5 Optimization of high performance recycled aggregate concrete

To find optimum composition of different components of HPC containing recycled aggregate, the "Response optimizer" function of Minitab was used.

Minitab defined the desirability function for each optimized response (between 0 and 1).

The desirability function was interpreted thus:

i. for a goal to maximize a response, the desirability is 1 at and beyond the targeted response, and less than 1 below the targeted response.
ii. for a goal to target a particular response, the desirability is 1 at the targeted response and less than 1 below or beyond the targeted response.
iii. for a goal to minimize a response, the desirability is 1 below the targeted response and less than 1 beyond the targeted response (details given in section 2.5.4).

Optimization was done to obtain a high performance recycled aggregate concrete meeting the following specifications, more importance was placed on the 28-day compressive strength because the specified compressive strength of a concrete is the minimum compressive strength at which the concrete should fail in standard test of 28-day old concrete cube/cylinder, (ASTM C 39).

i. 1-day strength must be greater than 20MPa
ii. 28-day strength must be greater than 40MPa, and
iii. Slump in the range of 100 – 150 mm

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1. Tables from mixture experiment design and analysis

Table 4.1(a): weight, volume, and volume fractions of reference mixture

Proportions per cubic meter of concrete	Components						
	Water	Cement	Silica fume	HRWRA(L)	Natural Coarse agg.	Fine agg.	Total
Weight (kg/m^3)	153	416	34	11.4	1030	737	
Vol. (m^3/m^3)	0.153	0.1321	0.01545	0.0114	0.3679	0.2690	0.9489
Vol. fraction	0.1611	0.1391	0.01627	0.003160	0.3875	0.2929	1

Table 4.1(b): weight, volume, and volume fractions of reference mixture components where natural coarse aggregate is completely replaced with recycled coarse aggregate

Proportions per cubic meter of concrete	Components						
	Water	Cement	Silica fume	HRWRA(L)	Recycled Coarse agg.	Fine agg.	Total
Weight (kg/m^3)	153	416	34	11.4	1030	737	
Vol. (m^3/m^3)	0.1530	0.1321	0.01545	0.0114	0.4137	0.2690	0.9946
Vol. fraction	0.1538	0.1328	0.0155	0.0115	0.4159	0.2704	1

Table 4.1c: Components volume fraction ranges for mixture experiment with only natural aggregate

Components	**ID**	**Minimum Volume fraction**	**Maximum Volume fraction**
Water	A	0.16	0.185
Cement	B	0.128	0.148
Silica fume	C	0.015	0.029
HRWRA	D	0.0121	0.0401
Coarse aggregate	E	0.40	0.44
Fine aggregate	F	0.28	0.3054

Table 4.1d: Components volume fraction ranges for HPC with natural coarse aggregate partially replaced with recycled coarse aggregate

Components	**ID**	**Minimum Volume fraction**	**Maximum Volume fraction**
Water	A	0.16	0.185
Cement	B	0.128	0.148
Silica fume	C	0.015	0.029
HRWRA	D	0.0121	0.0401
Natural Coarse aggregate	E	0.060	0.340
Recycled Coarse aggregate	F	0.060	0.340
Fine aggregate	G	0.28	0.3054

Table 4.1e Extreme vertices design for mixture experiment

```
Components:         7  Design points:  81
Process variables:  0  Design degree:   2

Mixture total: 1.00000
```

```
Number of Boundaries for Each Dimension

Point Type   1    2    3    4    5   6  0
Dimension    0    1    2    3    4   5  6
Number      64  212  280  190   72  14  1
```

```
Number of Design Points for Each Type

Point Type     1   2  3  4  5  6  7  0  -1
Distinct      12  56  0  0  0  0  0  1  12
Replicates     1   1  0  0  0  0  0  1   1
Total number  12  56  0  0  0  0  0  1  12
```

```
Bounds of Mixture Components

            Amount              Proportion          Pseudocomponent
Comp     Lower     Upper      Lower     Upper      Lower     Upper
A     0.160000  0.164900  0.160000  0.164900  0.000000  0.017199
B     0.128000  0.132900  0.128000  0.132900  0.000000  0.017199
C     0.015000  0.019900  0.015000  0.019900  0.000000  0.017199
D     0.012100  0.017000  0.012100  0.017000  0.000000  0.017199
E     0.060000  0.340000  0.060000  0.340000  0.000000  0.982801
F     0.060000  0.340000  0.060000  0.340000  0.000000  0.982801
G     0.280000  0.284900  0.280000  0.284900  0.000000  0.017199
```

```
* NOTE * Bounds were adjusted to accommodate specified constraints.

Linear Constraints of Mixture Components

Constraint     Lower         A         B         C         D         E         F         G
         1  0.400000  0.000000  0.000000  0.000000  0.000000  1.000000  1.000000  0.000000
         2  0.500000  1.000000  1.000000  1.000000  1.000000  0.000000  0.000000  0.000000
```

```
Constraint     Upper
         1  0.440000   **
         2  0.650000  ***

** indicates inconsistent or unnecessary upper bound.
*** indicates inconsistent or unnecessary constraint.
* NOTE * Flagged constraints are ignored.
```

Table 4.1f Volume fractions of mixture components

StdOrder	RunOrder	PtType	Blocks	Water	Cement	Silica Fume	HRWRA	Natural Coarse agg.	Recycled Coarse agg.	Fine agg.
2	1	1	1	0.1600	0.1280	0.0199	0.0121	0.0600	0.3400	0.2800
67	2	2	1	0.1600	0.1280	0.0150	0.0123	0.1806	0.2194	0.2847
78	3	-1	1	0.1604	0.1309	0.0154	0.0125	0.2702	0.1302	0.2804
80	4	-1	1	0.1604	0.1284	0.0154	0.0125	0.2702	0.1302	0.2829
72	5	-1	1	0.1604	0.1309	0.0154	0.0125	0.1302	0.2702	0.2804
26	6	2	1	0.1600	0.1280	0.0199	0.0121	0.2000	0.2000	0.2800
47	7	2	1	0.1624	0.1280	0.0150	0.0121	0.3400	0.0600	0.2824
10	8	1	1	0.1649	0.1280	0.0150	0.0121	0.3400	0.0600	0.2800
46	9	2	1	0.1624	0.1280	0.0150	0.0121	0.0600	0.3400	0.2824
27	10	2	1	0.1604	0.1284	0.0154	0.0125	0.1327	0.2702	0.2804
17	11	2	1	0.1600	0.1280	0.0150	0.0145	0.0600	0.3400	0.2824
69	12	0	1	0.1608	0.1288	0.0158	0.0129	0.2004	0.2004	0.2808
5	13	1	1	0.1600	0.1280	0.0150	0.0121	0.0600	0.3400	0.2849
21	14	2	1	0.1600	0.1280	0.0150	0.0170	0.2000	0.2000	0.2800
35	15	2	1	0.1600	0.1329	0.0150	0.0121	0.2000	0.2000	0.2800
4	16	1	1	0.1649	0.1280	0.0150	0.0121	0.0600	0.3400	0.2800
7	17	1	1	0.1600	0.1280	0.0150	0.0121	0.0649	0.3400	0.2800
73	18	-1	1	0.1629	0.1284	0.0154	0.0125	0.1302	0.2702	0.2804
74	19	-1	1	0.1604	0.1284	0.0154	0.0125	0.1302	0.2702	0.2829
17(r_2)	20	2	1	0.1600	0.1280	0.0150	0.0145	0.0600	0.3400	0.2824
60	21	2	1	0.1616	0.1280	0.0166	0.0137	0.3400	0.0600	0.2800
8	22	1	1	0.1600	0.1280	0.0199	0.0121	0.3400	0.0600	0.2800
34	23	2	1	0.1600	0.1304	0.0150	0.0121	0.0624	0.3400	0.2800
1	24	1	1	0.1600	0.1280	0.0150	0.0121	0.3400	0.0649	0.2800
16	25	2	1	0.1600	0.1280	0.0150	0.0121	0.2000	0.2000	0.2849
72(r_4)	26	-1	1	0.1604	0.1309	0.0154	0.0125	0.1302	0.2702	0.2804
12	27	1	1	0.1600	0.1280	0.0150	0.0170	0.3400	0.0600	0.2800
75	28	-1	1	0.1604	0.1284	0.0154	0.0150	0.1302	0.2702	0.2804
22	29	2	1	0.1600	0.1280	0.0174	0.0121	0.0600	0.3400	0.2824
38	30	2	1	0.1600	0.1280	0.0150	0.0145	0.3400	0.0600	0.2824
11	31	1	1	0.1600	0.1280	0.0150	0.0121	0.3400	0.0600	0.2849
69(r_6)	32	0	1	0.1608	0.1288	0.0158	0.0129	0.2004	0.2004	0.2808
73(r_5)	33	-1	1	0.1629	0.1284	0.0154	0.0125	0.1302	0.2702	0.2804
8(r_1)	34	1	1	0.1600	0.1280	0.0199	0.0121	0.3400	0.0600	0.2800
79	35	-1	1	0.1629	0.1284	0.0154	0.0125	0.2702	0.1302	0.2804
35(r_3)	36	2	1	0.1600	0.1329	0.0150	0.0121	0.2000	0.2000	0.2800
3	37	1	1	0.1600	0.1329	0.0150	0.0121	0.0600	0.3400	0.2800
50	38	2	1	0.1649	0.1280	0.0150	0.0121	0.2000	0.2000	0.2800
70	39	-1	1	0.1604	0.1284	0.0154	0.0125	0.2702	0.1327	0.2804
69(r_6)	40	0	1	0.1608	0.1288	0.0158	0.0129	0.2004	0.2004	0.2808
69(r_6)	41	0	1	0.1608	0.1288	0.0158	0.0129	0.2004	0.2004	0.2808
9	42	1	1	0.1600	0.1329	0.0150	0.0121	0.3400	0.0600	0.2800
51	43	2	1	0.1616	0.1280	0.0166	0.0137	0.0600	0.3400	0.2800
24	44	2	1	0.1604	0.1284	0.0154	0.0150	0.2702	0.1302	0.2804
77	45	-1	1	0.1604	0.1284	0.0179	0.0125	0.2702	0.1302	0.2804
33	46	2	1	0.1600	0.1304	0.0150	0.0121	0.3400	0.0624	0.2800

Note: r represents replicated mixes

Table 4.1g Mix proportions for mixture experiment

Std Order	Run Order	Water (kg/m^3)	Cement (kg/m^3)	Silica Fume (kg/m^3)	HRWRA (l/m^3)	Natural Coarse agg. (kg/m^3)	Recycled Coarse agg.(kg/m^3)	Fine agg. (kg/m^3)
2	1	151.8	382.6	41.5	11.5	159.4	803.3	728.0
67	2	151.8	382.6	31.3	11.7	479.8	518.5	740.1
78	3	152.2	391.1	32.2	11.9	717.9	307.6	729.1
80	4	152.2	383.8	32.2	11.9	717.9	307.6	735.4
72	5	152.2	391.1	32.2	11.9	345.9	638.4	729.1
26	6	151.8	382.6	41.5	11.5	531.4	472.6	728.0
47	7	154.2	382.6	31.3	11.5	903.4	141.8	734.4
10	8	156.5	382.6	31.3	11.5	903.4	141.8	728.0
46	9	154.2	382.6	31.3	11.5	159.4	803.3	734.4
27	10	152.2	383.8	32.2	11.9	352.5	638.4	729.1
17	11	151.8	382.6	31.3	13.8	159.4	803.3	734.4
69	12	152.6	385.0	33.0	12.3	532.5	473.5	730.1
5	13	151.8	382.6	31.3	11.5	159.4	803.3	740.7
21	14	151.8	382.6	31.3	16.1	531.4	472.6	728.0
35	15	151.8	397.2	31.3	11.5	531.4	472.6	728.0
4	16	156.5	382.6	31.3	11.5	159.4	803.3	728.0
7	17	151.8	382.6	31.3	11.5	172.4	803.3	728.0
73	18	154.5	383.8	32.2	11.9	345.9	638.4	729.1
74	19	152.2	383.8	32.2	11.9	345.9	638.4	735.4
17	20	151.8	382.6	31.3	13.8	159.4	803.3	734.4
60	21	153.4	382.6	34.7	13.0	903.4	141.8	728.0
8	22	151.8	382.6	41.5	11.5	903.4	141.8	728.0
34	23	151.8	389.9	31.3	11.5	165.9	803.3	728.0
1	24	151.8	382.6	31.3	11.5	903.4	153.3	728.0
16	25	151.8	382.6	31.3	11.5	531.4	472.6	740.7
72	26	152.2	391.1	32.2	11.9	345.9	638.4	729.1
12	27	151.8	382.6	31.3	16.1	903.4	141.8	728.0
75	28	152.2	383.8	32.2	14.2	345.9	638.4	729.1
22	29	151.8	382.6	36.4	11.5	159.4	803.3	734.4
38	30	151.8	382.6	31.3	13.8	903.4	141.8	734.4
11	31	151.8	382.6	31.3	11.5	903.4	141.8	740.7
69	32	152.6	385.0	33.0	12.3	532.5	473.5	730.1
73	33	154.5	383.8	32.2	11.9	345.9	638.4	729.1
8	34	151.8	382.6	41.5	11.5	903.4	141.8	728.0
79	35	154.5	383.8	32.2	11.9	717.9	307.6	729.1
35	36	151.8	397.2	31.3	11.5	531.4	472.6	728.0
3	37	151.8	397.2	31.3	11.5	159.4	803.3	728.0
50	38	156.5	382.6	31.3	11.5	531.4	472.6	728.0
70	39	152.2	383.8	32.2	11.9	717.9	313.4	729.1
69	40	152.6	385.0	33.0	12.3	532.5	473.5	730.1
69	41	152.6	385.0	33.0	12.3	532.5	473.5	730.1
9	42	151.8	397.2	31.3	11.5	903.4	141.8	728.0
51	43	153.4	382.6	34.7	13.0	159.4	803.3	728.0
24	44	152.2	383.8	32.2	14.2	717.9	307.6	729.1
77	45	152.2	383.8	37.3	11.9	717.9	307.6	729.1
33	46	151.8	389.9	31.3	11.5	903.4	147.6	728.0

