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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

STUDY ON THE VARIABILITY OF ORDINARY PORTLAND CEMENT PROPERTIES IN ETHIOPIA

BY

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Declaration

I, the undersigned, declare that this thesis is my original work and had not presented for a degree in any other university and that all sources of material used for the thesis had duly acknowledged.

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Abstract

Cement is the key ingredient in the production of concrete. It has two functions strength inducing and binding property. Concrete production aims to satisfy the acceptable workability of freshly mixed concrete and desired strength and durability of hardened concrete. Among many factors material properties, mix proportioning, handling, placing, curing condition, testing of concrete are major considerations to produce concrete for a particular condition of use. An increase in the variation of cement properties leads to a corresponding variation in concrete properties. This forces one to use higher cement content during mix proportioning. The cement that is classified as the same type varies considerably from one plant to another plant depending on the changes in raw material, burning condition, and cooling rate.

Therefore, this study focuses on the evaluation of locally produced Portland cement performance. Specifically, the variability of physical and mechanical properties of Portland cements as per the Ethiopian standard, CES 28, studied. The scope of this study was limited to thirty cement samples from five cement producers having large market-shares in the Ethiopian cement market, (i.e. Dangote Cement, Derba Midroc Cement, Messebo Cement, Mugher Cement, and National Cement) for six consecutive months (March 2018 – August 2018). The cement samples were collected monthly from retail shops and cement factory stores. All the cement samples were grade 42.5. For the analysis of compressive strength, setting time, consistency, and soundness of cement variability, coefficient of variation (CoV) and student t-Distribution were used.

Two out of five cement brands did not fulfill the requirement of CES 28 in 2nd day compressive strength. Moreover, the variability of 2nd day compressive strength within six months varied from 5% to 20% within the same brand of cement. For 28th day compressive strength results, one out of five cement brands did not fulfill the requirement of CES 28. Additionally, the variability of 28th day compressive strength within six months varied from 3% to 8% within the same brands of cement. In the case of setting time and soundness properties, all cement brands conformed to the requirement of CES 28 initial setting time and soundness requirements. However, the variability of the results showed that all cement brands have high variability in both setting time and soundness.

Keywords: *Cement, compressive strength, setting time, soundness, consistency*

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Acronyms

ASTM	=	American Society for Testing and Materials
CES	=	Compulsory Ethiopian Standard
CoV	=	Coefficient of Variation
C_2S	=	Dicalcium silicate
C_3A	=	Tricalcium aluminate
C_3S	=	Tricalcium silicate
C_4AF	=	Tetracalcium aluminoferrite
EN	=	European Standard
ES	=	Ethiopian Standard
ESA	=	Ethiopian Standard Agency

CHAPTER 1

INTRODUCTION

Portland cement is hydraulic cement composed primarily of hydraulic calcium silicates. Hydraulic cement types set and harden by reacting chemically with water. During this reaction, called hydration, cement combines with water forming a paste. When the paste (cement and water) is added to aggregates (sand and gravel, crushed stone, or other granular material) it acts as an adhesive and binds the aggregates together to form concrete, the world's most versatile and most widely used construction material (1 p. 21).

With the improvements in concrete technology, concrete has become more versatile, but also more complex in that the number of mixture constituents has increased. To minimize the variability of concrete, it is necessary to control the uniformity of the constituent materials as well as the uniformity of batching, mixing, transporting, placing, and curing (2 p. 30).

Most engineers in construction, which are mostly civil engineers, make their preferred choice of Portland cement, based on strength classification. However, other information on cement such as chemical composition, mineralogical, and even physical properties could be an important factor for the selection of best-performing cement. Best performing cement is the cement that can fulfill its workability, setting, strength, and durability requirement.

This study focuses on the evaluation of locally produced cement performance specifically the variability of physical and mechanical properties of cement as per Ethiopian standard, CES 28. The study sample is limited to thirty cement samples from five cement factories having large market shares on cement production, (i.e. Dangote Cement, Derba Midroc Cement, Messebo Cement, Mugher Cement, and National Cement) for consecutive six months (March 2018 – August 2018). The cement samples were collected monthly from the city of Addis Ababa retail shops and cement factory stores. All the cement samples were grade 42.5. The analysis were conducted using the coefficient of variation (CoV) and student t distribution for compressive strength, setting time, consistency, and soundness properties of cement.

1.1 Statement of the problem

In Ethiopia, the total production capacity of seventeen cement factories is about sixteen million tons of cement per annum. The average annual cement production is eight million tons. Since various research show that the same factory will not produce uniform cement through its production life (3) (4), the cement produced from those seventeen factories will not be the same.

Therefore, this study shows the extent of variation of cement produced in Ethiopia from the same factory for six months period.

1.2 Objective of the study

The objective of the study is to determine the extent of variability of ordinary Portland cement properties in Ethiopia by examining the mechanical and physical properties (i.e. compressive strength, setting time, consistency, and soundness) of locally produced cement.

Specifically, the study aims to -

- Study the extent of variation in performance of cement in terms of compressive strength, setting time, consistency, and soundness.
- Determine whether locally produced cement brands fulfill Ethiopian cement standards or not.

1.3 Scope and limitation of the study

This study is limited to the variability of 42.5 MPa strength class Ordinary Portland Cement (OPC), which is a widely used cement strength class for structural application, for six-month monthly.

Moreover, cement samples used for the study are limited to products of Dangote, Derba Midroc, Messebo, Mugher, and National cement factories.

Compulsory Ethiopian Standard (CES 28), *cement - part 1: composition, specifications, and conformity criteria for common cement*, specifies physical, mechanical, and chemical requirements for ordinary Portland cement. However, due to budget constraints, the chemical requirements of cement are excluded from the study.

The date of cement production is not written on the cement bags. This has created difficulties to make sure the cement samples are fresh.

1.4 Significance of the study

Once the extent of variation or uniformity of the cement brands is determined, the following stakeholders in the construction industry can benefit from this research in the following ways.

- The Ethiopian Conformity Assessment Enterprise, a government institution that is responsible to control the performance of all cement products, will get the status of cement product performance in the market. The finding will help them as input for their control mechanism.
- The finding may assist the standardization authority of Ethiopia, Ethiopian Standard Agency to develop a standard for the variability of material from a single source.
- Assist consultants and contractors to take considerations for the effect of variation in cement properties before adopting concrete mix designs. The finding may help them to know the extent of cement performance variation from time to time. Therefore, it can help them to take considerations while preparing mix designs.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The goal of concrete suppliers is to provide a material that consistently meets requirements set out by the buyer, whether these are defined in the form of prescriptive or performance specification. A user may itself produce concrete on construction site, mostly in Ethiopia concrete users are producing concrete on site. Either the ready mix supplier or on-site producer aims to get concrete that performs uniformly throughout.

Concrete performance is expressed as the ability to satisfy the design requirements for the particular conditions of use: acceptable workability of freshly mixed concrete; and durability, strength, and uniform appearance of hardened concrete (2 p. 31).

To assure concrete performance the process starts with mix-design and specification developed for the particular application. It is followed by the selection and purchasing of constituent materials and processing of those materials in accordance with the specifications. The steps to get concrete performance are shown in Figure 2-1.

Likely, if the design, selection, and implementation steps are properly conducted, the concrete properties and performance will meet the intended requirements. However, it is unlikely to assume that the steps to obtaining properties and performance can be achieved without accommodating variations. However, what level of variation can be accepted without an unfavorable impact on concrete performance?

With improvements in concrete technology, concrete has become more versatile, but also more complex in that the number of mixture constituents has increased. To minimize the variability of concrete, it is necessary to control the uniformity of constituent materials as well as the uniformity of batching, mixing, transporting, placing, and curing. Additionally, concrete producers take consideration in the mix design to overcome constituent material variation (2 p. 30).

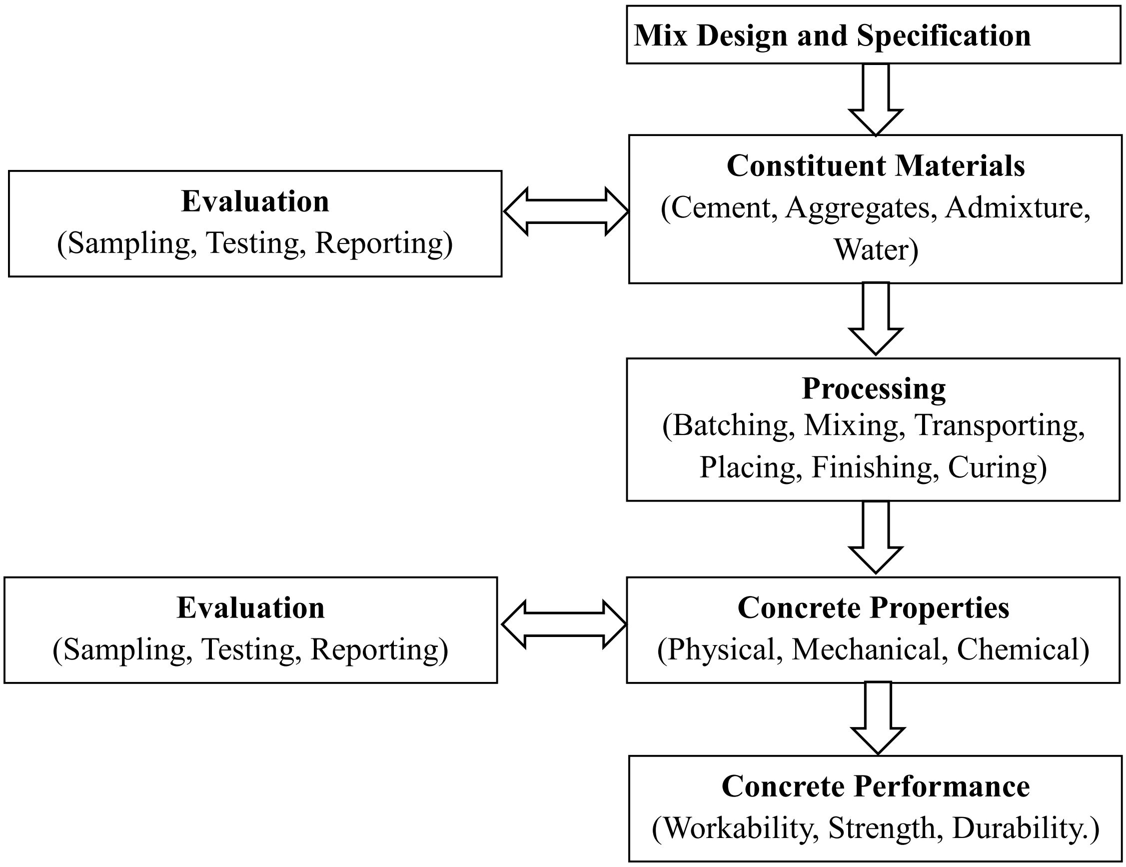


Figure 2-1 Uniformity of concrete is a function of the entire design and construction (2 p. 31).

Mindess S. and Francis J. described factors that are involved in the production of desired concrete: Material, proportion, handling and placing, curing, and testing of concrete. They described concrete is a variable material because of the following attributes.