Table 4.1h Model predictions and experimental results

Responses	Models predictions	Experimental results
Slump mm	125	130
1-day strength MPa	22.114	21.86
28-day strength MPa	48.693	46.53

Table 4.1i comparison of model predictions and experimental results for design point 6

RESPONSES	DESIGN POINT 6		95% CI		95% PI	
	Model prediction	Experiment result	low	High	low	high
SLUMP(mm)	139.94	145.0	130.29	149.59	122.48	157.40
1-DAY(MPa)	22.88	22.00	21.11	24.66	20.07	25.70
28DAY(MPa)	49.35	51.00	46.71	51.98	44.19	54.50

Table 4.1j comparison of model predictions and experimental results for design point 22

RESPONSES	DESIGN POIN 22		95% CI		95% PI	
	Model prediction	Experiment result	low	High	low	high
SLUMP	156.29	170.0	146.07	166.51	138.52	174.07
1-DAY	23.83	26.40	22.28	25.37	21.15	26.50
28-DAY	54.53	57.40	51.72	57.34	49.29	59.77

Table 4.1k comparison of model predictions and experimental results for design point 38

RESPONSES	DESIGN POINT 38		95% CI		95% PI	
	Model prediction	Experiment result	Low	high	low	high
SLUMP(mm)	112.43	117.5	103.66	121.21	95.45	129.42
1-DAY(MPa)	23.28	20.20	21.47	25.09	20.44	26.12
28-DAY(MPa)	42.17	44.70	39.54	44.81	37.02	47.32

Table 4.1l response Optimization for 28-day strength of 45MPa

```
Parameters

             Goal    Lower  Target  Upper  Weight  Import
28-DAY(MPa)  Target     44      45     46       1       1

Linear Constraints of Mixture Components

Constraint  Lower  A  B  C  D  E  F  G   Upper
         1    0.4  0  0  0  0  1  1  0  0.4049
         2    0.5  1  1  1  1  0  0  0       *  **

** indicates inconsistent or unnecessary constraint.

Global Solution
Components
A   =    0.161294
B   =    0.129191
C   =       0.015
D   =   0.0124307
E   =    0.207512
F   =    0.192488
G   =    0.282084

Predicted Responses

28-DAY(MPa)   =   45  ,   desirability =   1.000000

Composite Desirability = 1.000000
```

Table 4.1m response Optimization for 28-day strength of 55MPa

```
Parameters
                Goal    Lower  Target  Upper  Weight  Import
28-DAY(MPa)   Target     55      56     57       1       1
Linear Constraints of Mixture Components

Constraint  Lower  A  B  C  D  E  F  G   Upper
         1    0.4  0  0  0  0  1  1  0  0.4049
         2    0.5  1  1  1  1  0  0  0       *  **

** indicates inconsistent or unnecessary constraint.
Global Solution

Components

A   =       0.16
B   =   0.128795
C   =  0.0190905
D   =     0.0121
E   =       0.34
F   =       0.06
G   =   0.280014
Predicted Responses

28-DAY(MPa)   =   55.1  ,   desirability =   0.100000

Composite Desirability = 0.100000
```

4.1.2. Presentation of materials characterization results

I) **Sieve analysis:** The results of sieve analysis carried out on natural coarse aggregate, recycled coarse aggregate, and fine aggregate are shown in Table 4.2a. Table 4.2b show comparison of results of grading of the coarse aggregates with the grading limits for coarse aggregate while Table 4.2c show comparison of results of grading of fine aggregates with the limits of grading for fine aggregates all in accordance with BS 882 (1992). Figures 4.1a – 4.1c show the gradation curves of natural coarse aggregate, recycled coarse aggregate and fine aggregate respectively, while Figure 4.1d shows the variation in grading between natural coarse and recycled coarse aggregates.

Table 4.2a Aggregates grading

Sieve Sizes (mm)	Aggregate Cum. % passing		
	Natural	Recycled	Fine
25	96.08	65.66	-
19	39.9	18.69	-
13.2	3.62	2.02	-
9.5	-	0.3	-
6.3	-	-	-
4.75	-	-	-
3.35	-	-	97.79
2.36	-	-	96.59
1.18	-	-	87.16
600µm	-	-	29.3
425µm	-	-	14.2
300µm	-	-	4.5
212µm	-	-	1.3
150µm	-	-	0.4
75µm	-	-	-

Table 4.2b: Comparison of results of grading of the coarse aggregates with the grading limits for coarse aggregate

Recommended Limits		**Result obtained**		
			Natural Coarse Aggregate	**Recycled Coarse Aggregate**
Sieve Size	Overall Limits (% Passing)	Sieve Size	% Passing	% Passing
50	100	-	-	-
37.5	90-100	37.5	100	100
20	35-70	25.0	96.08	65.66
14	25-55	13.20	39.9	18.69
10	10-40	9.5	3.62	2.02
5	0-5	6.3	0	0.30
2.36	-	4.75	-	0

Table 4.2c: Comparison of results of grading of fine aggregates with the limits of grading for fine aggregates.

Recommended Limits		**Obtained Result**	
		Fine Aggregate	
Sieve Size	**Overall Limits (% Passing)**	**Sieve Size**	**% Passing**
10mm	100	-	-
5mm	89-100	-	-
-	-	3.35mm	97.79
2.36mm	60-100	2.36mm	96.59
1.18mm	30-100	1.18mm	87.16
600µm	15-100	600µm	29.29
-	-	425 µm	14.24
300µm	5-70	300µm	4.51
150µm	0-20	212 µm	1.30
-	-	150 µm	0.40
-	-	75 µm	0

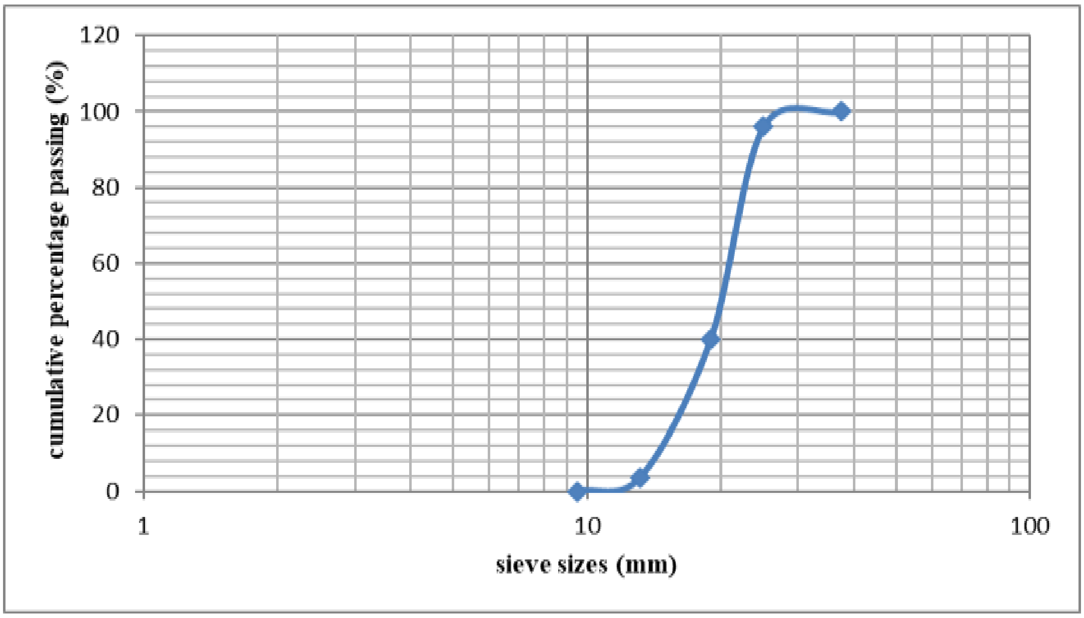


Fig.4.1 a: Gradation curve of Natural Coarse Aggregate

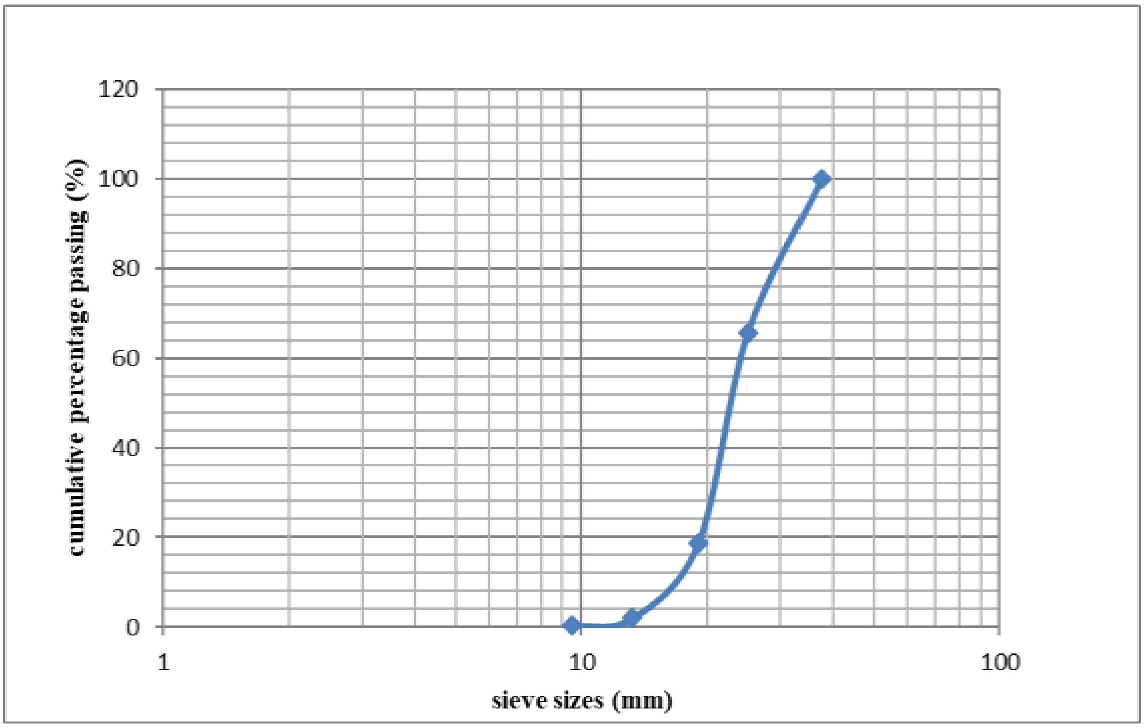


Fig.4.1 b: Gradation curve of Recycled Coarse Aggregate

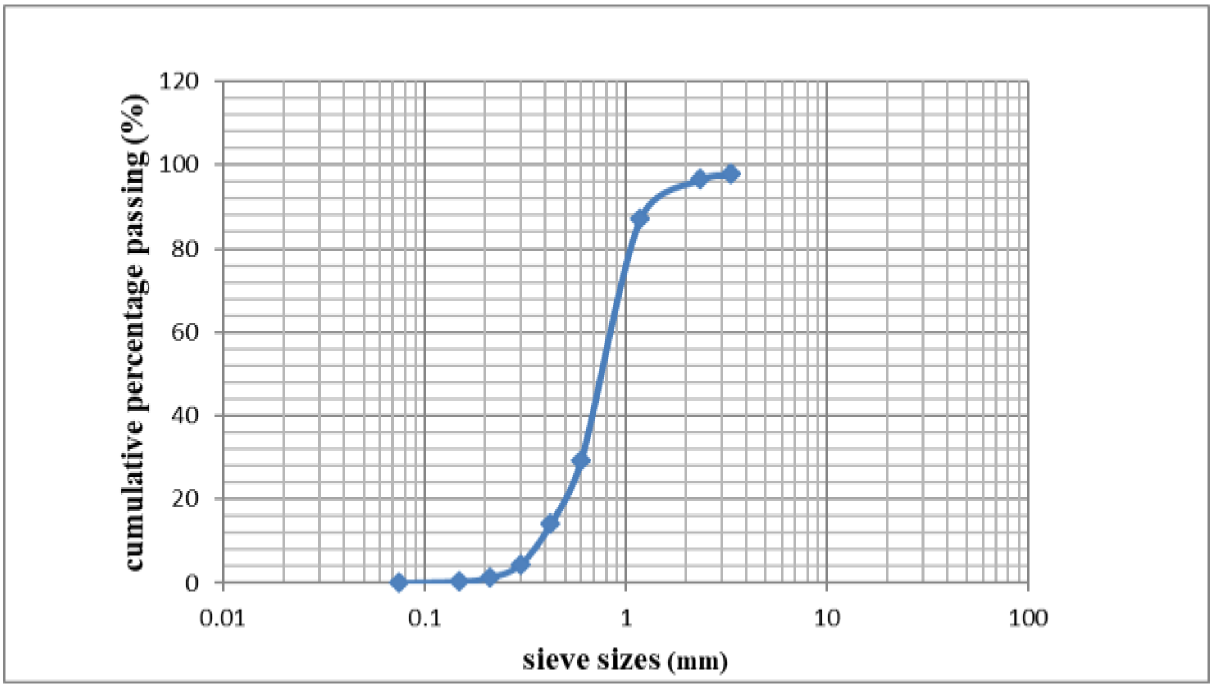


Fig.4.1c: Gradation curve of Fine Aggregate

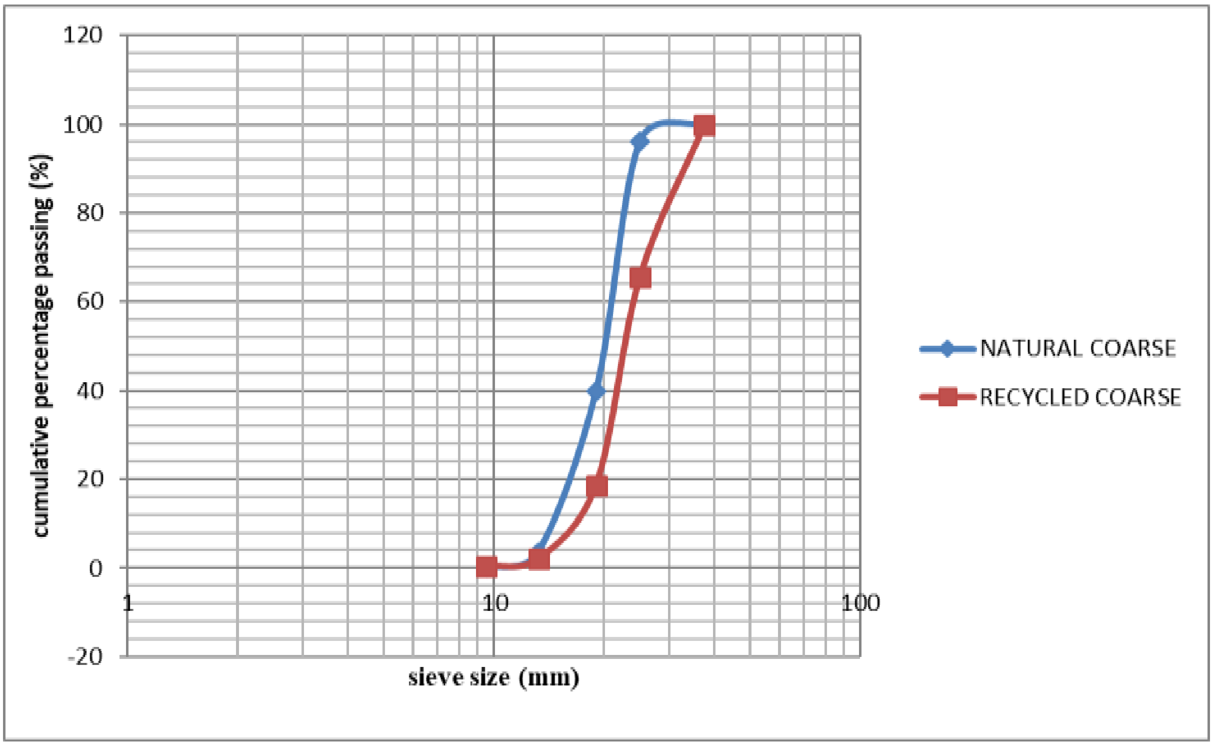


Fig.4.1d: Gradation curves showing variation in grading of natural and recycled coarse aggregates

II) **Specific gravity tests results**: Results for specific gravity tests for Natural aggregate, recycled aggregate, fine aggregate, cement, and silica fume are shown in Table 4.3a – Table 4.3e respectively.

Table 4.3a: Specific gravity of Natural coarse aggregate

Label		A	B
mass of bottle (m_1)	g	487	484
mass of bottle + sample (m_2)	g	1340	1397
mass of bottle + sample + water (m_3)	g	2156	2180
mass of bottle full of water (m_4)	g	1603	1600
mass of water used (m_3-m_2)	g	818	783
mass of sample used (m_2-m_1)	g	853	913
specific gravity, sg= $\frac{m2-m1}{(m4-m1)-(m3-m2)}$		2.86	2.74
sg average		2.8	

Table 4.3b: Specific gravity of Recycled coarse aggregate

Label	A	B
mass of bottle (m_1) g	487	484
mass of bottle + sample (m_2) g	1165	1163
mass of bottle + sample + water (m_3) g	2017	2012
mass of bottle full of water (m_4) g	1610	1607
mass of water used (m_3-m_2) g	852	849
mass of sample used (m_2-m_1) g	678	679
specific gravity, sg= $\frac{m2-m1}{(m4-m1)-(m3-m2)}$	2.50	2.48
sg average	2.49	

Table 4.3c: Specific gravity of Fine aggregate

Label	A	B
mass of bottle (m_1) g	487	482
mass of bottle + sample (m_2) g	1112	1136
mass of bottle + sample + water (m_3) g	2016	2026
mass of bottle full of water (m_4) g	1620	1610
mass of water used (m_3-m_2) g	904	890
mass of sample used (m_2-m_1) g	625	654
specific gravity, sg= $\frac{m2-m1}{(m4-m1)-(m3-m2)}$	2.73	2.75
sg average	2.74	

Table 4.3d: Specific gravity of Cement

Label	A	B
mass of bottle (m_1) g	33.0	31.0
mass of bottle + sample (m_2) g	57.0	58.0
mass of bottle + sample + water (m_3) g	97.0	98.0
mass of bottle full of water (m_4) g	80.5	79.8
mass of water used (m_3-m_2) g	40.0	40.0
mass of sample used (m_2-m_1) g	24.0	27
specific gravity, sg= $\frac{m2-m1}{(m4-m1)-(m3-m2)}$	3.2	3.1
sg average	3.15	

Table 4.3e: Specific gravity of Silica fume

Label		A	B
mass of bottle (m_1)	g	24.5	26.0
mass of bottle + sample (m_2)	g	29.0	30.5
mass of bottle + sample + water (m_3)	g	52.0	53.5
mass of bottle full of water (m_4)	g	49.6	51.0
mass of water used (m_3-m_2)	g	23.0	23.0
mass of sample used (m_2-m_1)	g	4.5	4.5
specific gravity, sg= $\frac{m2-m1}{(m4-m1)-(m3-m2)}$		2.14	2.25
sg average		2.2	

III) **Aggregate crushing value:** Tables 4.4a and 4.4b show the results of aggregate crushing value for Natural and recycled coarse aggregates respectively:

Table 4.4a: Aggregate crushing value of Natural Coarse Aggregate.

Label		A	B
Total mass of dry sample (m_1)	g	3000	3000
Mass of the portion of crushed material passing 2.36mm sieve (m_2)	g	707	711
Aggregate Crushing Value (%) $\frac{m_2}{m_1} \times 100$		23.57	23.7
Average aggregate Crushing Value (%)		23.64	

Table 4.4b: Aggregate crushing value of Recycled Coarse Aggregate

Label		A	B
Total weight of dry sample (m_1)	g	3000	3000
Mass of the portion of crushed material passing 2.36mm sieve (m_2)	g	861	874
Aggregate Crushing Value (%) $\frac{m_2}{m_1} \times 100$		28.70	29.13
Average aggregate Crushing Value (%)		28.92	

IV) **Aggregate Impact Value:** The results of impact value tests are shown in Table 4.5a and Table 4.5b below for natural and recycled coarse aggregates respectively.

Table 4.5a: Aggregate impact value of Natural Coarse Aggregate.

Label	A	B
Total mass of test specimen (m_1) g	500	500
Mass of the material passing 2.36mm test sieve (m_2) g	109.25	98.05
Aggregate Impact Value (%) $\frac{m_2}{m_1}$ x 100	21.85	19.61
Average aggregate Impact Value (%)	20.73	

Table 4.5b: Aggregate impact value of recycled coarse Aggregate.

Label	A	B
Total mass of test specimen (m_1) g	500	500
Mass of the material passing 2.36mm test sieve (m_2) g	124.55	127.15
Aggregate Impact Value (%) $\frac{m_2}{m_1}$ x 100	24.91	25.43
Average aggregate Impact Value (%)	25.17	

V) **Moisture Absorption**

Results of moisture absorption test on natural coarse and recycled coarse aggregates are shown in Table 4.6a and 4.6b below respectively.

Table 4.6a: moisture absorption value of Natural Coarse Aggregate

Label	A	B
Mass of the oven-dry test portion in air (m_1) g	1000	1000
Mass of the saturated surface-dry test portion in air (m_2) g	1000	1000
Moisture absorption (%) $\frac{(m_2 - m_1)}{m_1} \times 100$	0.00	0.00
Average moisture absorption (%)	0.00	

Table 4.6b: Water absorption value of Recycled Coarse Aggregate

Label		A	B
Mass of the oven-dry test portion in air (m_1)	g	1000	1000
Mass of the saturated surface-dry test portion in air (m_2)	g	1045	1047
Moisture absorption (%) $\frac{m_2 - m_1}{m_1} \times 100$		4.5	4.7
Average moisture absorption (%)		4.6	

The physical properties of the coarse aggregates used in this work are summarized in Table 4.7.

Table 4.7: Summary of physical properties of coarse aggregates

Physical Properties	**Aggregate**	
	Natural	**Recycled**
Specific Gravity	2.8	2.49
Aggregate Crushing Value (%)	23.64	28.91
Aggregate Impact Value (%)	20.73	25.17
Moisture Absorption Value (%)	0.0	4.6

4.1.3. Presentation of mixture experiments results

The average values for slump, 1-day strength, and 28-day strength, for each of 46 concrete mixes are shown in Table 4.8, along with the estimated cost per cubic meter of concrete. Detailed experiments results are given in the appendix.

Table 4.8: Results of Experiments

Std. Order	Run Order	Slump(mm)	1-day(MPa)	28day(MPa)	Cost(N)/cubic meter
2	1	120.0	18.9	44.2	37483.71
67	2	130.0	20.5	41.2	39898.80
78	3	127.5	20.5	46.2	43310.93
80	4	120.0	23.9	50.5	42989.36
72	5	110.0	19.2	42.6	38847.25
26	6	145.0	22.0	51.0	41947.38
47	7	130.0	22.3	52.6	44849.65
10	8	137.5	24.7	48.4	44805.06
46	9	102.5	18.3	42.6	35922.31
27	10	100.0	19.8	39.4	38559.21
17	11	91.4	16.7	38.1	36898.74
69	12	115.5	19.9	40.1	41084.47
5	13	120.0	19.9	36.5	35966.90
21	14	120.0	17.7	38.7	42294.25
35	15	145.0	20.2	47.0	41073.71
4	16	95.0	19.6	38.2	35877.72
7	17	80.0	19.9	37.1	36033.95
73	18	115.0	17.4	40.6	38481.09
74	19	110.0	22.4	36.2	38525.68
17	20	90.5	17.9	37.0	36898.74
60	21	150.0	24.1	47.7	45991.35
8	22	170.0	26.4	57.4	46411.06
34	23	110.0	19.5	39.3	36321.99
1	24	115.0	25.1	53.7	44805.06
16	25	145.0	22.1	42.3	40430.57
72	26	107.5	19.7	42.1	38847.25
12	27	127.5	16.3	44.5	46757.92
75	28	97.5	14.6	40.1	39457.52
22	29	102.5	14.9	40.7	36725.30
38	30	145.0	20.2	47.3	45826.08
11	31	152.5	18.9	46.4	44894.24
69	32	115.5	17.6	44.6	41084.47
73	33	125.0	16.4	44.8	38481.09
8	34	160.0	23.8	55.5	46411.06
79	35	140.0	16.9	42.5	42944.77
35	36	125.0	20.2	47.0	41073.71
3	37	117.5	17.9	43.1	36610.04
50	38	117.5	20.2	44.7	40341.39
70	39	110.0	18.9	45.5	42944.77
69	40	100.0	18.8	43.2	41084.47
69	41	100.0	20.0	43.1	41084.47
9	42	145.0	22.5	49.2	45537.38
51	43	95.0	17.0	36.7	37064.00
24	44	120.0	18.9	43.1	43921.19
77	45	95.0	22.0	51.7	43747.76
33	46	125.0	23.0	48.6	45171.22
REF 1	0% Replacement	185	27.1	60.73	48462.08
REF 2	100%Replacement	185	22.1	38.66	36102.08

4.1.4. Presentation of mixture experiment data analysis results

The results of mixture experiment data analysis are shown in Tables 4.9a to 4.9c. They are the results for the final analysis where only significant terms are present. The results for the initial analysis, where all model terms are present are shown in Table A-3 – A-5. Figures 4.3a – 4.3c are the residual plots for each response property.

Table 4.9a Final regression for Mixtures: slump (mm) versus A, B, C, D, E, F, G

```
Estimated Regression Coefficients for SLUMP(mm) (component
proportions)

Term        Coef  SE Coef      T      P         VIF
A       -1966225   437870      *      *  4395750206
B       -2132746   516084      *      *  3921021580
C        7087461  1006876      *      *   224660793
D         246436    78908      *      *      920179
E         248676    78833      *      *   281304401
F         248799    78831      *      *   276347345
G         446914    85165      *      *   507403907
A*B     17330515  4023008   4.31  0.000  6165279798
B*C    -25587799  5163330  -4.96  0.000    98070535
C*G    -12692418  4037156  -3.14  0.003   285043839
D*E        20164     8656   2.33  0.026         571
S = 7.12695     PRESS = 3315.33
R-Sq = 90.46%   R-Sq(pred) = 81.69%   R-Sq(adj) = 87.66%
Analysis of Variance for SLUMP(mm) (component proportions)

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression      10  16379.4  16379.4  1637.94  32.25  0.000
   Linear        6  12689.6   6325.8  1054.31  20.76  0.000
   Quadratic     4   3689.8   3689.8   922.45  18.16  0.000
     A*B         1     61.3    942.6   942.60  18.56  0.000
     B*C         1   2854.3   1247.4  1247.42  24.56  0.000
     C*G         1    498.6    502.0   502.05   9.88  0.003
     D*E         1    275.6    275.6   275.62   5.43  0.026
Residual Error  34   1727.0   1727.0    50.79
   Lack-of-Fit  26   1183.2   1183.2    45.51   0.67  0.792
   Pure Error    8    543.8    543.8    67.97
Total           44  18106.4
```