1. *"Material: This includes variability in the cement itself, in the grading, moisture content, mineral composition, physical properties, and particle shape of the aggregates, and in the admixture used.*
2. *Production: This involves the type of batching plant and equipment, the method of transporting the concrete to the site, and the procedures and workmanship used to produce and place the concrete.*

3. *Testing: This includes the sampling procedures, the making, and curing of test specimens, and the test procedure used."* (5 p. 401)

In 1988, members of ASTM Committee C1 on Cement and Committee C9 on Concrete and Concrete Aggregates surveyed to obtain their impressions on the relative importance of concrete-making materials. Members were asked to rank major constituent materials in their order of importance relative to variability. Twenty-seven members responded to the survey. The respondents are among the world's most knowledgeable and experienced individuals in concrete materials technology. Therefore, the survey can be considered a valid representation of industry experience and perceptions regarding those materials' characteristics that affect concrete performance. Besides, evidences indicate these perceptions remain unchanged today. The survey guides specific materials' properties and performance attributes that impact concrete properties and performance. This information is valuable in identifying properties that must be controlled to achieve uniformity of performance (2 pp. 30-32).

Figure 2-2 is a summary of responses to a question that required the respondents to rank ten major constituent materials in order of importance from one being most important to ten being the least important. No distinction was made as to which performance aspect - workability, strength, or durability might be affected, but strength was likely the most commonly considered attribute. Variations in cement are identified as the most important by a significant margin. Variations in batch water are identified as least important. The relatively "unimportant" rankings given to slag and silica fume may be related to a belief that these materials have little variability, or to the fact that they are less frequently used than the other constituents (2 p. 31).

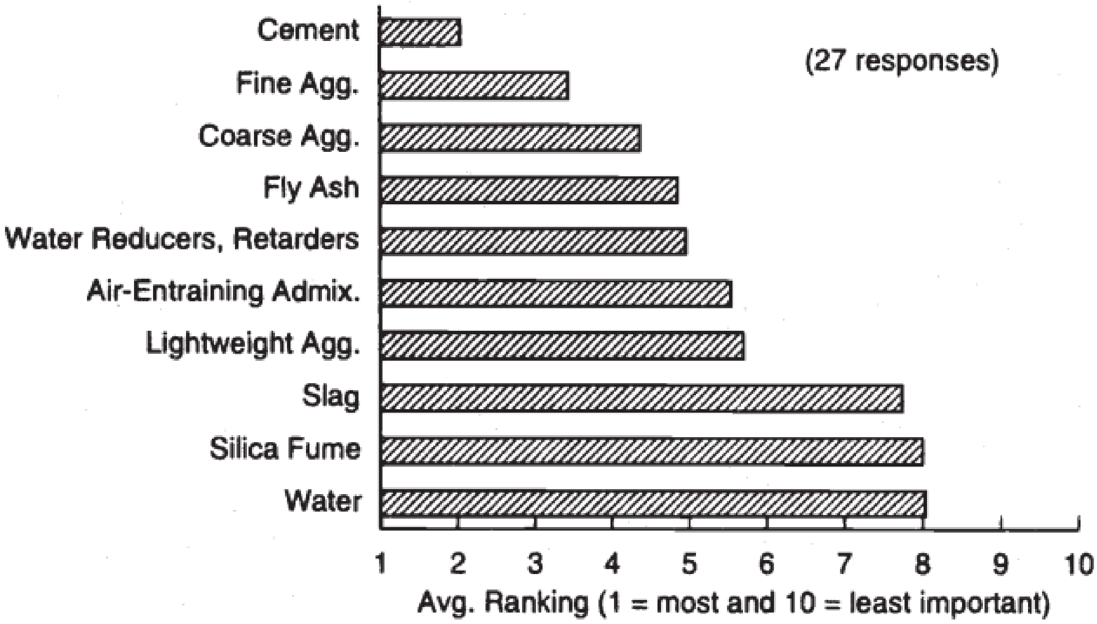


Figure 2-2 1988 Survey of ASTM C1 and ASTM C9 committee members (2 p. 32).

This led to the establishment of a joint committee of the Portland Cement Association and the National Ready Mixed Concrete Association to address strength uniformity. The joint committee planned a program to develop data on the uniformity of cement strengths from individual cement plants.

The joint committee selected 7th day and 28th day strengths of mortar cubes that conform to the ASTM C 109, Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2 in. or 50 mm cube specimens) as the reference for cement strength. Forty-six cement companies, representing over a hundred plants in the United States and Canada, participated. They came up with a result of 32.3 MPa for 7th day and 42.5 MPa for 28th day average cylindrical compressive strength with 1.75 for 7th day and 2.14 for 28th day standard deviation. The result helped to develop the ASTM testing method for the evaluation of cement strength uniformity from a single source (ASTM C 917) (2 p. 32).

ASTM C917 is a standard test method intended for use in instances where the purchaser desires information on the strength uniformity of hydraulic cement produced at a single source. Trained personnel shall perform sampling. A minimum of 4.5 kg of the sample will be taken at a rate of ten samples per month or two samples per week. Test all samples for 7^{th} and 28^{th} day compressive strength following ASTM C109 test method. Five or more batches may be necessary to obtain a valid comparison. The standard deviation and coefficient of variation of cement strength are calculated. The less the value of standard deviation and coefficient of variation means the more consistent the cement (6).

2.2. Cement

2.2.1 Definition of cement

Ethiopian Cement Standard defines cement as a hydraulic binder, i.e. finely ground inorganic material which, when mixed with water, forms a paste which sets and hardens by hydration reaction processes and which, after hardening, retains its strength and stability even underwater (7 p. 3).

Neville, A. M. defines cement, in the general sense of the word, as a material with adhesive and cohesive properties that make it capable of bonding mineral fragments into a compact whole. For constructional purposes, the meaning of the term 'cement' is restricted to the bonding materials used with stones, sand, bricks, and building blocks (8 p. 1).

2.2.2 Cement variability

Cement variability is to mean the extent to which cement from the same source and produced to the same specification varies over time. In other words, cement produced from the clinker made on Monday and then another bag from the clinker made on Friday, will the cement in the two bags behave in the same way when mixed with water? On the other hand, bulk cement delivered today, will behave identically to that delivered last month? The main difference that may be noticed is typically related to color, setting time, early-age strength, and later age strength or how the cement responds to admixtures (9 p. 102). The age of cement at testing and storage conditions also affects cement properties.

2.2.3 Classification of cement

According to Brandt Andrzej M. (10 pp. 67-73), the following are the main classifications of cement.

A. Hydraulic cement (Portland cement), also blended with various secondary cementing materials, like pozzolans, slag cement, fly ash, etc.;
B. High alumina cement
C. Non-hydraulic cement (gypsum, lime, magnesium cement)
D. Hydrothermal cement
E. Sulfur cement

A. Hydraulic cement:

The term hydraulic means that the product gets strength when mixed with water. Portland cement is the most important hydraulic cement. It is produced by pulverizing Portland cement clinker, consisting essentially of hydraulic calcium silicate, usually by intergrading with small amounts of calcium sulfate compounds to control reaction rates. It may be used in combination with one or more supplementary cementations material such as fly ash, blast furnace slag, and silica fume or calcined clay.

Standard of Portland cement

The two principal worldwide standards for Portland cement are EN 197-1 (European standard, which Ethiopian cement standard is adopted from) and ASTM C 150 (USA) classifies Portland cement as follows.

1. **EN 197-1:2011, Cement Composition, Specifications, and Conformity Criteria for Common Cements**, classifies cement into five categories. The classification of cement-based on the composition of cement materials is presented in Table 2-1**.** The detailed components of the major constituent are presented in appendix H.

Table 2-1 Classification of cement per EN 197-1:2005 (11 p. 15)

Designation	Description
CEM I	**Portland cement:** clinker with up to 5% of minor additional constituents
CEM II	Clinker with up to 35% of other constitutes (slag, silica fume, pozzolans, fly ash, burnt shale, and limestone) with 5% minor constituents: • Portland slag cement • Portland silica fume cement • Portland pozzolana cement • Portland fly ash cement • Portland burnt shale cement • Portland limestone cement • Portland composite cement
CEM III	**Blast furnace cement:** Clinker with more than 35% blast furnace slag with 5% minor constituents.
CEM IV	**Pozzolanic cement:** Clinker with up to 55% of a composite of other constitutes (silica fume, pozzolana and fly ash) with 5% minor constituents.
CEM V	**Composite Cement:** Clinker with up to 49% pozzolana or fly ash with 5% minor constituents.

2. **ASTM C 150:2011**, **Standard Specification for Portland Cements** covers only Portland cement. The classifications of blended cement are covered in ASTM C 595. The classification of Portland cement is as follows (12).

- **Type I: -** For use when special properties specified for any other types are not required.

- **Type II: -** For general use, more especially when moderate sulfate resistance or moderate heat of hydration is desired.
- **Type III:** - For use when high early-age strength is desired.
- **Type IV: -** For use when a low heat of hydration is desired
- **Type V: -** For use when high sulfate resistance is desired.

B. High alumina cement:

These cement types are obtained from bauxite (Al_2O_3) fused with limestone at a temperature of 1600 °C to form clinker, which is then ground to power (10 pp. 70-71). The family of aluminous cement includes several hydraulic binders, whose main constituent is the monocalcium aluminate $CaAl_2O_3$ (CA) that has chemistry completely different from the family of Portland cement (13 p. 37). The mineralogical composition are CA - 40-50%, C_4AF – 20-40% and a minority (<10%) of $C_{12}A_7$, CA_2, C_2S, TiO_2 and FeO (14 p. 29).

Aluminous cement gives rise to calcium aluminate hydrate (CAH) and insoluble alumina trihydrate (AH_3) when mixed with water (13 p. 37).

The properties of aluminous cement that make them particularly attractive for some applications of civil engineering are the following.

- **High initial strength: -** the fast hydration rate of calcium aluminate leads to higher early-age strength gain. Since this cement can achieve 20 - 40 MPa compressive strength within 24 hours, it is largely used in precast concrete production (13 p. 40).
- **Strength development at low temperature: -** the fast heat released during cement hydration promotes self-healing that support the progress of hydration under low temperature (13 p. 40).

- **Resistance to the aggressive environment: -** the absence of CH & ettringite makes the cement, less susceptible to acid, carbon dioxide, and sulfate attack (10 p. 71).
- **The resistance of high temperature: -** hardened aluminous cement maintains its stability at high temperatures up to 110 °C (13 p. 40).

Even though high alumina cement types have the above-listed advantages, they are not widely used in the market, because of its expensiveness. High alumina cement types are about three times more expensive than Portland cements mainly because of the higher consumption of energy necessary for grinding hard clinkers (13 p. 40) (10 p. 71).

C. Non Hydraulic cement

Non-hydraulic cement types are those that decompose when subjected to moisture and cannot harden underwater. Gypsum, lime, and magnesium oxychloride are common types of non-hydraulic cement.

Gypsum: - Gypsum is a kind of non-hydraulic binder obtained from a mineral of gypsum, composed mainly with $CaSO_4.2H_2O$ and a certain amount of different impurities. The production of gypsum is based on crushing the raw material and heating it to a temperature between 130 ˚C and 170 ˚C for dehydration. Gypsum is used as a paste with water for indoor decoration partitions and plaster for internal walls and ceiling surfaces. When gypsum mixed with sand and lime, various kinds of mortars are obtained. Those mortars can be used for structural and non-structural elements (10 p. 71).

Lime (CaO): - Lime is obtained from natural limestone or dolomite, burned at a temperature between 950 °C and 1100 °C. Lime mortar is obtained by mixing lime with sand, which gives less than one MPa compressive strength. Nowadays lime is limited to minor jobs and reconstruction of traditional buildings (10 pp. 71-72).

Magnesium oxychloride: - Magnesium oxychloride is obtained from the reaction of magnesium oxide (MgO) and magnesium chloride (MgCl). The hardening process is quick and it can produce about 100 MPa compressive strength in twenty-eight days. The application of magnesium oxychloride is limited to interiors of buildings because its durability is insufficient when exposed to moisture. Its main use is as a binder for sawdust to produce a composite material for the top layers of floors. (10 p. 72)**.**

D. Hydrothermal cement

Hydrothermal cement types are produced from finely ground lime and silicates mixed and cured in high-pressure steam. Hydrothermal cement types are used mostly to produce bricks. As silicates, the fly ash may be used, but its addition increases the hydration time (10 p. 72).

E. Sulfur cement

Sulfated cement types are obtained from blast-furnace slag (80–85%), calcium sulfate (10–15%), and lime or Portland cement clinker (approximately 5%). After hardening, the strength comparable to that of ordinary Portland cement may be obtained with a considerably lower heat of hydration. Sulfated cement may be used in various special concrete structures, particularly in situations where the action of acid fluids, seawater, and oils are expected; e.g. for foundations and harbor structures (10 p. 72).

2.2.4 The manufacturing process of Portland cement

Cement is produced mainly from a mixture of limestone (about 75%) and clay (13 p. 11). The physical and chemical phenomena that occur during the cement manufacturing process determine the chemical and mineralogical composition of the final cement product and its compliance with the compulsory specifications.

The process of manufacturing consists essentially of grinding the raw materials into powder, mixing them intimately in a predetermined proportion, and burning in a large rotary kiln at a temperature of about 1450 °C. The material formed (clinker) is cooled and ground to a fine powder with some gypsum added, produce Portland cement (13 pp. 11-14).

The mixing and grinding of raw materials can be done either wet condition or dry condition. Once this mixture moves down the kiln, it encounters a progressively higher temperature, which leads to various chemical reactions to takes place.

According to Taylor (14 p. 55), the following chemical reaction takes place.

1. Reactions below 1300 °C

- Water drove off from the mixture
- Decomposition of calcium carbonate ($CaCO_3 + heat \rightarrow CaO + CO_2$)
- Decomposition of clay minerals
- The reaction of lime with quartz and clay mineral decomposition products to give belite (impure C_2S), aluminate (impure C_3A), and ferrite (impure C_4AF)

2. Reactions at 1300-1450 °C (Clinkering)

- Melt is formed mainly from the aluminate and ferrite. 20-30% of the mix became a liquid.
- Much of the belite and nearly all lime react in the presence of melt to give alite (impure C_3S).
- The materials nodulize to form clinker

3. Reaction during cooling

- Cooling and crystallization of the various mineral phases formed in the kiln.

2.2.5 Chemical composition of cement

The main oxides used to produce Portland cement are lime, silica, alumina, and iron oxide. These oxides interact in the kiln, forming four main compounds as shown in Table 2-2.

Table 2-2 Main compounds of Portland cement (15 p. 212)

Compound	Chemical formula	Common formula	Usual range by weight (%)
Tricalcium Silicate	$3CaO.SiO_2$	C_3S	45-60
Dicalcium Silicate	$2CaO.SiO_2$	C_2S	15-30
Tricalcium Aluminate	$3CaO.Al_2O_3$	C_3A	6-12
Tetracalcium Alminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF	6-8
The cement industry commonly uses shorthand notation for chemical formulas: C = Calcium oxide, A = Aluminium oxide, S = silicon dioxide, and F = Iron oxide.			

In addition to these main compounds, there are minor compounds, such as magnesium oxide, titanium oxide, manganese oxide, sodium oxide, and potassium oxide. (15 p. 212).

The potential mineralogical composition of a Portland cement clinker can be estimated from a result of its chemical composition analysis using Bogue's equation.

$$C_3S = 4.071CaO - 7.600SiO_2 - 6.718Al_2O_3 - 1.430Fe_2O_3 - 2.852SO_3 \quad \text{[Eq. 2.1]}$$

$$C_2S = 2.867SiO_2 - 0.7544C_3S \quad \text{[Eq. 2.2]}$$

$$C_3A = 2.650Al2O3 - 1.692Fe_2O_3 \quad \text{[Eq. 2.3]}$$

$$C_4AF = 3.043Fe_2O_3 \quad \text{[Eq. 2.4]}$$

But nowadays most cement plants are equipped with the experimental X-ray diffraction technique to perform quantitative analysis of the clinker phase.

2.2.6 Hydration of Portland cement

Hydration is the chemical reaction between the cement particles and water. Calcium silicates combine with water to form calcium-silicate-hydrate, C-S-H. The crystals begin to form a few hours after the water and cement are mixed and can be developed continuously as long as there are unreacted cement particles and free water. C_3S hydrates more rapidly than C_2S contributing to the final setting time and early-age strength gain of the cement paste (15 pp. 214-215). The characteristics of hydration of major compounds are shown in Table 2-3.

Table 2-3 Characteristics of hydration of cement compounds (16 p. 11)

Compounds	Reaction rate	Amount of heat librated	Contribution to cement	
			Strength	Heat libration
C_3S	Moderate	Moderate	High	High
C_2S	Slow	Low	Low initially, high later	Low
C_3A	Fast	Very high	Low	Very High
C_4AF	Moderate	Moderate	Low	Moderate

2.3. Properties of cement and its significance on concrete performance

Hydraulic cement is a manufactured product that is used in concrete and related construction materials. When cement and water are mixed, they undergo various chemical reactions that gradually change the mixture from plastic (or fluid) to a rigid solid capable of bearing substantial compressive loads. Thus, cement and its reactions with water are largely responsible for most of the key aspects of concrete: its workability, setting, strength, creep, shrinkage, and durability.

Specifications for cement limit both its physical properties and chemical properties. An understanding of the significance of the physical and chemical properties is helpful to interpret the results of cement tests and their effect on concrete properties. During production, cement is continuously monitored for its chemistry and the following properties:

2.3.1 Physical properties of cement

2.3.1.1 Heat of hydration:

The heat of hydration is the quantity of heat (in Joule) per gram of un-hydrated cement, evolved upon complete hydration at a given temperature. For a usual range of Portland cement, about one-half of the total heat is liberated between 1 and 3 days, about three-quarters in 7 days and nearly 90% in six months (8 p. 38).

The heat of hydration depends on the chemical composition of cement. Major cement compounds C_3S, C_2S, C_3A; C_4AF has about 502J/g, 260J/g, 867J/g, and 419J/g of energy respectively (8 p. 39). It is to mean that when the cement has a higher amount of C_3A and C_3S compound the higher heat of hydration expected when mixed with water. The heat of hydration affects the strength property of cement at early-ages. The higher C_3S hydration gives higher early-age strength. The fineness of cement affects the rate of heat development but not the total amount of heat liberated.

2.3.1.2 Fineness of cement:

Portland cement consists of individual cement particles with a variety of sizes. Approximately 95% of cement particles are smaller than 45 micrometers, with the average particle around 15 micrometers (1 p. 43).

The fineness of cement affects the rate of hydration of cement. Greater cement fineness increases the rate at which cement hydrates and thus accelerates strength development. The effects of greater fineness on paste strength are manifested principally during the first seven days. Cement types with finer particles have more surface area in square meters per kilogram of cement (1 p. 44).

'The rates of strength development and heat evolution can also be controlled by controlling the fineness of the cement. For instance, with a given compound composition, by making a change in the surface area of the cement from 300 to 500 m^2/kg Blaine, it was possible to increase the 1, 3, and 7 days compressive strengths of the cement mortar by about 50 to 100 %, 30 to 60 %, and 15 to 40 %, respectively." (17 p. 224).

The fineness of cement has a considerable influence on the unhardened and hardened property of cement mixtures (paste, mortar, and concrete). The increasing fineness of cement tends to decrease the amount of bleeding (5 p. 47) and adsorb chemical admixtures more rapidly in cement mixtures (2 p. 438). However, increasing further fineness leads to a high hydration rate which affects the workability of fresh cement mixtures at a given water-to-cement ratio. High cement fineness reduces the durability of concrete to freeze-thaw cycles (5 p. 47) since air entrainment is ineffective for less workable mix (18 p. 288). Moreover, the higher water requirement of fine cement types increases the drying shrinkage of cement mixtures. (10 p. 438) (5 p. 47)

2.3.1.3 Compressive strength of cement

The strength of cement is the property that is most important to engineers, both as a general indicator of concrete quality. Although concrete strength may be measured in tension, shear, or compression, compressive strength is generally most important and most often specified.

Strength is increased by reducing the water-to-cement ratio and increasing the degree of hydration. Based on these considerations, one would expect a good correlation between concrete strength and strength of mortar at the same water-to-cement ratio and degree of hydration.

Many of the potential problems in cement hydration affect its strength. Furthermore, the permeability of hydrated cement is a function of water-to-cement ratio and degree of hydration just as is strength, so permeability decreases as strength increases, and many aspects of durability are improved by increasing strength. Thus, strength indicates the overall performance of hydrated cement, mortar, or concrete (2 p. 444).

It is widely recognized that concrete strength depends on the strength of cement paste and the paste-aggregate bond. The strengths of both paste and the paste-aggregate bond depend largely on paste porosity (2 p. 444). However, the cementitious property of cement itself has a great influence on the strength of cement paste.

Factors affecting the strength of cement

The effect of fineness of cement on the strength of cement is considerable since the rate of hydration increase with fineness and leads to a higher rate of strength gain in early-ages. Typically for the maximum particle size of about 50*u*m, there is 10 to 15% less strength as compared to 5*u*m maximum particle size (5 p. 354).

Burning conditions in the kiln, cooling rate, and characteristics of raw materials used in the manufacturing of cement greatly affect the cementitious property of cement compounds (5 p. 354).

The strength of hardened cement paste comes primarily from C_3S (earlier strength) and C_2S (later strength). For a given degree of hydration the strength increase in order $C_3A<C_4AF<C_3S<C_2S$, indicating the existing difference in the intrinsic strength of hydrates formed in the hydration of different clinker compounds (19 p. 286).

Besides the clinker phase composition, the presence of minor oxides may also affect the resultant cement strength. Free lime (CaO) and MgO affect cement strength by inducing unsoundness of cement (19 p. 288).