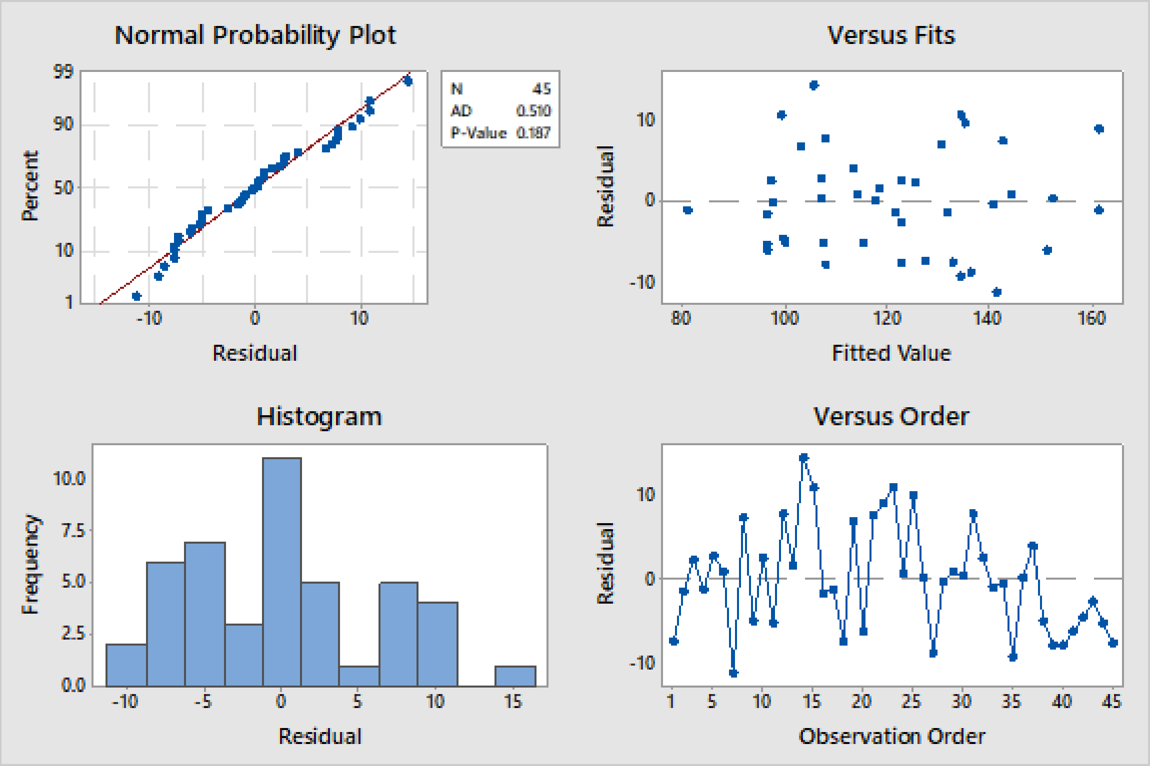


Fig 4.3a: Residual Plots for slump

Table 4.9b Final regression for Mixtures: 1-day compressive strength (MPa) versus A, B, C, D, E, F, G

```
Estimated Regression Coefficients for 1-DAY(MPa)(component
proportions)

Term       Coef  SE Coef       T      P          VIF
A        480266    99405       *      *   5822040572
B       -178902   138386       *      *   7245336979
C         26523    20319       *      *      2351174
D         25224    20322       *      *      1568435
E         26388    20316       *      *    480130349
F         26375    20316       *      *    471691841
G       -326970    81128       *      *  11832961790
A*B    -3546383   732574   -4.84  0.000   5253759178
B*G     2758789   761150    3.62  0.001  17306675666
S = 1.40587      PRESS = 113.854
R-Sq = 76.10%    R-Sq(pred) = 61.75%    R-Sq(adj) = 70.79%
Analysis of Variance for 1-DAY(MPa) (component proportions)
Source          DF   Seq SS   Adj SS  Adj MS      F      P
Regression       8  226.541  226.541  28.318  14.33  0.000
   Linear        6  179.817  226.099  37.683  19.07  0.000
   Quadratic     2   46.724   46.724  23.362  11.82  0.000
     A*B         1   20.759   46.319  46.319  23.44  0.000
     B*G         1   25.965   25.965  25.965  13.14  0.001
Residual Error  36   71.153   71.153   1.976
   Lack-of-Fit  28   62.555   62.555   2.234   2.08  0.141
   Pure Error    8    8.598    8.598   1.075
Total           44  297.694
```

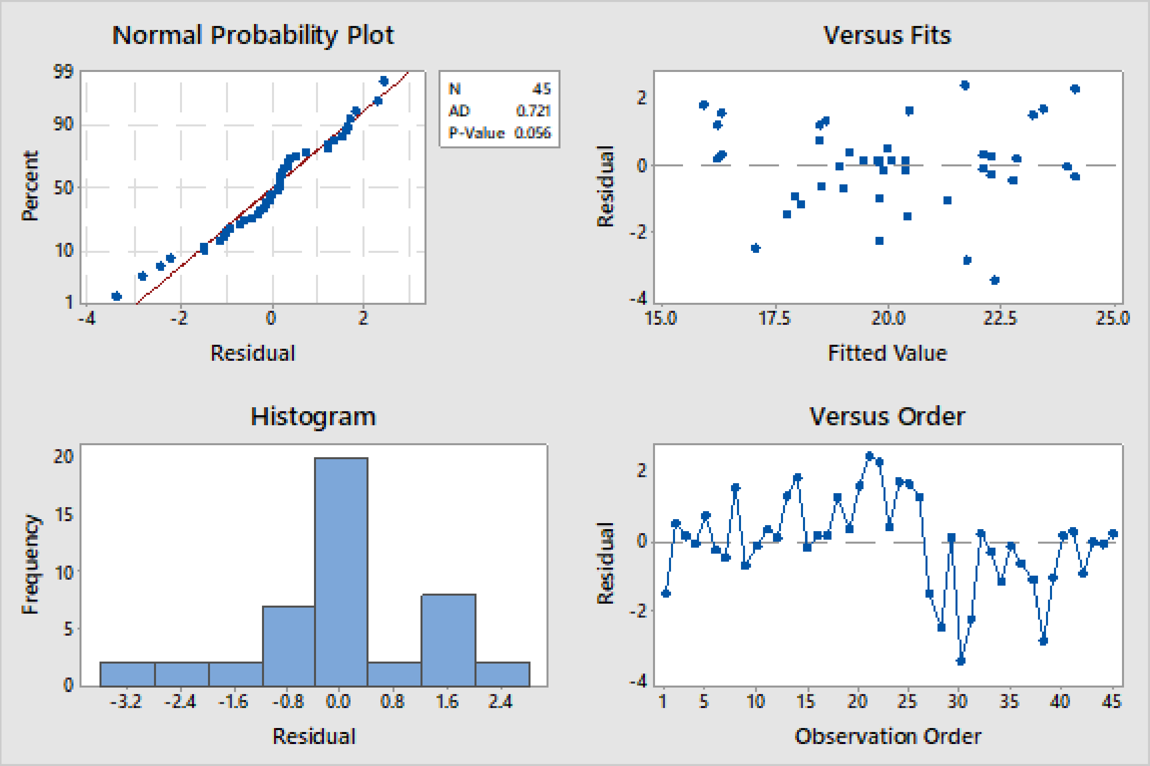


Fig 4.3b: Residual Plots for 1-day Strength

Table 4.9c Final regression for Mixtures: 28-Day compressive strength (MPa)

```
Estimated Regression Coefficients for 28-DAY(MPa) (component
proportions)

Term        Coef  SE Coef       T      P         VIF
A        -158734    64613       *      *  1157840390
B          30767    12330       *      *    27070388
C          31745    12332       *      *      409719
D         213038    86028       *      *    13198612
E          30335    12326       *      *    81531391
F          30298    12326       *      *    84067836
G         -85977    31469       *      *   838464896
A*D     -1146652   539851   -2.12  0.040    13438597
A*G       724715   272950    2.66  0.012  1631899100
S = 2.07153      PRESS = 235.506
R-Sq = 87.15%    R-Sq(pred) = 80.95%   R-Sq(adj) = 84.38%
Analysis of Variance for 28-DAY(MPa) (component proportions)

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression       8  1077.23  1077.23  134.654  31.38  0.000
   Linear        6  1026.56   918.32  153.053  35.67  0.000
   Quadratic     2    50.67    50.67   25.336   5.90  0.006
     A*D         1    20.42    19.36   19.360   4.51  0.040
     A*G         1    30.25    30.25   30.252   7.05  0.012
Residual Error  37   158.78   158.78    4.291
   Lack-of-Fit  29   136.59   136.59    4.710   1.70  0.221
   Pure Error    8    22.19    22.19    2.773
Total           45  1236.00
```

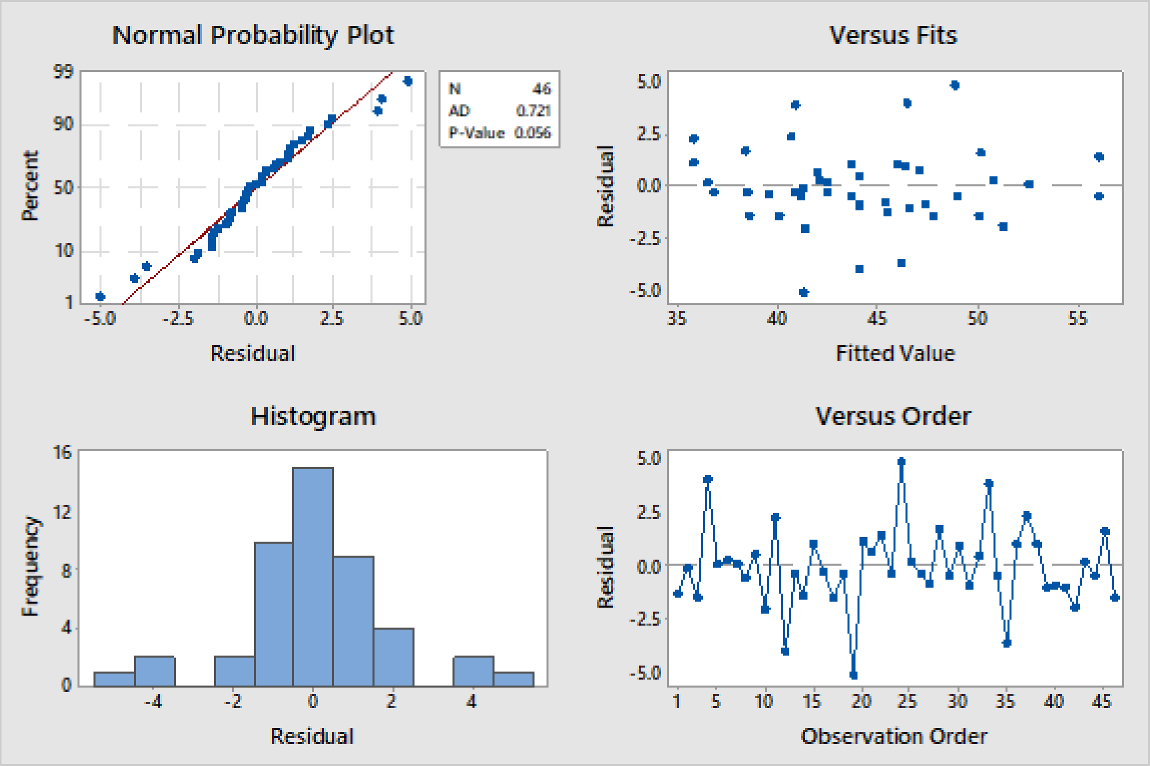


Fig 4.3c: Residual Plots for 28-day compressive strength

: The response traces for slump, 1-day strength, and 28-day compressive strengths are shown in Figures 4.4a – 4.4c respectively.