2.3.1.4 Soundness of cement:

Soundness refers to the ability of a hardened paste to retain its volume (15 p. 220). Thus cement is to be rated as sound if, after it has hardened it remains free from expansion effects which may crack, loosen and destroy the hardened paste. Excessive expansion (unsoundness) may occur due to the hydration of free lime (CaO) to form calcium hydroxide ($Ca(OH)_2$) and the hydration of periclase (MgO) to form magnesium hydroxide ($Mg(OH)_2$) (20 pp. 168-169). Excessive expansion may also occur due to the formation of ettringite ($C_3A.3C\overline{S}.H_{32}$) through the reaction of calcium aluminate (C_3A) or calcium monosulfoaluminate ($C_3A.3C\overline{S}.H_{12}$) with gypsum ($C\overline{S}.H_2$) or some other source of calcium and sulfate (2 p. 442).

If there is appreciable expansion, however slow, cracking and failure of concrete will result after many months or even years (5 p. 51). Most specifications for Portland cement limit the magnesia content and the maximum expansion as measured by the autoclave-expansion test (1 p. 44).

2.3.1.5 Consistency of cement:

The normal consistency of hydraulic cement refers to the amount of water required to make a neat paste of satisfactory workability. It is determined using a Vicat apparatus. This apparatus measures the resistance of the paste to the penetration of a plunger or needle of 300 gm released at the surface of the paste (21 pp. 1-2).

Consistency refers to the relative mobility of a freshly mixed cement paste or mortar or to its ability to flow. The significance of cement consistency is twofold. Autoclave expansion, setting time, premature stiffening, and other properties are measured at a specified consistency rather than a specified water-to-cement ratio. A standard consistency is used in these tests to avoid errors due to incomplete consolidation in samples with a very stiff consistency and errors due to bleeding in samples with a very fluid consistency. More importantly, cement consistency is generally assumed to affect concrete workability (2 p. 439).

Concrete workability (slump) is assumed to correlate with paste consistency at the same water-to-cement ratio and including the same mineral and chemical admixtures.

During cement testing, pastes are mixed to normal consistency as defined by penetration of 6 ± 1 mm of the Vicat plunger. Mortars are mixed to obtain either a fixed water-to-cement ratio or to yield a flow within a prescribed range (22).

2.3.1.6 Setting time of cement:

Setting time refers to the time required for the transformation of cement paste, mortar, or concrete from a fluid material to a rigid solid. The setting is a gradual and progressive change controlled by hydration of the cement and is closely linked to consistency. It is logical to expect that setting times of concrete would correlate with setting times of cement paste or mortar prepared using the same cement and the same water-to-cement ratio (2 p. 440).

Regarding the hydration of cement compounds, the effect of C_3S content highly affects the setting time of the cement paste, mortar, or concrete. A higher C_3S content the faster the setting time will be. C_3A plays a minor role in setting behavior of cement rather than influences in the abnormal setting behavior, false, and flash setting (5 p. 211).

It is particularly important to show that the cement is not prone to premature stiffening. The normal set is generally attributed to the formation of calcium silicate hydrate (C-S-H). Cement occasionally shows premature stiffening, either a false set or flash setting. In a false set, the cement stiffens rapidly soon after mixing but regains its fluidity if remixed. Flash set, on the other hand, occurs when the level of calcium sulfate is not sufficient to retard hydration of tricalcium aluminate (C_3A), allowing the formation of hexagonal calcium aluminate hydrates (C_4AH_{13}). In the case of a flash set, fluidity cannot be regained on remixing (5 pp. 211-213).

Two setting times, initial and final setting times, are recognized. These times are arbitrary, in that they do not correspond exactly to any specific change in properties or any specific levels of hydration reaction.

Initial setting: It indicates that the paste is beginning to stiffen considerably and can no longer be molded.

Final setting: it indicates that the cement has hardened to the point at which it can sustain some load.

An initial set of cement paste must not occur too early and the final set must not occur too late. Sulfate (from gypsum or other sources) in the cement regulates the setting time, but setting time is also affected by cement fineness, water-to-cement ratio, and any admixtures that may be used. (1 pp. 45-46).

2.3.2 Chemical properties of cement

Many aspects of hydraulic cement chemistry directly influence cement properties and performance in concrete.

Bye (23 p. 81) describes the limits stated in the specification as follows. The limit for chloride ion content is necessary to reduce the risk of corrosion of steel in reinforced and pre-stressed concrete. Limits for loss on ignition and insoluble residue protect the consumer from a product that has suffered either excessive exposure to the atmosphere during storage or contamination.

The chemical properties most commonly addressed in cement specification are the following.

2.3.2.1 Loss on ignition

It is the weight percentage lost when a Portland cement is heated at 950ºC (2 p. 454). The major contributor to loss on ignition is water from gypsum and carbon dioxide from limestone.

Another source of loss on ignition is moisture picked up from the clinker components during storage as well as during grinding. For example, free lime not combined during burning is hygroscopic and readily absorbs water. During storage, particularly if stored outside and exposed to rain, free lime hydrates to form $Ca(OH)_2$and it may absorb CO_2 from the atmosphere to form $CaCO_3$ (2 p. 454).

Normally, a high loss on ignition is an indication of pre-hydration and carbonation, which may be caused by improper or prolonged storage or contamination during transport (1 p. 49).

High loss on ignition is to mean, the cement has free water or carbon dioxide, which are capable of reacting with cement compounds lead hydration reaction though time before use in mortar or concrete.

2.3.2.2 Insoluble residue

It is the portion of the cement that cannot be dissolved in strong acid or alkaline solutions. The insoluble residue may result from raw materials that did not combine completely in the burning process or possibly from contamination during clinker handling. It is usually a silicate or aluminosilicate material that mostly comes from silicates impurities in calcium sulfate and limestone added during finishing and grinding (2 p. 454).

If the availability of insoluble residue is higher, those portion of the cement is unreactive or do not have a contribution of cementitious property in cement hydration.

2.4. Causes of cement variability

It is unrealistic to expect cement from a given source never to vary, what degree of variation might be expected, and what might be the causes?

The purchaser can expect that all cement will conform to the standard to which it was produced. However, the standard is likely to permit a range of physical and compositional characteristics. Usually, purchasers have a choice of several different sources of cement and they will probably have a preferred source. This preference may be based on price or the ease of availability of cement products.

Perhaps one source might has dark or light color that suits the application better than other cement, or good early-age strength.

Changes in the color of cement may be due to differences in the amount of ferrite (impure tetracalcium aluminoferrite) in the clinker; since ferrite is dark grey or black, it gives clinker its characteristics grey or black color. If the proportion of the ferrite changes, the color of cement may also change. The change of ferrite content may be due to the change in the overall oxide composition, but differences in burning conditions can also affect the color (9 p. 105).

2.4.1 Strength variability

Changes in strength may be due to the number of causes; lower strengths tend to be the cause of more concern than increased strengths.

It must be recognized that the variability inherent in cement leads to a corresponding variability in concrete strength and therefore requires higher average concrete design strength. Not only do cement types that are classified as the same type vary considerably from plant to plant but within a given plant, cement characteristics vary over time, owing to changes in raw material and burning condition. According to Sidney Mindess, the variability of cement leads to a coefficient of variation in concrete strength about 5% (5 pp. 354-355).

According to Nicholas B. Winter (9 pp. 105-107), a few of the most common causes of lower strengths include:

- **Cement fineness**: the cement particles may be coarser. This could be due to a difference in the overall fineness of the cement, or due to a difference in particle size distribution. This might be due to an intentional change in cement fineness, or it might be due to a temporary mill problem. Note that this is primarily a physical difference, rather than chemical. It is related to the performance or operation of the cement mill, although other factors may have been the trigger. One example might be that the raw feed to the kiln contains more coarse silica resulting in a large cluster of belite (impure dicalcium silicate), hard and resistant to being ground, getting into the cement. Another could be that the normal cement mill is under repair and the alternative mill produces a different particle size distribution.
- **Lower alite content:** concrete strength is mainly due to calcium silicate hydrate formation from the hydration of alite (impure tricalcium silicate) and belite (impure dicalcium silicate). Alite is more reactive than belite, so if less alite is present in the cement; early-age strengths are likely to be lower. If there is less alite, there is likely to be more belite (provided that the silica ratio of the clinker has not altered appreciably); later age strengths may be restored to near-normal as belite hydration continues.
- **Different kiln conditions:** for good early-age concrete strength it is not simply the total amount of alite present that is important, but the reactivity of the individual alite crystals. The reactivity of the alite and belite crystals is higher if the clinker is brought to burning temperature rapidly; the temperature maintained for as long as is necessary and the clinker cooled as rapidly as possible. The length and temperature of the flame in the kiln are of prime importance in this. Other factors are also relevant, for example, the size of the clinker nodules will affect the rate at which the clinker cools the interior of coarser nodules will cool more slowly. Over-burning or under-burning the clinker can also cause strength loss.

- **Optimum gypsum:** the gypsum content of the cement affects the rate of strength development and the volume stability of the concrete.

2.4.2 Controlling mechanism of cement variability

To minimize the variation of cement, its manufacturing process requires rigorous and effective control of raw material processing, proportioning, and characterization namely in terms of chemical composition and particle size distribution. As such, raw material quality checks are typically carried out at regular pre-determined intervals of time in different sampling points.

Four main oxides, lime, silica, ferric oxide, and alumina comprise typically 94 - 97 % of inputs (9 pp. 43-44). The chemical reactivity of the remaining 3 – 6% of raw material affects the final product of the clinker. In such a way alkalis, sulfate, and magnesium oxide containing minerals shall be within appropriate limits.

Excess alkali over sulfate will inhibit the combination of CaO and C_2S to form C_3S in the burning zone. Moreover, it has been found to react with reactive silica in some aggregates, which then produces expansion leading to the disintegration of concrete (9 p. 44).

To produce intended Portland cement clinker the chemical composition of the kiln feedstock must respect the relationship between main oxides present in raw materials. Inside the kiln proportion of raw materials is controlled in the following known ratios.

- Lime saturation factor
- Silica ratio
- Alumina ratio

Lime saturation factor (LSF): - is the relationship that quantifies the lime content available in raw material to combine with silica and alumina. It determines whether the clinker is likely to contain an acceptable property of free lime. The ratio between 0.92-0.98 is acceptable (14 pp. 56-57).

$$LSF = \frac{CaO}{2.8SiO_2 + 1.2Al_2O_3 + 0.65Fe_2O_3} \quad \text{[Eq. 2.5]}$$

When the value equals 1, total CaO reacts and when it is greater than 1 there is an excess in the lime content that will persist in the final product in the form of free CaO (lime) (13 p. 13). The free CaO in hardened concrete reacts with water produce $Ca(OH)_2$, in which the density is half of that CaO. This leads to creating stress in concrete due to an increase in volume (13 p. 36).

Silica ratio (SR):

It is inversely proportional to the amount of liquid formed in the kiln because of only alumina and ferric phase melt. Therefore, the higher value of this ratio, the lower the liquid content in the kiln, and thus the occurrence of the chemical reaction is more difficult. Silica ratio 2.0-3.0 is usually appropriate (14 pp. 56-57).

$$SR = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad \text{[Eq. 2.6]}$$

Alumina ratio: It determines the quantity of liquid formed at relatively low temperatures.

$$AR = \frac{Al_2O_3}{Fe_2O_3} \quad \text{[Eq. 2.7]}$$

AR values from 1.0 - 4.0 are appropriate for cement final product since the liquid formed at low temperature is enough for the intended chemical reaction to takes place (14 pp. 56-57).

2.4.3 Expected variation of cement properties

Current specifications on concrete making materials do not have uniformity limits (2 p. 19) However, based on the examination and analysis of compressive strength data by ACI Committees 214, Guide to Evaluation of Strength Tests Results of Concrete, control standards for concrete compressive strength exceeding 35 MPa for a very good class of operation expressed as follows. (24)

Table 2-4 Standard of concrete compressive strength variations (25)

Variation for laboratory trial batches	Coefficient of variation, %
Overall variation	3.5 – 4.5
Within batch variation	2.0 – 3.0

Moreover, under laboratory conditions with single laboratory ASTM C39 shows 2.37% of the coefficient of variation of concrete compressive strength is expected (25).

According to Lamond and Pieler (2 p. 32) the variations in cement are identified as the most important factor for the variation of concrete, it is acceptable to take the variation expected from concrete for the variation of cement. Therefore, the variation of cement of about 3.0% is the expected coefficient of variation of testing. Whereas the variation of cement due to testing and variation due to cement together accounts about 4.5% coefficient of variation.

2.5. Ethiopian cement standard

Compulsory Ethiopian standard (CES 28), which is adapted from EN 197-1:2011, defines and gives the specification of 27 distinct common cement types, 7 sulfate resisting low early-age strength blast furnace cement types and their constitutes. The definition of each cement includes the proportion in which constitutes are to be combined to produce these distinct products in a range of nine strength classes, requirements which constitute have to meet, and also it includes mechanical, physical, and chemical requirements. Necessary durability requirements also provided.

2.5.1 Composition and notation of common cement

The product in the family of common cement in the standard is grouped into five main cement types as follows.

- CEM I Portland cement
- CEM II Portland- composite cement
- CEM III Blast furnace cement
- CEM IV Pozzolanic cement
- CEM V Composite cement

The composition of each of the products in the family of common cement types detailed under Appendix H.

2.5.2 Mechanical and physical requirements

2.5.2.1 Mechanical requirements

A. Standard strength

The standard strength of cement is the compressive strength determined following ES 1176-1:2005 on the 28^{th} day and shall conform to the requirements in Table 2-4.

Three classes of standard strength are included: class 32.5, class 42.5, and class 52.5.

B. Early-age strength

The early-age strength of cement is the compressive strength determined following ES 1176-1:2005 at either 2 days or 7 days and shall conform to the requirements in Table 2-4.

Three classes of early-age strength are included for each class of standard strength, a class with ordinary early-age strength, indicated by N, a class with high early-age strength, indicated by R and a class with low early-age strength, indicated by L. class L is only applicable for CEM III cements.

2.5.2.2 Physical requirements

A. **Initial Setting time**

B. The initial setting time, determined following ES 1176-3:2005, shall conform to the requirements in Table 2-4.

C. Soundness

The expansion, determined following ES 1176-3:2005, shall conform to the requirements in Table 2-4.

D. Heat of hydration

The heat of hydration of low heat common cement shall not exceed the value of the characteristic of 270J/g, determined following either EN 196-8 at 7th day or following EN 196-9 at 41 hours.

Table 2-5 Mechanical and physical requirements of cement (7 p. 11)

<table>
<tr><th rowspan="3">Strength Class</th><th colspan="4">Compressive strength, MPa</th><th rowspan="2">Initial setting time</th><th rowspan="2">Soundness (expansion)</th></tr>
<tr><th colspan="2">Early-age strength</th><th colspan="2">Standard Strength</th></tr>
<tr><th>2nd day</th><th>7th day</th><th colspan="2">28th day</th><th>min</th><th>mm</th></tr>
<tr><td>32.5 L</td><td></td><td>≥12.0</td><td rowspan="3">≥ 32.5</td><td rowspan="3">≤ 52.5</td><td rowspan="3">≥ 75</td><td rowspan="9">≤ 10</td></tr>
<tr><td>32.5 N</td><td></td><td>≥ 16.0</td></tr>
<tr><td>32.5 R</td><td>≥ 10.0</td><td></td></tr>
<tr><td>42.5 L</td><td></td><td>≥ 16.0</td><td rowspan="3">≥ 42.5</td><td rowspan="3">≤ 62.5</td><td rowspan="3">≥ 60</td></tr>
<tr><td>42.5 N</td><td>≥ 10.0</td><td></td></tr>
<tr><td>42.5 R</td><td>≥ 20.0</td><td></td></tr>
<tr><td>52.5 L</td><td>≥ 10.0</td><td></td><td colspan="2" rowspan="3">≥ 52.5</td><td rowspan="3">≥ 45</td></tr>
<tr><td>52.5 N</td><td>≥ 20.0</td><td></td></tr>
<tr><td>52.5 R</td><td>≥ 30.0</td><td></td></tr>
</table>

2.6. Previous studies on cement performance

Different studies have been done so far for cement and concrete performance. Nigus G/Egziabhere in 2005 has studied on *Comparison of Concrete Properties Produced using Muger, Messobo, and Diredawa Cements.* He studied the compressive strength gain on five products of those brands namely, Messobo OPC, Messobo PPC, Mugher OPC, Mugher PPC, and Dire Dawa PPC cement for 3, 7, 28 and 91 days. He has made for normal, intermediate, and high strength concrete grades. From his finding, he has shown that, at all ages and classes of concrete, Messebo OPC has produced the highest compressive strength concrete, followed by Mugher OPC, Messebo PPC, Mugher PPC and Diredawa PPC in descending order (4 pp. 39-41).

Thushara Priyadarshana and Ranjith Dissanayake studied *Importance of Consistent Cement Performance for a Sustainable Construction in Sri Lanka*. They conducted a study on 48 cement samples from five cement brands for consecutive 10 months in 2013. They conducted mortar strength, chemical composition, fineness, setting time tests on the same cement type (42.5N cement). The tests were performed as per Sri Lanka's standard, which most parameters are similar to European standards. They found all cement types complied with the requirement of Sri Lanka's standard. However, the coefficient of variation in cement varied significantly within individual suppliers (3). Their finding is presented as follows.

- **28th day compressive strength** – the results were between 43.2 MPa to 62.2 MPa for all cement types, which complied with the standard [42.5 MPa - 62.5 MPa]. However, there was a 3% to 6% variation within an individual supplier's compressive strength of mortar.
- **Setting time –** Three cement brands showed a quite stable setting time (120-130 min initial setting time & 175-185 min final setting time), whereas two cement brands varied significantly within testing months (125-170 minutes of initial setting time & 180-225 minutes of final setting time). All cement types complied with the standard, 60 min for initial

setting time, and no limit for final setting time.

- **Soundness** – All cement types complied with the standard, less than 10 mm expansion, all showed less than 1 mm expansion**.**
- **Fineness** – Fineness of cement varied from 3110 cm^2/g to 3995 cm^2/g, according to Sri Lanka Standard 107- 2 requirements, fineness should be higher than 2250 cm^2/g. Even all cement types complied with the requirement; two cement types showed 5% of the variation within testing periods.

The authors recommended cement customers, to check the variability of cement before purchase for their use and better to use fewer variable cement.

Birhanu (2007) studied *Comparison of Concrete Durability as Produced by Various Cement Manufactured in Ethiopia.* He studied the durability characteristics of concrete produced from Mugher, Messobo, and Dire Dawa cement. He found that the compressive strength, water penetration, and chloride diffusion of concrete produced from different cement types were varied significantly and he recommended rigorous product standardization at a national level required (26).

Bediako and Amankwah have studied *Analysis of Chemical Composition of Portland Cement in Ghana, a Key to Understand the Behaviour of Cement* concluded that, the performance of Portland cement in concrete or mortar formation very well influenced by chemical compositions among other factors. Their work analyzed five different brands of Portland cement in Ghana, namely, Ghacem ordinary Portland cement (OPC) and Portland limestone cement (PLC), CSIR-BRRI Pozzomix, Dangote OPC, and Diamond PLC. The chemical compositions were analyzed with X-Ray Fluorescence (XRF) spectrometer. Their result showed that there were no significant differences between standard chemical composition values and that of commercial Portland cement. Moreover, their finding also indicated that each brand of commercial Portland cement varied in terms of chemical composition; however, the specific brands of cement had no significant differences. They recommended that using any brand of cement in Ghana was good for any construction works be it concrete or mortar formation (27).

All previous works by different scholars showed that the variation of cement performance has a significant effect on the performance of mortar or concrete. It is known that there is variation in cement performance from the product of one cement factory to another. Moreover, the same factory will not produce consistent cement from time to time.

In Ethiopia there is lack of cement variability testing practice. Therefore, this study aims to quantify the extent of variation in the physical and mechanical properties of cement products in the Ethiopian market.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The main objective of this research is to quantify the extent of cement properties variation in Ethiopian cement. This includes physical and mechanical properties of cement, specifically compressive strength, setting time, consistency, and soundness of cement.

Laboratory tests were conducted on five cement factory products namely Dangote cement, Derba Midroc cement, Mugher cement, Messobo cement, and National cement. Compressive strength, setting time, consistency, and soundness tests of cement were conducted monthly for six-months.

Before checking the variability of cement performance, each test result values are checked whether they conform to CES 28 using *Student t-Distribution*.

Variation of cement performance for a single factory product within time was analyzed using the coefficient of variation. The high coefficient of variation is to mean high variability of cement performance, which leads to the high variability of cement products.

3.2 Selection of cement samples

There are seventeen cement factories in Ethiopia, which manufacture cement in different parts of the country. As shown in Table 3-1 below, the average annual production of cement in Ethiopia is about 8.7 million tons in the period 2008 – 2010 E.C.

Among the seventeen, cement factories, five namely Dangote Cement, Messeboo Cement, Derba Midroc Cement, Mugher Cement, and National Cement have large production capacity and produce more than 7.1 million tons of cement annually (81% of total production in Ethiopian market) were selected.

Since cement of Dangote, Messobo, Derba Midroc, Mugher, and National, take the largest market share in Ethiopian construction industry. Therefore, Ordinary Portland cement (OPC 42.5 grade) cement from these factories is studied.