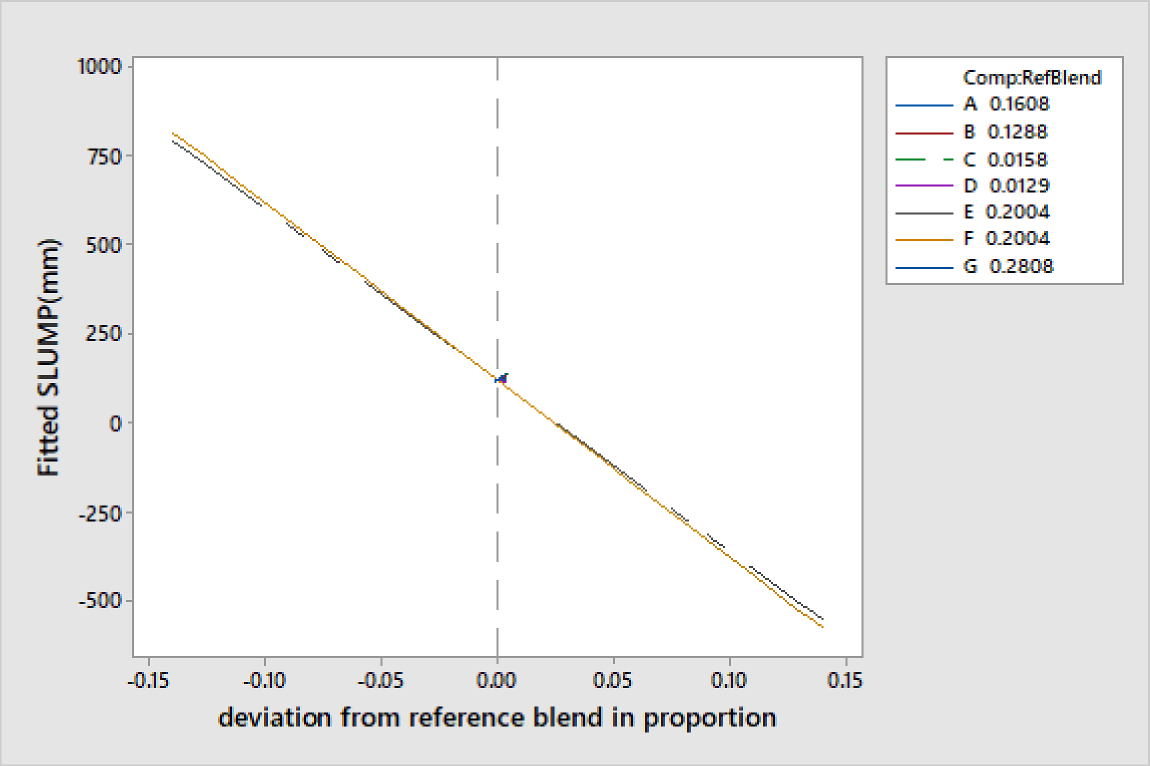


Fig 4.4a: Response trace plot for slump

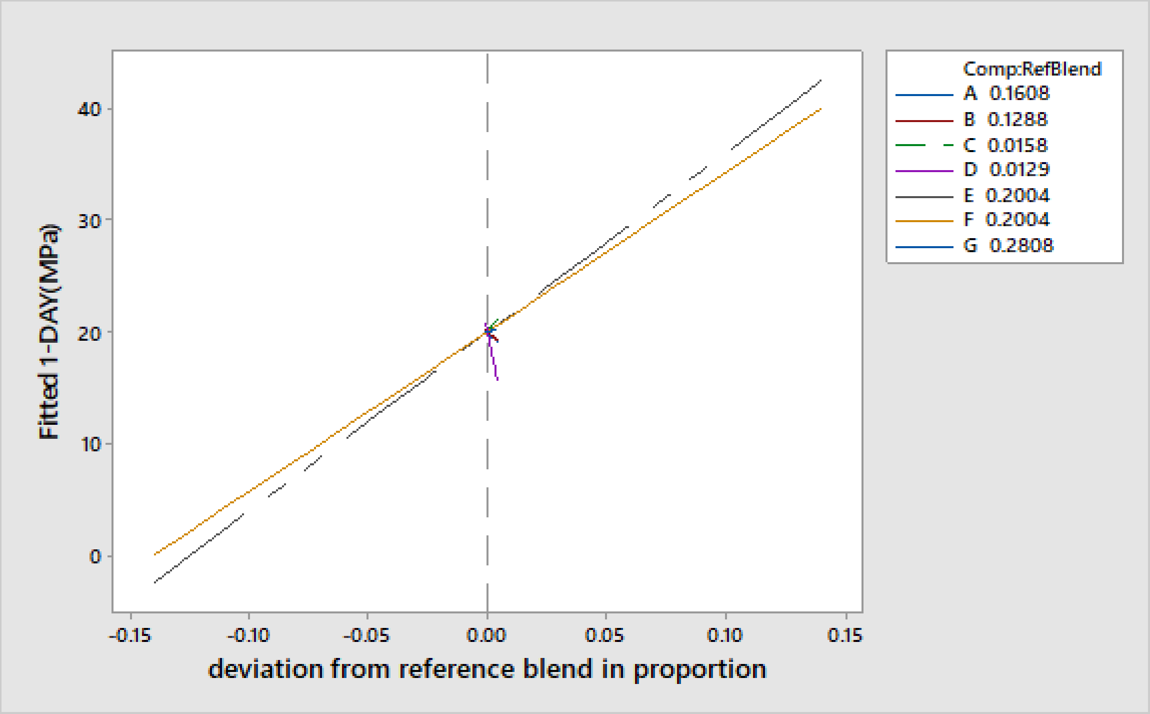


Fig 4.4b: Response trace plot for 1-day compressive strength

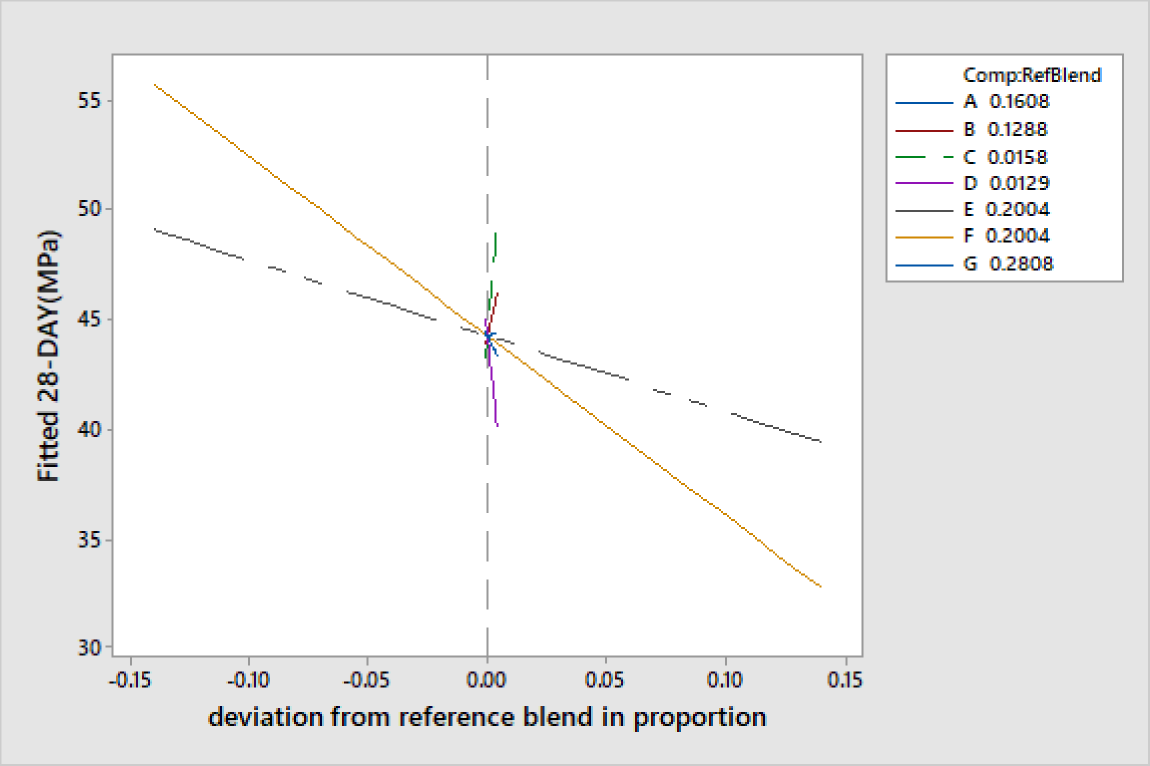


Fig 4.4c: Response trace plot for 28-day compressive strength

4.1.6. Presentation of mathematical or numerical optimization results

Using the “response optimizer” function of Minitab, the results in Table 4.9 were obtained for the numerical optimization of the high-performance recycled aggregate concrete.

Table 4.10 response Optimization

```
Parameters
             Goal      Lower  Target  Upper  Weight  Import
28-DAY(MPa)  Maximum      40      45     45       1       2
1-DAY(MPa)   Maximum      20      22     22       1       1
SLUMP(mm)    Target      100     125    150       1       1

Linear Constraints of Mixture Components

Constraint  Lower  A  B  C  D  E  F  G   Upper
         1    0.4  0  0  0  0  1  1  0  0.4049
         2    0.5  1  1  1  1  0  0  0       *  **

** indicates inconsistent or unnecessary constraint.
Global Solution
Components
A   =    0.160706
B   =    0.128385
C   =   0.0158992
D   =   0.0128065
E   =    0.321648
F   =   0.0797841
G   =    0.280771
Predicted Responses

28-DAY(MPa)    =    48.683  ,   desirability =   1.000000
1-DAY(MPa)     =    22.114  ,   desirability =   1.000000
SLUMP(mm)      =   124.991  ,   desirability =   0.999625

Composite Desirability = 0.999906
```

4.1.7. Presentation of results for model testing

a) Results from response optimizer

Table 4.11 shows the results of optimized concrete mix obtained from response optimizer.

Table 4.11 Experimental results of optimized concrete mix

Responses	Experimental results
Slump	130mm
1-day strength	21.86MPa
28-day strength	46.53MPa

b) Results of data analysis with 43 design points

Tables 4.12a – 4.12c show the results of data analysis for 43 design points, and Table 4.12 shows the predicted responses for design points 6, 22, and 38, from models generated with 43 design points.

Table 4.12a Regression for Mixtures: slump (mm) versus A, B, C, D, E, F, G (for 43 design points).

```
Estimated Regression Coefficients for SLUMP(mm) (component
proportions)

Term         Coef  SE Coef      T      P         VIF
A      -1979580   453423      *      *  4388773882
B      -2157090   534158      *      *  3917659213
C       6818565  1032502      *      *   214529775
D        253762    81618      *      *      925271
E        256161    81535      *      *   274843802
F        256302    81532      *      *   284181342
G        442358    87559      *      *   499985486
A*B    17491806  4164668   4.20  0.000  6158015280
B*C   -25188222  5262430  -4.79  0.000    92628138
C*G   -11891028  4073899  -2.92  0.006   263752240
D*E       21267     8706   2.44  0.020         534

S = 7.13304     PRESS = 3201.98
R-Sq = 89.42%   R-Sq(pred) = 78.51%   R-Sq(adj) = 86.00%
Analysis of Variance for SLUMP(mm) (component proportions)

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression      10  13325.4  13325.4  1332.54  26.19  0.000
   Linear        6  10015.3   5686.1   947.69  18.63  0.000
   Quadratic     4   3310.1   3310.1   827.53  16.26  0.000
     A*B         1     38.4    897.5   897.55  17.64  0.000
     B*C         1   2534.2   1165.7  1165.66  22.91  0.000
     C*G         1    433.8    433.5   433.48   8.52  0.006
     D*E         1    303.6    303.6   303.61   5.97  0.020
Residual Error  31   1577.3   1577.3    50.88
   Lack-of-Fit  24   1083.5   1083.5    45.15   0.64  0.805
   Pure Error    7    493.8    493.8    70.54
Total           41  14902.7
```

Table 4.12b Regression for Mixtures: 1-day (MPa) versus A, B, C, D, E, F, G
(for 43 design points)

```
The following terms cannot be estimated and were removed:
F*G
```

```
Estimated Regression Coefficients for 1-DAY(MPa) (component
proportions)

Term      Coef  SE Coef      T      P          VIF
A      1143151   208135      *      *  42171931680
B      -731595   172595      *      *  18650564144
C       142080    79223      *      *     57945498
D       155425   105187      *      *     69889289
E       319449    80231      *      *  11877150405
F       318683    80232      *      *  12912397881
G      -505819    71061      *      *  15025026717
A*B   -1787604   835282  -2.14  0.041  11292607505
A*E   -2482071   760749  -3.26  0.003  27613675973
A*F   -2482980   760736  -3.26  0.003  30020787476
B*D   -1838504   713669  -2.58  0.016     53423960
B*G    3431036   701172   4.89  0.000  24321839567
C*G    -788689   196377  -4.02  0.000     28125064
E*F         62       29   2.14  0.042           29
E*G      -3199     1040  -3.08  0.005       157649
```

```
S = 1.06865     PRESS = 75.3227
R-Sq = 88.41%   R-Sq(pred) = 72.69%   R-Sq(adj) = 82.61%
```

```
Analysis of Variance for 1-DAY(MPa) (component proportions)

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression      14  243.826  243.826  17.4161  15.25  0.000
   Linear        6  148.676   87.465  14.5775  12.76  0.000
   Quadratic     8   95.150   95.150  11.8938  10.41  0.000
     A*B         1   17.813    5.231   5.2305   4.58  0.041
     A*E         1    1.382   12.157  12.1567  10.65  0.003
     A*F         1   17.617   12.166  12.1660  10.65  0.003
     B*D         1    0.003    7.579   7.5789   6.64  0.016
     B*G         1   27.286   27.345  27.3446  23.94  0.000
     C*G         1   15.454   18.420  18.4204  16.13  0.000
     E*F         1    4.796    5.206   5.2056   4.56  0.042
     E*G         1   10.799   10.799  10.7995   9.46  0.005
Residual Error  28   31.976   31.976   1.1420
   Lack-of-Fit  21   26.724   26.724   1.2726   1.70  0.243
   Pure Error    7    5.253    5.253   0.7504
Total           42  275.802
```

Table 4.12c Regression for Mixtures: 28-day (MPa) versus A, B, C, D, E, F, G (for 43 design points)

```
Estimated Regression Coefficients for 28-DAY(MPa) (component
proportions)

Term      Coef  SE Coef      T       P         VIF
A      -189520    69706      *       *  1136211249
B        36629    13301      *       *    26606061
C        37340    13314      *       *      393129
D        35273    13324      *       *      269357
E        36190    13299      *       *    78385720
F        36153    13299      *       *    85217336
G       -92921    34127      *       *   832401123
A*G     804983   296004   2.72   0.010  1619003734

S = 2.18044      PRESS = 245.123
R-Sq = 83.44%   R-Sq(pred) = 75.61%   R-Sq(adj) = 80.13%
Analysis of Variance for 28-DAY(MPa) (component proportions)

Source           DF   Seq SS  Adj SS   Adj MS      F      P
Regression        7   838.62  838.62  119.803  25.20  0.000
   Linear         6   803.46  823.91  137.319  28.88  0.000
   Quadratic      1    35.16   35.16   35.161   7.40  0.010
     A*G          1    35.16   35.16   35.161   7.40  0.010
Residual Error   35   166.40  166.40    4.754
   Lack-of-Fit   28   146.08  146.08    5.217   1.80  0.216
   Pure Error     7    20.32   20.32    2.903
Total            42  1005.02
```

Table 4.13 Models predicted responses for design points 6, 22, and 38

Responses	POINT 6	POINT 22	POINT 38
SLUMP(mm)	139.89	156.18	112.38
1-DAY(MPa)	22.97	23.95	23.36
28-DAY(MPa)	49.14	54.32	41.96

4.2. Result Discussions

The results presented in Section 4.1 are here discussed accordingly.

4.2.1 Discussion on the results of materials characterization

I) Sieve analysis: Table 4.2b shows the comparison of grading of coarse aggregates (natural and recycled) used in this work with grading of coarse aggregate suitable for concrete works given in Table 2.2a, and Table 4.2c shows the comparison of grading of fine aggregate used in this work with fine aggregate suitable for concrete works given in Table 2.2b, all in accordance with BS 882 (1992)

From Table 4.2b, it is seen that natural coarse aggregate falls perfectly within the limits given in BS 882: 1992, while the recycled coarse aggregate falls nearly within the limit, and from Table 4.2c, it is seen that the fine aggregate used in this work is within the limit given in BS 882: 1992.

II) Specific gravity: From Tables 4.3a and 4.3b, it is seen that the specific gravity of the natural coarse aggregate and recycled coarse aggregate are 2.8 and 2.49 respectively. This indicate that the natural coarse aggregate meets the BS 882 (1992) requirements of greater than 2.6 for concrete while the recycled coarse aggregate almost met the requirement. From Tables 4.3c – 4.3e, it is seen that the specific gravity of fine aggregate, cement, and silica fumes are 2.74, 3.15, and 2.2 respectively. These conform to relevant specifications.

III) Aggregate crushing value: As seen in Table 4.4a and Table 4.4b, the aggregate crushing value of the recycled aggregate (28.91%) is higher than that of the natural aggregate (23.63%). This indicates that the recycled aggregate has lower compressive strength than the natural aggregate, however, both meet the limit of specification in BS 812-part 3-1975 of not greater than 30%.

IV) Aggregate impact value: As seen in Table 4.5a and Table 4.5b, the aggregate impact value for recycled aggregate is (25.17%) while that of the natural aggregate is (20.73%). According to BS 812-part 3-1975, the aggregate impact value of coarse aggregate for use in concrete production shall not exceed 30%, hence both met the requirement.

V) Water absorption: From Tables 4.6a, it is seen that water absorption of recycled aggregate is 4.6%; this is within the limits of 3.7% to 8.7% observed by Hansen and Narud

(1983) for water absorptions of coarse recycled aggregates. From Table 4.6b, the natural aggregate was observed to have no moisture absorption.