Table 3-1 Cement production companies and their market share (28)

Item No.	Factory name	Production amount, (Ton)			Market share %	Remark
		2008 E.C	2009 E.C	2010 E.C (half-year data)		
1.	**Dangote**	1,854,985	2,041,521	1,054,517	22.7%	
2.	**Messebo**	1,724,997	1,803,220	827,898	20.0%	
3.	**Derba Midroc**	1,818,820	1,570,972	865,933	19.5%	
4.	**Mugher**	673,982	1,073,313	444,465	10.1%	
5.	**National**	631,981	797,844	521,065	8.9%	
6.	**Pioneer**	289,620	318,347	96,026	3.2%	
7.	**East**	225,668	254,549	134,373	2.8%	
8.	**Capital**	167,327	289,019	142,219	2.7%	
9.	**Inchini Bed rocks**	86,826	102,050	357,733	2.5%	
10.	**Ture**	189,144	209,844	123,106	2.4%	
11.	**Zhongshun**	195,098	164,883	83,838	2.0%	
12.	**Abyssinia**	33,634	19,989	0	0.2%	
13.	**Dashen**	134,687	83,835	0	1.0%	
14.	**Jema**	1,084	0	0	0.0%	
15.	**Habesha**	-	32,736	128,175	0.7%	New cement factories
16.	**Feng Huan**	-	-	162,697	0.7%	
17.	**Ethio**	-	9,818	65,593	0.3%	

3.3 Collection and preparation of cement samples

Cement samples are collected from the market where the cement is available (five cement brands), every month from different suppliers from March 2018 to August 2018 (for six month period).

Thirty cement samples are collected and tested throughout the study (five brands for six months). Samples are named C1, C2, C3, C4, and C5 to make an unbiased study on their properties and variations.

Ordinary Portland cement (OPC) with 42.5 strength class is used for the study. Laboratory tests were performed at the *Ethiopian Conformity Assessment Enterprise* laboratory since it was suitable for testing cement as per the Ethiopian cement standard.

Each of the 30 cement samples has a distinct name. The naming of cement samples consists of four letters **(AC_nB)**; each refers respectively as follows;

- **A** is an indicator for the month of sample collection, those samples collected on the first month are associated with the number “1”, whereas second month “2”, third month “3”, up to a sixth month “6”.
- **C_n** represents a given name of each cement brands. The five cement brands are referred as C1 - Derba Midroc, C2 - Mugher, C3 - Dangote, C4 - National, and C5 - Messebo.
- **B** indicates the rate of hydration of cement. As per CES 28 (7 p. 11), cement with ordinary early-age strength indicated by the letter, N, whereas cement with high early-age strength is indicated by the letter, R. Thus, C1 and C2 are type N, whereas C3, C4, and C5 are type R.

Table 3-2 Naming of cement samples

Cement factories	The testing month of cement samples					
	1st	2nd	3rd	4th	5th	6th
C1	1C1N	2C1N	3C1N	4C1N	5C1N	6C1N
C2	1C2N	2C2N	3C2N	4C2N	5C2N	6C2N
C3	1C3R	2C3R	3C3R	4C3R	5C3R	6C3R
C4	1C4R	2C4R	3C4R	4C4R	5C4R	6C4R
C5	1C5R	2C5R	3C5R	4C5R	5C5R	6C5R

3.4 Testing of cement samples

3.4.1 Compressive strength of mortar

40 mm X 40 mm X 160 mm prismatic test specimens were prepared according to *ES 1176-1:2005, method of testing cement part 1: Determination of strength* (29). These specimens were casted from a batch of plastic mortar containing one part by mass of cement and three parts by mass of standard sand with a water/cement ratio of 0.5.

The mortars were prepared by mechanical mixing using 450 g cement, 1350 g standard sand (complies with EN 196-1), and 225 g of water mixed and compacted in a mold using a standard jolting apparatus. The specimens in the molds were stored in a moist atmosphere for 24 hours and then the de-molded specimens cured underwater until strength tests were carried out.

Thirty cement samples collected over the period were used for the testing. Each cement sample was casted for 2nd and 28th day compressive strength testing. Following the test method, *ES 1176-1:2005, method of testing cement part 1: Determination of strength* (29), altogether 180 specimens were casted for compressive strength tests. The loading rate was 2400 N/s.

3.4.2 Normal consistency, setting time and soundness of cement

Normal consistency and setting time of cement pastes were determined using the Vicat Apparatus according to *ES 1176-3:2005, method of testing cement part 3: Designation of setting time and soundness* (30) for collected 30 cement samples.

Cement paste of standard consistency has a specified resistance to penetration by the standard plunger. The water required for such a paste is determined by trial penetration of pastes with different water contents. (30)

The soundness is determined by observing the volume expansion of cement paste of standard consistency as indicated by the relative movement of the needles using Le Chaterier Apparatus according to *ES 1176-3:2005, method of testing cement part 3: Designation of setting time and soundness* (30)

3.5 Controlling mechanism of testing errors

During laboratory testing of cement, the following precautions were taken to minimize the variability of test results arising from testing.

- All cement samples were collected using a plastic kit so that exposure to moisture was protected.
- All cement samples were tested in one single laboratory, at the *Ethiopian Conformity Assessment* laboratory.
- Standard sand complies with EN 196-1 specification used throughout the testing period (Germany product).
- The temperature and humidity requirement of laboratory room and equipment were adjusted as per standard requirements of testing methods before mixing. The temperature of laboratory room was 20 ± 2 ºC and relative humidity not less than 50%. Whereas the

temperature of large cabinet for storage of specimen was 20 ± 1 ºC and relative humidity not less than 90%

- All equipment, weighing balance, mixer, molds, jolting apparatus, flexural strength testing machine, Le Chatelier apparatus compressive strength testing machine, and Vicat apparatus was calibrated by national metrology agency on every three months interval.

3.6 Method of analysis

The 2nd day compressive strength, 28th day compressive strength, initial setting time, final setting time, consistency, and soundness of cement samples were tested following Ethiopian cement standard procedures.

To determine the extent of variability of cement performance, the coefficient of variation is used. Whereas student t-distribution is used to determine whether locally produced cement fulfill Ethiopian cement standard on not.

For each cement: mean, standard deviation, coefficient of variation, 95 % confidence level of population mean in each property of cement were calculated as follows.

Mean, standard deviation, and coefficient of variation of the samples are calculated using the following formulae.

$$\overline{X} = \frac{\sum X_n}{n} \quad \text{[Eq. 3.1]}$$

$$S = \sqrt{\frac{\sum (X_n - \overline{X})^2}{n-1}} \quad \text{[Eq. 3.2]}$$

$$CoV = \frac{S}{\overline{X}} x100\% \quad \text{[Eq. 3.3]}$$

Where;

$\overline{X}$ = mean of samples

S = Standard deviation of samples

X_n = test result of a sample in each month

n = number of month, (i.e. n = 6)

CoV = Coefficient of variation

Student t-test is a statistical test used for the mean of a population and used when the population is normally distributed and the population standard deviation is unknown (31 p. 427).

The confidence interval for the mean, when population standard deviation is unknown and the sample size is less than 30 is as follows (31 p. 371).

$$\overline{X} - t_{\alpha/2}\left(\frac{S}{\sqrt{n}}\right) < \mu < \overline{X} + t_{\alpha/2}\left(\frac{S}{\sqrt{n}}\right) \quad \text{[Eq. 3.4]}$$

Where;

$\overline{X}$ = Mean of samples

S = Standard deviation of samples

n = Number of months, (i.e. n = 6)

μ = Population mean

$t_{\alpha/2}$ = Is read from the *t-distribution table* (Appendix G) with a degree of freedom 5 and

Thus, for the 95% confidence level for the population mean equation is reduced to:

$$\overline{X} - 1.05\text{S} < \mu < \overline{X} + 1.05S \quad \text{[Eq. 3.5]}$$

Where: $\alpha = 0.05$, $t_{\alpha/2}$=2.571, n = 6

CHAPTER 4

TEST RESULTS, ANALYSIS AND DISCUSSION

4.1 Introduction

In this section, the test results of compressive strength, setting time, soundness, and consistency of the five cement brands are presented, analyzed, and discussed.

4.2 Compressive strength of cement

4.2.1 2nd day compressive strength test results

The 2nd day compressive strength (early-age strength) of cement was conducted as per *ES 1176 - 1: 2005 method of testing cement part 1: Determination of strength*. The test results for 2nd day compressive strength are presented in Table 4-1 & Figure 4-1 below.

Table 4-1 2nd day compressive strength

Cement	2nd day compressive strength, Mpa						$\overline{X}$, MPa	S, MPa	CoV, %	Population mean, MPa		Conformity criteria, MPa		Result
	Testing month													
	1st	2nd	3rd	4th	5th	6th				LL	UL	Min.	Max.	
C1	22.8	31.6	25.9	39.2	28.9	25.1	28.9	5.9	20	22.7	35.1	10	-	Conform
C2	15.9	18.3	12.7	15.5	15.8	17.7	16.0	2.0	12	13.9	18.0	10	-	Conform
C3	21.2	19.3	17.7	21.0	22.8	20.8	20.5	1.8	9	18.6	22.3	20	-	Not conform
C4	23.8	24.9	18.6	21.4	20.9	22.1	22.0	2.2	10	19.6	24.3	20	-	Not conform
C5	20.9	22.0	22.2	20.6	22.9	20.5	21.5	1.0	5	20.5	22.6	20	-	Conform

$\overline{X}$ = sample mean of 2nd day compressive strength for six months

S = sample standard deviation of 2nd day compressive strength for six months

CoV = coefficient of variation of sample data = $(S/\overline{X})*100\%$

Population mean LL/UL = lower/upper limit value of population mean with 95% confidence level = $\overline{X} \pm 1.05*S$

Conformity criteria Min/Max. = a minimum/maximum amount of 2nd day compressive strength should attain as per CES 28.

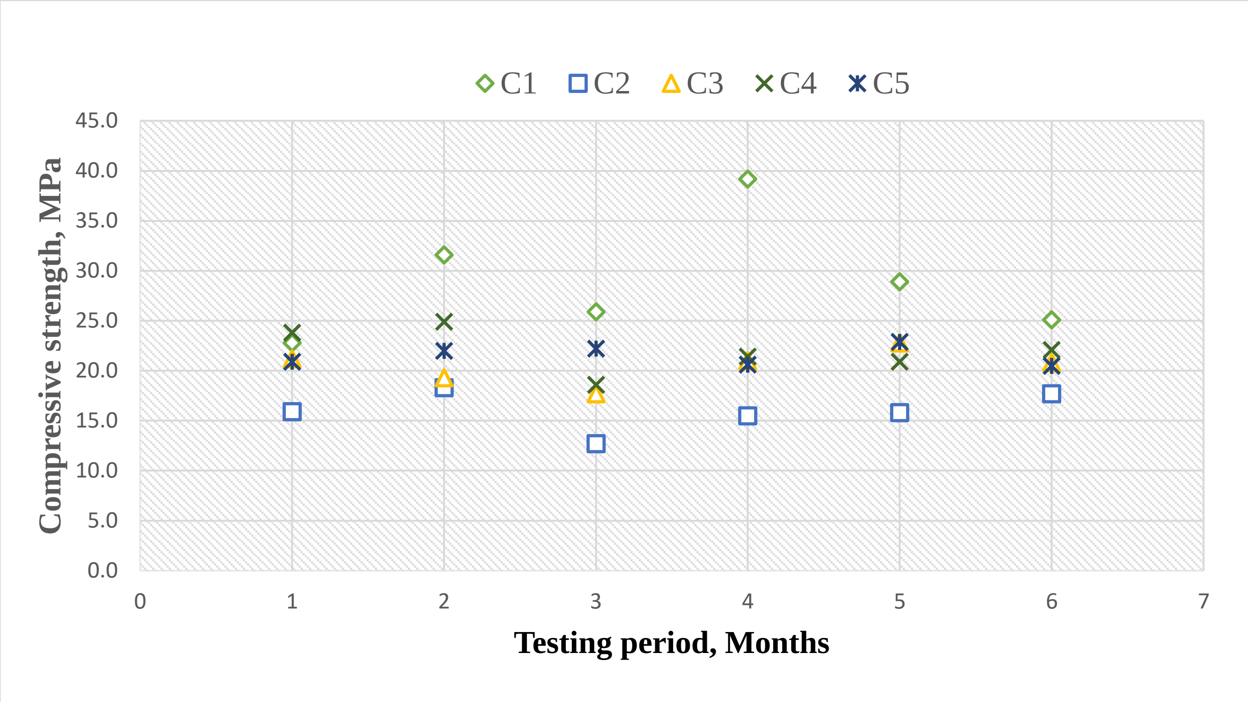


Figure 4-1 2nd day compressive strength

According to CES 28, the 2nd day compressive strength of cement should be more than 10 MPa for 42.5N and 20 MPa for 42.5R strength class cement. This means the population lower limit value of C1 and C2 cement types have to achieve a minimum compressive strength of 10 MPa. Whereas the population lower limit value of C3, C4, and C5 cement types have to achieve a minimum compressive strength of 20 MPa. There is no upper limit for 2nd day compressive strength in CES 28.