Table 4.7 shows the summary of the physical properties of coarse aggregates (natural and recycled).

4.2.2 Discussion of mixture experiment results

Table 4.8 shows results of slump, 1-day strength, and 28-day strength for 46 different mixtures of high performance recycled aggregate concrete and also the results for the reference mixtures 1 and 2. Results of reference mixture 1 are results obtained from using the component proportion in Table 4.1a, which is the proportion of the reference mixture which served as a guide for selecting the mixture components volume fraction ranges used for producing the extreme vertices design of mixture experiment in this work. While results of reference mixture 2 are results obtained from using recycled coarse aggregate in place of natural coarse aggregate in reference mixture 1, which component proportions are given in Table 4.1b.

From reference mixture 1, it is observed that slump close to 200mm, 1-day strength of 27MPa, and 28-day strength of 60MPa is attainable using only natural coarse aggregate. From reference mixture 2, it is also observed that slump close to 200mm, 1-day strength of 22MPa, and 28-day strength of 39MPa is attainable using only the recycled coarse aggregate. These indicate no noticeable reduction in slump, a reduction of 18.5% and 35% in 1-day strength and 28-day strength respectively when only recycled aggregate is used. These observations on compressive stregnths seem to be in line with the observations made by Mulhedron and O'Mahony (1988), Nishibayashi and Yamura (1988), and Kasai (1985), who all reported a reduction between 14% and 32% for the strength of a recycled aggregate concrete. Initial experiment indicated that at the water component settings for reference mixture 2, there was zero slump; this was thought to be as a result of the absorption of the recycled aggregate, hence, the recycled aggregate were soaked before used in batching to bring its moisture condition to SSD. When this was done, it was observed that reference mixture 2 (with only recycled coarse aggregate) gave the same slump as reference mixture 1 (with only natural coarse aggregate). This would mean that an increase in the water content needed to bring about the same slump with recycled coarse aggregate as with natural coarse aggregate in the HPC mixture; is dependent on the proportion of the recycled coarse aggregate contained in the mixture, and the moisture absorption capacity of the recycled aggregate (4.6% in this work).

The results in Table 4.8 were imputed into the design worksheet of Minitab and they were analyzed with the extreme vertices design initially created. Each response property was analyzed one after the other and the results for data analysis as presented in section 4.1.3 were obtained.

4.2.3 Discussion of mixture experiment data analysis results

Tables 4.9a - 4.9c contain the results of the final analysis of mixture experiment data of the three studied responses, (i.e. Tables where only significant terms are left after model reduction). Tables A3 – A5 contain results for the initial data analysis (i.e. Tables where all the model terms are present, before model reduction was performed). It can be seen from Table 4.9a that after performing model reduction, four quadratic terms were found to be significant for the slump model including interaction of water*cement, cement*silica fume, silica fume*fine aggregate, and HRWRA*natural coarse aggregate. From Table 4.9b, it is seen that two interaction terms were found to be significant including water*cement, and cement*fine aggregate. From Table 4.9c, it is seen that two interaction terms are also significant, including water*HRWRA, and water*fine aggregate. The coefficients of model terms which are used for the formulation of models for each response property are also presented in the respective tables. An inspection of the “R-squared” values in the final analysis suggests adequate models, and the suggestions were confirmed by assessing the residual plots as stated in section 2.5.2.5 for each response property. It is seen that all residual plots meet all the least squares assumptions for multiple linear regression as stated in section 2.5.2.1. Also, lack of fit for all models was found to have insignificant p-values indicating that the models chosen explain the variation in responses.

4.2.4 Discussion on Cox response trace plots

Figures 4.4a – 4.4c show the response trace plots for slump, 1-day strength, and 28-day strength respectively. As stated previously, the Cox response trace plot is used to study the effect of changing the proportion of each component on the mixture. As also mentioned earlier, the response trace plot is interpreted relative to a reference mixture usually the centroid of the design points.

Figure 4.4a is the response trace plot for the slump, and it is interpreted thus:

a) As the proportion of natural coarse aggregate:

i. Increases (and other mixture component decrease), the slum of the mixture is decreased.

ii. Decreases (and other mixture components increase), the slump of the mixture is increased.

b) As the proportion of recycled coarse aggregate:

i. Increases (and other mixture component decrease), the slum of the mixture is decreased.

ii. Decreases (and other mixture components increase), the slump of the mixture is increased.

c) As could be observed, exactly the same interpretation applies for both natural and recycled coarse aggregate. This implies that both natural and recycled coarse aggregates have exactly the same effect on the mixture, therefore, the variation in slump property may as well have been determine by other mixture components.

Figure 4.4b is the response trace plot for 1-day strength and is interpreted thus:

a) As the proportion of natural coarse aggregate:

i. increases (and the other mixture components decrease), the 1-day strength of the HPC increases.

ii. decreases, (and other mixture components increase), the 1-day strength of the HPC decreases.

b) As the proportion of recycled coarse aggregate:

i. Increases (and the other mixture components decrease), the 1-day strength of the HPC increases.

ii. Decreases, (and other mixture components increase), the 1-day strength of the HPC decreases.

c) As also could be observed, the same interpretation applies to both natural and recycled aggregate; however, increase in proportion of natural coarse aggregate has a greater positive effect on the 1-day strength of the mixture than increase in proportion of recycled coarse aggregate.

Figure 4.4c is the response trace plot for 28-day strength, it is interpreted thus:

a) As the proportion of natural coarse aggregate

i. Increases, (and other mixture components decrease), the 28-day strength is decreased.

ii. Decreases, (and other mixture component increase), the 28-day strength is increased.

b) As the proportion of recycled coarse aggregate

i. Increases, (and other mixture components decrease), the 28-day strength is decreased.

ii. Decreases, (and other mixture component increase), the 28-day strength is increased.

c) The same interpretation for natural coarse aggregate also go for recycled coarse aggregate, however, greater strength is achievable in reducing the proportion of recycled coarse aggregate than in reducing the proportion of natural coarse aggregate. Hence, in applying the models in this study, one may wish to keep the proportion of recycled coarse aggregate low.

It is observed from Figures 4.4a – 4.4c that both natural and recycled coarse aggregates have the same trace direction in all the trace plots, this implies that they both have the same effect on the mixture (i.e. the both affect the mixture as “coarse” aggregate). However, the natural coarse aggregate has more positive effect on the mixture for all response property, even though its effect on the 1-day strength and slump is not truly great.

A quadratic model could not give an interpretable response traces because of the particular nature of the mixture experiment, which involves partial replacement of natural coarse aggregate with recycled aggregate. Partial replacement of the coarse aggregate prompted the selection of large volume fraction ranges for both natural and recycled coarse aggregates (relative to other components volume fractions) in order to obtain an alternate random selection of both components in all concrete mixes, so as to achieve partial replacements in high and low percentages. The large difference in volume fraction ranges of natural and coarse aggregates compared to other mixture components, caused other mixture components on the trace plots to appear insignificant to sight, and also created the problem of interpreting a response trace plot from a quadratic model. However, according to the developed models, the interaction effects involving natural coarse aggregate or recycled coarse aggregate are not significant except for slump where natural coarse aggregate has only one interaction effect. Therefore, a linear model was adequate to explain the effects of these two components on the mixture. When the mixture component proportions are restricted by lower and upper bounds of the form $0 \leq Li \leq xi \leq Ui \leq 1$, the ranges $Ri = Ui - Li$, $i = 1, 2, \ldots, q$, are seldom equal or even close to being equal to each other (as is the case in this work), we cannot be assured of reliable estimates of the effects of the individual components (Cornell, 2011).

4.2.5 Discussion on mathematical or numerical optimization results

In section 4.1.4, a high performance recycled aggregate concrete, was optimized with Minitab and the results presented in that section. The said HPC was to have the following properties:

i. 1-day compressive strength must be greater than 20MPa
ii. 28-day compressive strength must be greater than 40MPa, and
iii. Slump in the range of 100 – 150 mm

After the optimization, it was obtained that the concrete meeting the above requirement should have the following components proportion as given in Table 4.9

Water = 0.160706
Cement = 0.128385
Silica fume = 0.0158992
HRWRA = 0.0128065
Natural agg. = 0.321648
Recycled agg. = 0.0797841
Fine agg. = 0.280771

This implies that this is the best component settings that would produce the predicted responses at the most considerate cost, and that when the same materials used to prepare concrete mixes in this work are used at these component settings to make a concrete mix, under same conditions, the response properties that would be obtained should be the same or close to the predicted optimized responses.

These components proportion in weight per cubic meter of concrete could be given as: water = 152.5Kg, cement = 383.7Kg, silica fume = 33.2Kg, HRWRA = 12.2L, natural coarse aggregate = 854.5Kg, recycled coarse aggregate = 188.5Kg, and fine aggregate = 730Kg at a cost of N44, 862.13 per cubic meter of concrete.

The predicted responses are: 28-day strength of 48.693MPa, 1-day strength of 22.114MPa, and a slump of 124.991mm with a composite desirability of 0.999906.

A composite desirability of 0.999906 which is close to 1 implies that Minitab was able to find a combination of the input variables that is quite likely to satisfy the goals that have been defined for each response simultaneously.

4.2.6 The models

Models were formed by adding up the products of coefficients and corresponding terms (linear and interactions) as presented in the Scheffe's quadratic model. The coefficients and corresponding terms are given in Tables 4.7d – 4.7f for slump, 1-day strength, and 28-day strength respectively. Equations 4.1 – 4.3 are models for slump, 1-day compressive strength, and 28-day compressive strength respectively.

$$y_1 = -1966225*A - 2132746*B + 7087461*C - 246436*D + 248676*E + 248799*F + 446914*G + 17330515(A*B) - 25587799(B*C) - 12692418(C*G) + 20164(D*E) \quad (4.1)$$

$$y_2 = 480266*A - 178902*B + 26523*C + 25224*D + 26388*E + 26375*F - 326970*G - 3546383(A*B) + 2758789(B*G) \quad (4.2)$$

$$y_3 = -158734*A + 30767*B + 31745*C + 213038*D + 30335*E + 30298*F - 85977*G - 1146652(A*D) + 724715(A*G) \quad (4.3)$$

Where the terms A – G represent appropriate volume fractions of the mixture components as previously defined.

(y_1 = Slump, y_2 = 1-Day strength, y_3 = 28-Day strength)

4.2.7 Discussion on results for testing the models

The models developed in this work were tested using two approaches.

a) Using the components settings obtained from response optimization in Table 4.9, and
b) By removing three randomly selected design points from the 46 design points, then fitting a model with the remaining 43 design points and then using the fitted models to predict the three design points that were removed.

a) Using the components settings obtained from response optimization in Table 4.9

The result from response optimizer in Table 4.9 suggests that when the component settings given are used to make a concrete mix with exactly the same components used in the experimental design, the predicted responses shall be obtained. The component settings given in Table 4.9, gives the following weight of components per cubic meter of concrete:

water = 152.5Kg, cement = 383.7Kg, silica fume = 33.2Kg, HRWRA = 12.2L, natural coarse aggregate = 854.5Kg, recycled coarse aggregate = 188.5Kg, and fine aggregate = 730Kg at a cost of N44, 862.13 per cubic meter of concrete. The mixture gave the experimental response properties shown in Table 4.10. Table 4.1h shows the model predicted results from response optimizer and the experimental results of optimized mix.

From Table 4.1h, it is seen that the experimental responses are quite close to the predicted responses; this indicates that the models are reasonably accurate.

b) Removing three randomly selected design points from the 46 design points, then fitting a model with the remaining 44 design points and then using the fitted models to predict the three design points that were removed.

Design points 6, 22, and 38 were randomly selected and removed from the set of 46 candidate design points. The remaining 43 design points were used to fit models to the data of the three studied responses. The results of these analyses are given in Tables 4.10a – 4.10c. Equations 4.4 – 4.6 are the models developed from 43 design points.

$y_1'y_1'$ = -1979580*A – 2157090*B + 6818565*C + 253762*D + 256161*E + 256302*F +
442358*G + 17491806(A*B) – 25188222(B*C) – 11891028(C*G) + 21267(D*E) (4.4)

$y_2'y_2'$ = 1143151*A – 731595*B + 142080*C + 155425*D + 319449*E + 318683*F –
505819*G – 1787604(A*B) – 2482071(A*E) – 2482980(A*F) – 1838504(B*D) +
3431036(B*G) – 788689(C*G) + 62(E*F) – 3199(E*G) (4.5)

$y_3'y_3'$ = -189520*A + 36629*B + 37340*C + 35273*D + 36190*E + 36153*F –
92921*G + 804983(A*G) (4.6)

$y_1'y_1'$ = slump, $y_2'y_2'$= 1-day strength, $y_3'y_3'$= 28-day strength.

The models (equations 4.4 – 4.6) were used to predict design points 6, 22, and 38 and the results in Table 4.13 were obtained. These results are compared with the experimental results in Table 4.1i – Table 4.1k. for design points 6, 22, and 38 respectively

As observed in Tables 4.1i – 4.1k, the experimental results are close to the models predicted results and they all fall within the prediction intervals at 95% confidence level. This indicates that the models work. The confidence interval (CI) at a confidence level of 95% implies that there is a 95% certainty that the mean response would fall within the stated range for a number of observations. The prediction interval at 95% confidence level indicates that if the experiments were to be conducted a certain number of times, 95% of the times, the results obtained for a new observation would fall within the stated range.

It is known that models with more design points are likely to be more accurate than models with fewer design points; hence, it could be concluded that the initial models developed with 46 design points will give more accurate predictions than the ones developed with 43 design points.

4.6: Allowable replacement for natural aggregate

Assuming the ultimate strength (i.e. 28-day strength) to be more relevant than the other response properties studied; the allowable natural coarse aggregate replacement is estimated from the 28-day strength.

The range of 28-day strength obtained from experiment is 36.2 – 57.4 (MPa).

If 45MPa is considered minimum for high performance at 28-day strength, then from response optimizer, the component settings in Table 4.1l will produce a HPC of 45MPa.