For C1, C2, and C5 cement types, the results showed that the lower limit of the population means was greater than the minimum criteria. Therefore, these cement types conformed to the requirement of 2nd day compressive strength. However, C3 and C4 cement types have a probability of giving a minimum of 18.6 MPa and 19.6 MPa respectively. Therefore, C3 and C4 did not achieve the conformity requirement of CES 28.

With respect to the variability of 2nd day compressive strength, the coefficient of variation recorded as 20%, 12%, 10%, 9%, and 5% for C1, C2, C4, C3, and C5 respectively in descending order.

4.2.2 28th day compressive strength test results

28th day compressive strength of cement was conducted as per *ES 1176 - 1: 2005 method of testing cement part 1: Determination of strength*. The test results for 28th day compressive strength are presented in Table 4-2 & Figure 4-2 below.

Table 4-2 28th day compressive strength

Cement	28th day compressive strength, MPa – Testing month						$\overline{X}$, MPa	S, MPa	CoV, %	Population mean, MPa		Conformity criteria, MPa		Result
	1st	2nd	3rd	4th	5th	6th				LL	UL	Min.	Max.	
C1	51.3	56.8	54.2	51.4	51.7	52.4	53.0	2.2	4	50.7	55.2	42.5	62.5	Conform
C2	46.2	46.3	39.6	41.8	41.8	48.1	44.0	3.3	8	40.5	47.5	42.5	62.5	Not conform
C3	52.6	49.5	52	48.9	52.7	51.5	51.2	1.6	3	49.5	52.9	42.5	62.5	Conform
C4	51.1	53.3	43.6	46.4	46.4	46.8	47.9	3.6	7	44.2	51.7	42.5	62.5	Conform
C5	50.5	52.2	53.6	55.5	50.9	46.1	51.5	3.2	6	48.1	54.8	42.5	62.5	Conform

$\overline{X}$ = sample mean of 28th day compressive strength for six months.

S = sample standard deviation of 28th day compressive strength for six months

CoV = coefficient of variation of sample data = (S/$\overline{X}$)*100%

Population mean LL/UL = lower/upper limit value of population mean with 95% confidence level = $\overline{X} \pm 1.05*S$

Conformity criteria Min/Max. = a minimum/maximum amount of 28th day compressive strength should attain as per CES 28.

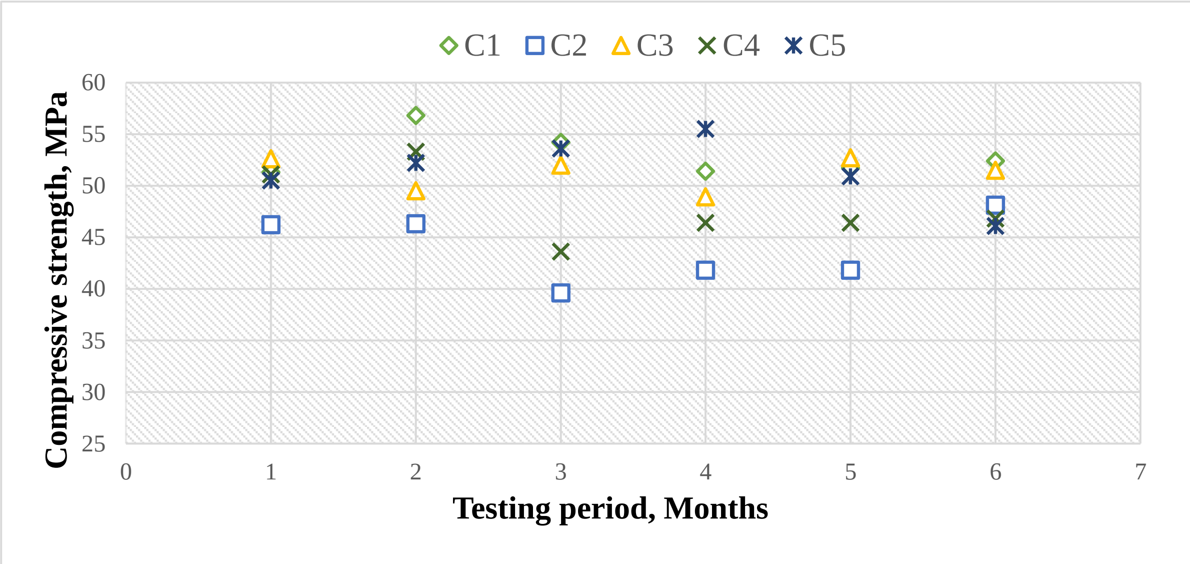


Figure 4-2 28th day compressive strength

According to CES 28, the 28th day the compressive strength of cement should be in the range of 42.5 MPa - 62.5 MPa for both 42.5N and 42.5R strength class cement.

For all cement except C2, the population mean ranges between 42.5 – 62.5 Mpa. Whereas, C2 has a probability of getting 40.5 MPa, which is less than 42.5 MPa. Therefore, it did not comply with the conformity requirement. For the variability of 28th day compressive strength, the coefficient of variation recorded as 8%, 7%, 6%, 4%, and 3% for C2, C4, C5, C1, and C3 respectively in descending order.

Since the variation of cement has a high impact on the properties of its products (i.e. concrete or mortar), cements having a high percent of compressive strength variation have a high probability of getting variable compressive strength of cement products.

This effect is more critical when cement products designed from samples of cement having high compressive strength value. In this case, a problem arises when a user gets a cement from the market a few months later, which has low compressive strength cement. Additionally when cement products designed from cement having low compressive strength value; users may use a large amount of cement to get design strength, leads to expending additional cost due to increasing additional cement.

The probable cause of variation in the compressive strength of cement might be the difference of burning and cooling rate of clinker and composition of raw material used in different production periods.

4.3 Setting time of cement

4.3.1 Initial setting time test results

Initial setting time of cement was conducted as per *ES 1176 – 3: 2005 method of testing cement part 3: Designation of setting time and soundness*. The results for the initial setting time are presented in Table 4-3 and Figure 4-3 below.

Table 4-3 Initial setting time

Cement	Initial setting time, min						$\overline{X}$, min	S, min	CoV, %	Population mean, min		Conformity criteria, min		Result
	Testing month													
	1st	2nd	3rd	4th	5th	6th				LL	UL	Min.	Max.	
C1	187	144	171	97	109	174	147	37	25	108	186	60	-	Conform
C2	180	146	123	132	117	133	139	23	16	115	162	60	-	Conform
C3	207	179	182	177	167	205	186	16	9	169	203	60	-	Conform
C4	168	162	137	132	136	141	146	15	10	130	162	60	-	Conform
C5	122	124	177	134	126	156	140	22	16	117	163	60	-	Conform

$\overline{X}$ = sample mean of initial setting time for six months.

S = sample standard deviation of initial setting time for six months

CoV = coefficient of variation of sample data = (S/ $\overline{X}$)*100%

Population mean LL/UL = lower/upper limit value of population mean with 95% confidence level = $\overline{X} \pm 1.05$*S

Conformity criteria Min/Max. = a minimum/maximum amount of initial setting time should attain as per CES 28. No upper limit provided.

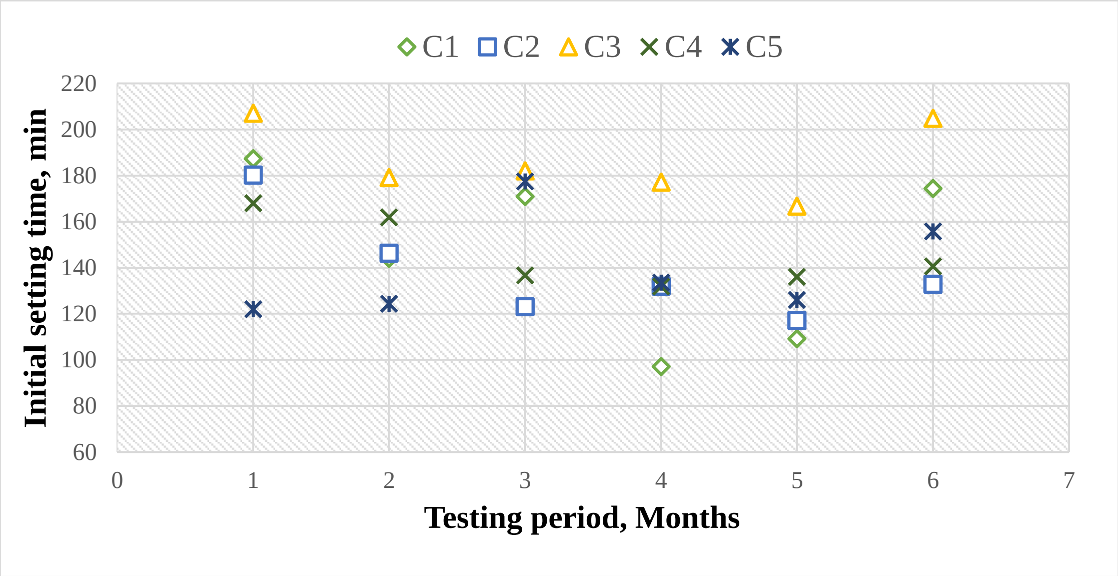


Figure 4-3 Initial setting time

As per CES 28, the minimum requirement for initial setting time is 60 minutes for both 42.5N and 42.5R strength classes, there is no maximum limit provided.

All cement types conform to the requirement of CES 28, which is a minimum of 60 minutes. All cement types have a setting time of more than 100 minutes, giving more time before paste begins to stiffen. It gives sufficient time to transport and place cement products.

However, the variation of initial setting time within the same cement varied by 25%, 16%, 16%, 10%, and 9% for C1, C2, C5, C4, and C3 respectively in descending order.