At these component settings, only a replacement of 43% by weight of natural coarse aggregate can be tolerated. Because, if only natural coarse aggregates were used, the volume fraction of coarse aggregate in this mixture would be (0.207512 + 0.192488 = 0.4);

Using equations 3.10 – 3.14, the weight of only natural coarse aggregate would be 1063Kg,

In the actual mixture, the weight of natural coarse aggregate is 551.35Kg and the weight of recycled coarse aggregate is 454.81Kg. Therefore,

$\frac{454.81}{1063} \times 100 = 43\%.$

Assuming strength at the upper bound of the range is desired, say 55MPa, then response optimizer gives the optimization in Table 4.1m. At these component settings, only a replacement of 13.3% by weight of natural coarse aggregate can be tolerated. Because, in this mixture, if only natural coarse aggregates were used, the volume fraction of coarse aggregate in this mixture would be (0.34 + 0.06 = 0.4);

Using equations 3.10 – 3.14, the weight of only natural coarse aggregate would be 1063Kg, in the actual mixture, the weight of natural coarse aggregate is 902.68Kg, and the weight of recycled coarse aggregate is 141.77Kg, therefore,

$\frac{141.77}{1063} \times 100 = 13.3\%$.

Response optimizer however could not find optimum solutions for 28-day strength beyond 55MPa. This is because regression models are limited to predicting response properties within the experimental results range. Values that are too close to the bounds of the range may not also be accurately predicted. The ranges of values obtained from experiments are:

80 – 170(mm) for slump; 14.6 – 26.4(MPa) for 1-day strength; and 36.2 – 57.4(MPa) for 28-day strength.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the results of this work, the following conclusions are drawn:

The results from materials characterization tests indicate that the natural and recycled coarse aggregates, as well as the fine aggregate, are within acceptable limits for use in general production of concrete mixes, and by extension, the production of high performance concrete mixes.

The mixture experiment results show that reasonable results for slump, 1-day compressive strength, and 28-day compressive strength are attainable if recycled coarse aggregate are used to partially replace natural coarse aggregate in a high performance concrete mix.

The analysis of the mixture experiment results produced quadratic models which were adequate for predicting and optimizing the studied properties of the HPC.

From the interpretation of the Cox response trace plot, it was concluded that the natural coarse aggregate and the recycled coarse aggregate both have positive effect on all studied response properties. However, the positive effect of the recycled coarse aggregate is minimally lower than the positive effect of the natural coarse aggregate for slump and 1-day compressive strength properties, but the disparity in their positive effect on the mixture is more pronounced in the 28-day compressive strength.

From the numerical optimization results, it was concluded that the developed models are adequate for the optimization of high performance recycled coarse aggregate concrete, because when the models were tested using results of the numerical optimization, experimental tests produced results of high accuracy.

As industrialists are task with sustainable development, and environmentalists clamor for environmental protection practices, it is important that the construction industry aligns its self to the global trend of achieving sustainable construction and good environmental practices.

As concrete is always a reliable construction material in the construction industry, it is important that other sources of coarse aggregate is sought, in order not to strain out or over depend on the existing sources of natural aggregate. The use of recycled aggregate will not only create sustainable construction but will also minimize construction waste for environmental protection. Apart from using recycled aggregate for conventional concrete production, this study has shown that recycled aggregate could as well be used where relatively high strength concrete is needed both at early and ultimate strengths, and also where high workability is needed, to produce high performance recycled aggregate concrete, hence, creating a diverse application of recycled aggregate.

5.2. Recommendations

The models developed in this study could be applied to obtain optimum high performance recycled aggregate mixes. Therefore, the use of recycled aggregate could be a way to achieving sustainable construction in the construction industry. The models developed in this work have been tested, and have been observed to be accurate; therefore, the following recommendations are made:

a) The models are hereby recommended for use in the production of high-performance recycled aggregate concrete within the following range of results obtained: 80 – 170(mm) for slump; 14.6 – 26.4(MPa) for 1-day strength; and 36.2 – 57.4(MPa) for 28-day strength; and in accordance with specifications for materials used in this work, for work of any scale.

b) When considering the use of these models, only a replacement of 13.3% - 43% by weight of natural coarse aggregate should be considered.

c) Future researches may focus on using different types of superplasticizers, and silica fumes in higher proportions to improve on the response properties obtained in this work.

d) Also, the method of total replacement of natural coarse aggregate with recycled coarse aggregate could be considered in future work.

5.3 Contributions to knowledge

This research work has contributed to knowledge in the following ways:

i. by establishing reliable models that could be used to optimize the 1-day and 28-day compressive strength, and the workability of high performance recycled aggregate concrete.

ii. by establishing the maximum allowable percentage replacement of natural coarse aggregate by recycled coarse aggregate in a high performance concrete mix, i.e. 43% replacement for minimum 28-day compressive strength of 45MPa and 13.3% replacement if strength up to 55MPa is required.

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APPENDIX A: Mixture experiment design and analysis detailed results

Table A-1. Mixture experiment results: 1-day and 28-day strength compressive strength

Std. Order	Run Order	1-Day Strength (MPa)			28-Day Strength (MPa)		
2	1	20.45	17.73	18.52	44.37	46.65	41.59
67	2	20.42	19.66	21.42	46.77	36.19	40.51
78	3	20.41	20.60	20.49	49.36	44.76	44.48
80	4	23.47	26.05	22.18	47.27	51.07	53.16
72	5	20.98	18.34	18.28	41.44	43.48	42.88
26	6	21.01	22.79	22.20	55.28	49.98	47.75
47	7	23.38	20.40	23.12	54.15	53.15	50.40
10	8	25.12	24.41	24.57	43.46	54.87	46.87
46	9	19.86	17.90	17.13	42.90	42.64	42.29
27	10	19.50	19.04	20.75	37.07	38.09	42.93
17	11	16.23	16.41	17.32	36.54	40.38	37.37
69	12	19.32	18.13	22.25	34.85	42.64	42.81
5	13	20.64	19.92	19.15	38.51	33.35	37.66
21	14	17.05	18.30	17.75	36.47	36.76	42.74
35	15	19.10	19.81	21.69	39.54	51.00	50.43
4	16	18.58	21.33	18.89	36.19	41.45	36.96
7	17	20.26	20.61	18.83	31.70	40.55	39.04
73	18	16.34	17.35	18.51	36.39	48.81	36.55
74	19	22.24	21.61	23.35	38.56	38.10	31.84
17	20	18.36	17.27	18.08	35.06	36.89	39.05
60	21	25.63	24.13	22.54	46.44	46.05	50.61
8	22	24.80	24.50	29.90	53.08	56.08	63.05
34	23	18.91	20.03	19.55	37.10	39.23	41.49
1	24	23.13	25.85	26.31	55.98	62.24	42.88
16	25	20.18	23.89	22.22	41.11	43.16	42.63
72	26	19.46	18.17	21.47	41.56	38.34	46.43
12	27	16.75	16.33	15.82	44.09	40.15	49.26
75	28	16.52	13.69	13.58	34.52	42.77	43.01
22	29	15.17	15.17	14.42	42.79	36.77	42.54
38	30	20.86	21.37	18.29	50.27	45.14	46.36
11	31	21.26	18.06	17.48	51.22	44.48	43.50
69	32	16.48	16.44	19.76	39.55	49.47	44.73
73	33	17.26	15.50	16.41	44.01	42.67	47.72
8	34	22.21	25.33	23.90	43.70	59.50	63.20
79	35	17.07	17.50	16.23	41.81	45.72	40.06
35	36	20.39	18.65	21.70	51.79	48.92	40.27
3	37	18.26	18.63	16.71	42.55	43.39	43.36
50	38	20.95	20.13	19.65	46.92	42.37	44.83
70	39	18.79	17.81	20.07	45.21	44.77	46.51
69	40	19.12	18.91	18.30	43.23	41.44	44.93
69	41	19.93	20.76	19.19	37.66	43.10	48.54
9	42	23.48	22.44	21.55	53.03	54.80	39.78
51	43	16.05	17.16	17.93	36.10	38.23	35.82
24	44	18.48	18.94	19.24	41.81	42.53	45.05
77	45	22.41	20.97	22.66	55.45	43.36	56.28
33	46	23.05	22.53	23.50	52.71	46.37	46.57
REF 1	0% Replacement	27.70	27.00	26.60	61.37	53.65	67.17
REF 2	100%Replacement	21.80	22.60	21.90	38.97	38.82	38.20

Table A-2: Mixture experiment result: Slump

Std. Order	**Run Order**	**Slump(mm)**	
2	1	110	130
67	2	120	140
78	3	120	135
80	4	120	120
72	5	135	85
26	6	145	145
47	7	130	130
10	8	150	125
46	9	95	110
27	10	110	40
17	11	70	70
69	12	120	125
5	13	130	110
21	14	115	125
35	15	110	180
4	16	80	110
7	17	130	30
73	18	110	120
74	19	120	100
17	20	70	145
60	21	130	170
8	22	170	170
34	23	90	130
1	24	130	100
16	25	150	140
72	26	130	85
12	27	140	115
75	28	130	65
22	29	110	95
38	30	135	110
11	31	140	165
69	32	130	145
73	33	140	110
8	34	150	170
79	35	140	140
35	36	120	130
3	37	110	125
50	38	140	95
70	39	90	130
69	40	115	85
69	41	110	90
9	42	150	140
51	43	95	65
24	44	130	115
77	45	90	100
33	46	140	110
REF 1	0% Replacement	180	190
REF 2	100%Replacement	190	180

Table A-3 Initial regression for Mixtures: slump (mm) versus A, B, C, D, E, F, G

```
The following terms cannot be estimated and were removed:

B*D
C*D
C*F
D*F
F*G
Estimated Regression Coefficients for SLUMP(mm) (component proportions)

Term         Coef  SE Coef       T       P          VIF
A          243302  1374046       *       *  41963580028
B        -3359316  1412942       *       *  28490601505
C         5294675  1029853       *       *    228981433
D           67346  1045646       *       *    156267560
E         1013872   587920       *       *  14864748921
F         1015790   587981       *       *  15330120838
G          482904   530921       *       *  19125833539
A*B      26198149  6181235    4.24   0.000  14105801154
A*C       -946505  5313253   -0.18   0.860    157592464
A*D        175537  5349480    0.03   0.974    105750886
A*E      -8255488  5221712   -1.58   0.128  30328949517
A*F      -8264693  5221639   -1.58   0.127  31287828042
A*G      -1820930  1001881   -1.82   0.082   1762036733
B*C     -34539111  6573822   -5.25   0.000    154825029
B*E        571896  1021266    0.56   0.581    744433892
B*F        576132  1021277    0.56   0.578    768109006
B*G      -2749231  5096142   -0.54   0.595  29270558561
C*E         11974     9204    1.30   0.206          931
C*G      -3387314  1394533   -2.43   0.023     33144964
D*E         20118    11508    1.75   0.094          958
D*G      -1179590  1034870   -1.14   0.266     12086795
E*F           164      183    0.90   0.378           27
E*G          2374     9203    0.26   0.799       287464

S = 7.31750      PRESS = 14727.7
R-Sq = 93.31%    R-Sq(pred) = 20.04%   R-Sq(adj) = 86.92%
```

```
Analysis of Variance for SLUMP(mm) (component proportions)

Source          DF   Seq SS    Adj SS   Adj MS      F      P
Regression      22  17186.3  17186.28   781.19  14.59  0.000
   Linear        6  12868.1   1464.84   244.14   4.56  0.003
   Quadratic    16   4318.2   4318.21   269.89   5.04  0.000
     A*B         1     52.4    961.87   961.87  17.96  0.000
     A*C         1     25.8      1.70     1.70   0.03  0.860
     A*D         1    412.3      0.06     0.06   0.00  0.974
     A*E         1      0.0    133.84   133.84   2.50  0.128
     A*F         1     22.1    134.14   134.14   2.51  0.127
     A*G         1    181.4    176.88   176.88   3.30  0.082
     B*C         1   2513.4   1478.13  1478.13  27.60  0.000
     B*E         1    294.3     16.79    16.79   0.31  0.581
     B*F         1     11.1     17.04    17.04   0.32  0.578
     B*G         1     34.0     15.58    15.58   0.29  0.595
     C*E         1     66.6     90.62    90.62   1.69  0.206
     C*G         1    259.9    315.92   315.92   5.90  0.023
     D*E         1    276.7    163.64   163.64   3.06  0.094
     D*G         1    120.4     69.57    69.57   1.30  0.266
     E*F         1     44.3     43.27    43.27   0.81  0.378
     E*G         1      3.6      3.56     3.56   0.07  0.799
Residual Error  23   1231.6   1231.55    53.55
   Lack-of-Fit  15    687.8    687.80    45.85   0.67  0.757
   Pure Error    8    543.8    543.75    67.97
Total           45  18417.
```

Table A-4 Initial regression for Mixtures: 1-day (MPa) versus A, B, C, D, E, F, G

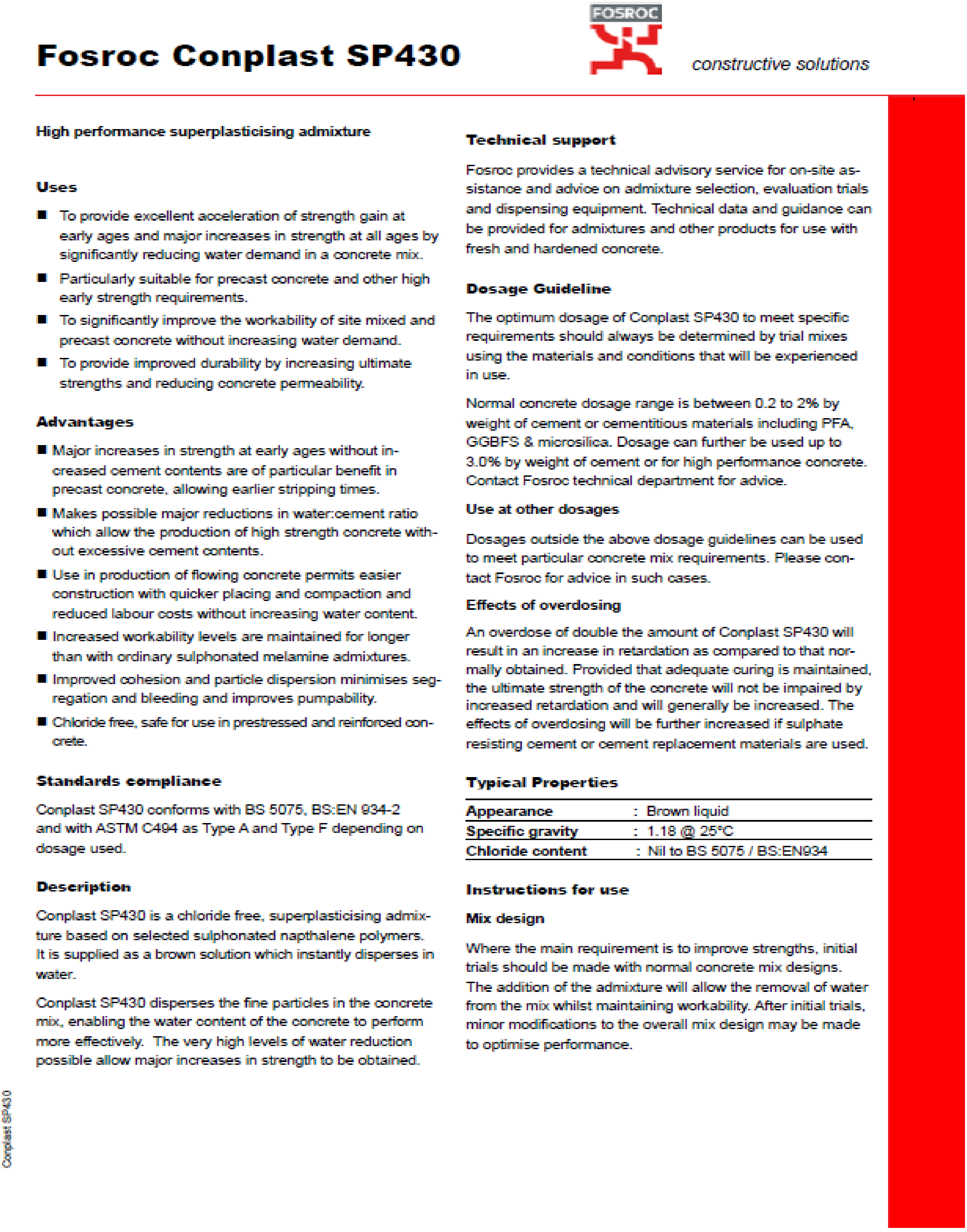
```
The following terms cannot be estimated and were removed:
B*D
C*D
C*F
D*F
F*G
Estimated Regression Coefficients for 1-DAY(MPa) (component proportions)

Term      Coef  SE Coef      T      P          VIF
A      1035647   234422      *      *  41963580028
B      -728138   241058      *      *  28490601505
C        71256   175700      *      *    228981433
D       148569   178394      *      *    156267560
E       287324   100303      *      *  14864748921
F       286636   100314      *      *  15330120838
G      -482252    90579      *      *  19125833539
A*B   -1769766  1054562  -1.68  0.107  14105801154
A*C    1863692   906478   2.06  0.051    157592464
A*D   -1488915   912658  -1.63  0.116    105750886
A*E   -2138728   890860  -2.40  0.025  30328949517
A*F   -2139598   890848  -2.40  0.025  31287828042
A*G     -64944   170928  -0.38  0.707   1762036733
B*C   -1745608  1121540  -1.56  0.133    154825029
B*E       8664   174235   0.05  0.961    744433892
B*F       8838   174237   0.05  0.960    768109006
B*G    3496072   869437   4.02  0.001  29270558561
C*E       1822     1570   1.16  0.258          931
C*G    -718097   237917  -3.02  0.006     33144964
D*E         12     1963   0.01  0.995          958
D*G     120391   176556   0.68  0.502     12086795
E*F         32       31   1.04  0.310           27
E*G      -2920     1570  -1.86  0.076       287464
S = 1.24842      PRESS = 217.711
R-Sq = 88.92%   R-Sq(pred) = 32.71%   R-Sq(adj) = 78.32%
Analysis of Variance for 1-DAY(MPa) (component proportions)

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Regression      22  287.693  287.693  13.0770   8.39  0.000
   Linear        6  186.427   68.542  11.4236   7.33  0.000
   Quadratic    16  101.266  101.266   6.3292   4.06  0.001
     A*B         1   18.750    4.389   4.3894   2.82  0.107
     A*C         1    0.041    6.588   6.5880   4.23  0.051
     A*D         1    2.397    4.148   4.1480   2.66  0.116
     A*E         1    0.748    8.983   8.9828   5.76  0.025
     A*F         1   17.866    8.990   8.9903   5.77  0.025
     A*G         1    0.156    0.225   0.2250   0.14  0.707
     B*C         1    0.807    3.776   3.7756   2.42  0.133
     B*E         1    0.023    0.004   0.0039   0.00  0.961
     B*F         1    0.015    0.004   0.0040   0.00  0.960
     B*G         1   22.616   25.200  25.2001  16.17  0.001
     C*E         1   17.563    2.097   2.0973   1.35  0.258
     C*G         1   13.105   14.198  14.1982   9.11  0.006
     D*E         1    0.133    0.000   0.0001   0.00  0.995
     D*G         1    0.201    0.725   0.7247   0.46  0.502
     E*F         1    1.456    1.676   1.6762   1.08  0.310
     E*G         1    5.389    5.389   5.3891   3.46  0.076
Residual Error  23   35.846   35.846   1.5585
   Lack-of-Fit  15   27.248   27.248   1.8166   1.69  0.230
   Pure Error    8    8.598    8.598   1.0748
Total           45  323.540
```

Table A-5 Initial regression for Mixtures: 28-day (MPa) versus A, B, C, D, E, F, G

```
The following terms cannot be estimated and were removed:
B*D
C*D
C*F
D*F
F*G
Estimated Regression Coefficients for 28-DAY(MPa) (component proportions)

Term       Coef  SE Coef      T      P          VIF
A        337043   372836      *      *  41963580028
B        263227   383390      *      *  28490601505
C       -230154   279442      *      *    228981433
D        -93368   283727      *      *    156267560
E        234984   159527      *      *  14864748921
F        232049   159544      *      *  15330120838
G        -92718   144061      *      *  19125833539
A*B     1020118  1677226   0.61  0.549  14105801154
A*C      323065  1441706   0.22  0.825    157592464
A*D    -1036863  1451536  -0.71  0.482    105750886
A*E    -2126848  1416867  -1.50  0.147  30328949517
A*F    -2121407  1416847  -1.50  0.148  31287828042
A*G      857057   271852   3.15  0.004   1762036733
B*C     -148069  1783751  -0.08  0.935    154825029
B*E     -336400   277112  -1.21  0.237    744433892
B*F     -328594   277115  -1.19  0.248    768109006
B*G    -1573031  1382795  -1.14  0.267  29270558561
C*E       -2522     2498  -1.01  0.323          931
C*G      176902   378395   0.47  0.645     33144964
D*E       -4849     3123  -1.55  0.134          958
D*G      391206   280803   1.39  0.177     12086795
E*F          33       50   0.67  0.511           27
E*G       -3256     2497  -1.30  0.205       287464

S = 1.98554      PRESS = 364.520
R-Sq = 92.66%    R-Sq(pred) = 70.51%   R-Sq(adj) = 85.65%
Analysis of Variance for 28-DAY(MPa) (component proportions)

Source          DF   Seq SS    Adj SS   Adj MS      F      P
Regression      22  1145.33  1145.330  52.0604  13.21  0.000
   Linear        6  1026.56    56.734   9.4557   2.40  0.060
   Quadratic    16   118.77   118.772   7.4232   1.88  0.081
     A*B         1     9.08     1.458   1.4584   0.37  0.549
     A*C         1    11.18     0.198   0.1980   0.05  0.825
     A*D         1     3.39     2.012   2.0116   0.51  0.482
     A*E         1     2.51     8.883   8.8833   2.25  0.147
     A*F         1     3.72     8.838   8.8381   2.24  0.148
     A*G         1    32.46    39.184  39.1844   9.94  0.004
     B*C         1     0.91     0.027   0.0272   0.01  0.935
     B*E         1    16.02     5.810   5.8098   1.47  0.237
     B*F         1     6.78     5.543   5.5432   1.41  0.248
     B*G         1     3.82     5.102   5.1017   1.29  0.267
     C*E         1     0.22     4.020   4.0197   1.02  0.323
     C*G         1     0.23     0.862   0.8617   0.22  0.645
     D*E         1    14.22     9.506   9.5060   2.41  0.134
     D*G         1     6.03     7.652   7.6518   1.94  0.177
     E*F         1     1.51     1.756   1.7563   0.45  0.511
     E*G         1     6.70     6.700   6.7000   1.70  0.205
Residual Error  23    90.67    90.675   3.9424
   Lack-of-Fit  15    68.49    68.489   4.5659   1.65  0.242
   Pure Error    8    22.19    22.186   2.7732
Total           45  1236.00
```

APENDIX B

Detailed information on High-range water reducing admixture (Conplast SP 430).



Fosroc Conplast SP430

FOSROC

constructive solutions

High performance superplasticising admixture

Uses

- To provide excellent acceleration of strength gain at early ages and major increases in strength at all ages by significantly reducing water demand in a concrete mix.
- Particularly suitable for precast concrete and other high early strength requirements.
- To significantly improve the workability of site mixed and precast concrete without increasing water demand.
- To provide improved durability by increasing ultimate strengths and reducing concrete permeability.

Advantages

- Major increases in strength at early ages without increased cement contents are of particular benefit in precast concrete, allowing earlier stripping times.
- Makes possible major reductions in water:cement ratio which allow the production of high strength concrete without excessive cement contents.
- Use in production of flowing concrete permits easier construction with quicker placing and compaction and reduced labour costs without increasing water content.
- Increased workability levels are maintained for longer than with ordinary sulphonated melamine admixtures.
- Improved cohesion and particle dispersion minimises segregation and bleeding and improves pumpability.
- Chloride free, safe for use in prestressed and reinforced concrete.

Standards compliance

Conplast SP430 conforms with BS 5075, BS:EN 934-2 and with ASTM C494 as Type A and Type F depending on dosage used.

Description

Conplast SP430 is a chloride free, superplasticising admixture based on selected sulphonated napthalene polymers. It is supplied as a brown solution which instantly disperses in water.

Conplast SP430 disperses the fine particles in the concrete mix, enabling the water content of the concrete to perform more effectively. The very high levels of water reduction possible allow major increases in strength to be obtained.

Technical support

Fosroc provides a technical advisory service for on-site assistance and advice on admixture selection, evaluation trials and dispensing equipment. Technical data and guidance can be provided for admixtures and other products for use with fresh and hardened concrete.

Dosage Guideline

The optimum dosage of Conplast SP430 to meet specific requirements should always be determined by trial mixes using the materials and conditions that will be experienced in use.

Normal concrete dosage range is between 0.2 to 2% by weight of cement or cementitious materials including PFA, GGBFS & microsilica. Dosage can further be used up to 3.0% by weight of cement or for high performance concrete. Contact Fosroc technical department for advice.

Use at other dosages

Dosages outside the above dosage guidelines can be used to meet particular concrete mix requirements. Please contact Fosroc for advice in such cases.

Effects of overdosing

An overdose of double the amount of Conplast SP430 will result in an increase in retardation as compared to that normally obtained. Provided that adequate curing is maintained, the ultimate strength of the concrete will not be impaired by increased retardation and will generally be increased. The effects of overdosing will be further increased if sulphate resisting cement or cement replacement materials are used.

Typical Properties

Appearance	:	Brown liquid
Specific gravity	:	1.18 @ 25°C
Chloride content	:	Nil to BS 5075 / BS:EN934

Instructions for use

Mix design

Where the main requirement is to improve strengths, initial trials should be made with normal concrete mix designs. The addition of the admixture will allow the removal of water from the mix whilst maintaining workability. After initial trials, minor modifications to the overall mix design may be made to optimise performance.

Conplast SP430

Fosroc Conplast SP430

Where the main requirement is to provide high workability concrete, the mix design should be one suitable for use as a pump mix. Advice on mix design for flowing concrete is available from Fosroc.

Compatibility

Conplast SP430 is compatible with other Fosroc admixtures used in the same concrete mix. All admixtures should be added to the concrete separately and must not be premixed together prior to addition. The resultant properties of concrete containing more than one admixture should be assessed by trial mixes.

Conplast SP430 is suitable for use with all types of Portland cements, SRC cements and cement replacement materials such as PFA, GGBFS and microsilica.

The use of a combination of admixtures in the same concrete mix and or cement replacements may alter the setting time. Trials should always be conducted to determine such setting times.

Dispensing

The correct quantity of Conplast SP430 should be measured by means of a recommended dispenser. Normally, the admixture should then be added to the concrete with the mixing water to obtain the best results. Where high workability concrete is required from normal workability concrete delivered to site, Conplast SP430 may also be added to concrete direct into a readymix truck. Full blending of the admixture and the concrete should be ensured by mixing at high speed for a period of at least two minutes.

Contact Fosroc for advice regarding suitable equipment and its installation.

Storage

Conplast SP430 has a minimum shelf life of 12 months provided the temperature is kept within the range of 2°C to 50°C. Should the temperature of the product fall outside this range contact Fosroc for advice.

Freezing point: Approximately -2°C

Estimating

Supply

Conplast SP430
210 litre drum, 1000 litre totes or bulk

For larger users, storage tanks can be supplied.

Precautions

Health and safety

Conplast SP430 does not fall into the hazard classifications of current regulations. However, it should not be swallowed or allowed to come into contact with skin and eyes.

Suitable protective gloves and goggles should be worn.

Splashes on the skin should be removed with water. In case of contact with eyes rinse immediately with plenty of water and seek medical advice. If swallowed seek medical attention immediately - do not induce vomiting.

For further information consult the Material Safety Data Sheet available for this product.

Fire

Conplast SP430 is water based and non-flammable.

Cleaning and disposal

Spillages of Conplast SP430 should be absorbed onto sand, earth or vermiculite and transferred to suitable containers. Remnants should be hosed down with large quantities of water.

The disposal of excess or waste material should be carried out in accordance with local legislation under the guidance of the local waste regulatory authority.

Additional information

Conplast SP430 was previously known as Conplast 430.

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ISO 9001 / ISO 14001
OHSAS 18001
BUREAU VERITAS
Certification