The probable cause of variation in initial setting time of cement might be the difference in the amount of gypsum added to clinker, the difference in the content of cement compounds, and fineness of cement particles in different production periods.

4.3.2 Final setting time results

Final setting time of cement was conducted as per *ES 1176 – 3: 2005 method of testing cement part 3: Designation of setting time and soundness*. The results of the final setting time are presented in Table 4-4 and Figure 4-4 below.

Table 4-4 Final setting time

Cement	Final setting time, min (Testing month)						$\overline{X}$, min	S, min	CoV, %	Population mean, min		Conformity criteria, min		Result
	1st	2nd	3rd	4th	5th	6th				LL	UL	Min.	Max.	
C1	237	205	222	137	162	237	200	42	21	156	244	-	-	
C2	220	190	157	163	145	175	175	27	15	147	203	-	-	
C3	249	256	247	245	209	266	245	19	8	225	266	-	-	
C4	218	224	183	178	165	192	194	23	12	169	218	-	-	
C5	154	164	249	173	149	191	180	37	20	141	219	-	-	

$\overline{X}$ = sample mean of final setting time for six months.

S = sample standard deviation of final setting time for six months

CoV = coefficient of variation of sample data = (S/ $\overline{X}$)*100%

Population mean LL/UL = lower/upper limit value of population mean with 95% confidence level = $\overline{X} \pm 1.05$*S

Conformity criteria Min/Max. = No requirement provided CES 28.

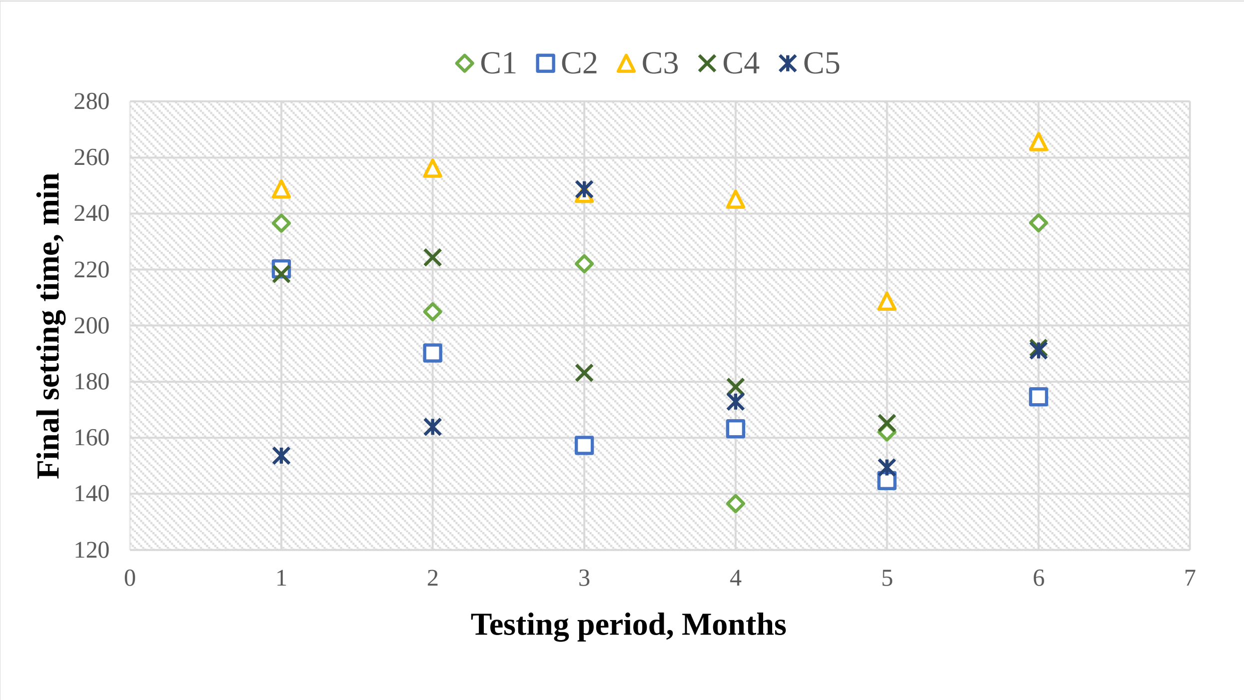


Figure 4-4 Final setting time

In CES 28, there is no requirement for the final setting time. However, the variation of final setting time within the same cement varied by 21%, 20%, 15%, 12%, and 8% for C1, C5, C2, C4, and C3 in descending order respectively within six months.

The probable cause of variation in final setting time of cement might be the difference amount of gypsum added in clinker, the difference in the content of cement compounds, and fineness of cement particles in different production periods.

4.4 Consistency

Consistency of cement was conducted as per *ES 1176 – 3: 2005 method of testing cement part 3: Designation of setting time and soundness*. The test results for the consistency of cement are presented in Table 4-5 and Figure 4-5 below.

In CES 28, there is no requirement for consistency of cement. All cement types have a water requirement of [127- 145] milliliter to give a standard consistency. The variation of consistency of cement varied by 8%, 4%, 2%, 2%, and 1% for C1, C2, C3, C4, and C5 cement respectively within six months.

Table 4-5 Consistency

Cement	Consistency, ml						$\overline{X}$, ml	S, ml	CoV, %	Population mean, ml		Conformity criteria, ml		Result
	Testing Month													
	1st	2nd	3rd	4th	5th	6th				LL	UL	Min.	Max.	
C1	132.5	145.0	133.0	162.0	140.0	132.5	140.8	11.5	8	128.7	153.0	-	-	
C2	131.0	131.0	116.0	128.0	129.5	128.5	127.3	5.7	4	121.4	133.3	-	-	
C3	131.0	137.0	135.0	134.0	130.0	132.6	133.3	2.6	2	130.5	136.0	-	-	
C4	133.0	135.0	131.0	130.0	136.6	127.7	132.2	3.3	2	128.8	135.7	-	-	
C5	132.0	134.0	133.0	130.0	132.5	134.5	132.7	1.6	1	131.0	134.3	-	-	

$\overline{X}$ = sample mean of consistency for six months.

S = sample standard deviation of consistency for six months

CoV = coefficient of variation of sample data = (S/$\overline{X}$)*100%

Population mean LL/UL = lower/upper limit value of population mean with 95% confidence level = $\overline{X} \pm 1.05*S$

Conformity criteria Min/Max. = No requirement provided in CES 28.

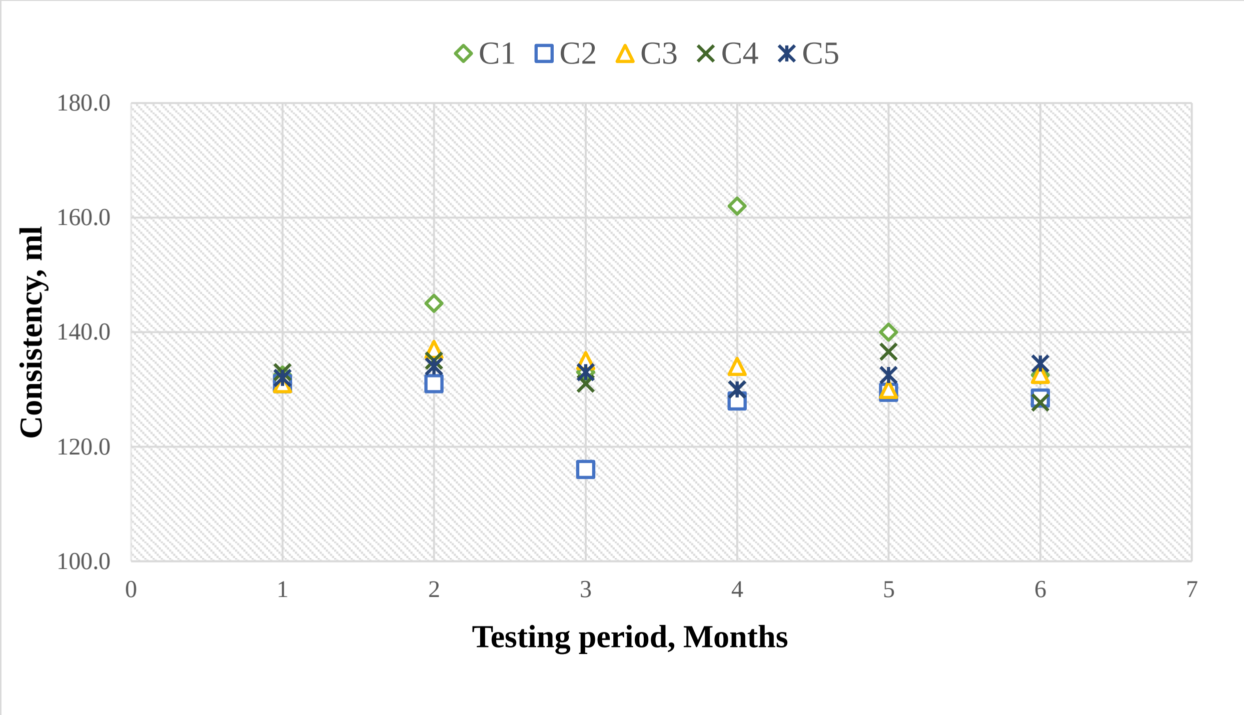


Figure 4-5 Consistency

4.5 Soundness

The soundness of cement was conducted as per *ES 1176 – 3: 2005 method of testing cement part 3: Designation of setting time and soundness*. The test results for soundness of cement are presented in Table 4-6 and Figure 4-6 below.

According to CES 28, the soundness of cement should be less than 10 mm for all strength class cement. According to the result shown in Table 4-6, all cement types conform to the requirement of CES 28.

In respect to the variability of soundness, the coefficient of variation varied from 50% up to 133% within six months. The diagrammatic view is presented in Figure 4-6 below

Table 4-6 Soundness

Cement	Soundness, mm						$\overline{X}$, mm	S, mm	CoV, %	Population mean, ml		Conformity criteria, mm		Result
	Testing month													
	1st	2nd	3rd	4th	5th	6th				LL	UL	Min.	Max.	
C1	0.3	0.2	0.2	0.3	0.3	0.1	0.2	0.1	50	0.1	0.3	0	10	Conform
C2	0.2	0.0	0.5	0.1	0.0	0.3	0.2	0.2	100	0	0.4	0	10	Conform
C3	0.5	0.2	0.2	0.3	0.0	0.2	0.2	0.2	100	0.1	0.4	0	10	Conform
C4	0.2	0.2	0.3	0.1	0.1	0.3	0.2	0.1	50	0.1	0.3	0	10	Conform
C5	2.1	0.2	0.3	0.3	0.2	0.2	0.6	0.8	133	0	1.3	0	10	Conform

$\overline{X}$ = sample mean of soundness for six months.

S = sample standard deviation of soundness for six months

CoV = coefficient of variation of sample data = (S/$\overline{X}$)*100%

Population mean LL/UL = lower/upper limit value of population mean with 95% confidence level = $\overline{X} \pm 1.05$*S

Conformity criteria Min/Max = a minimum/maximum amount of soundness should attain as per CES 28

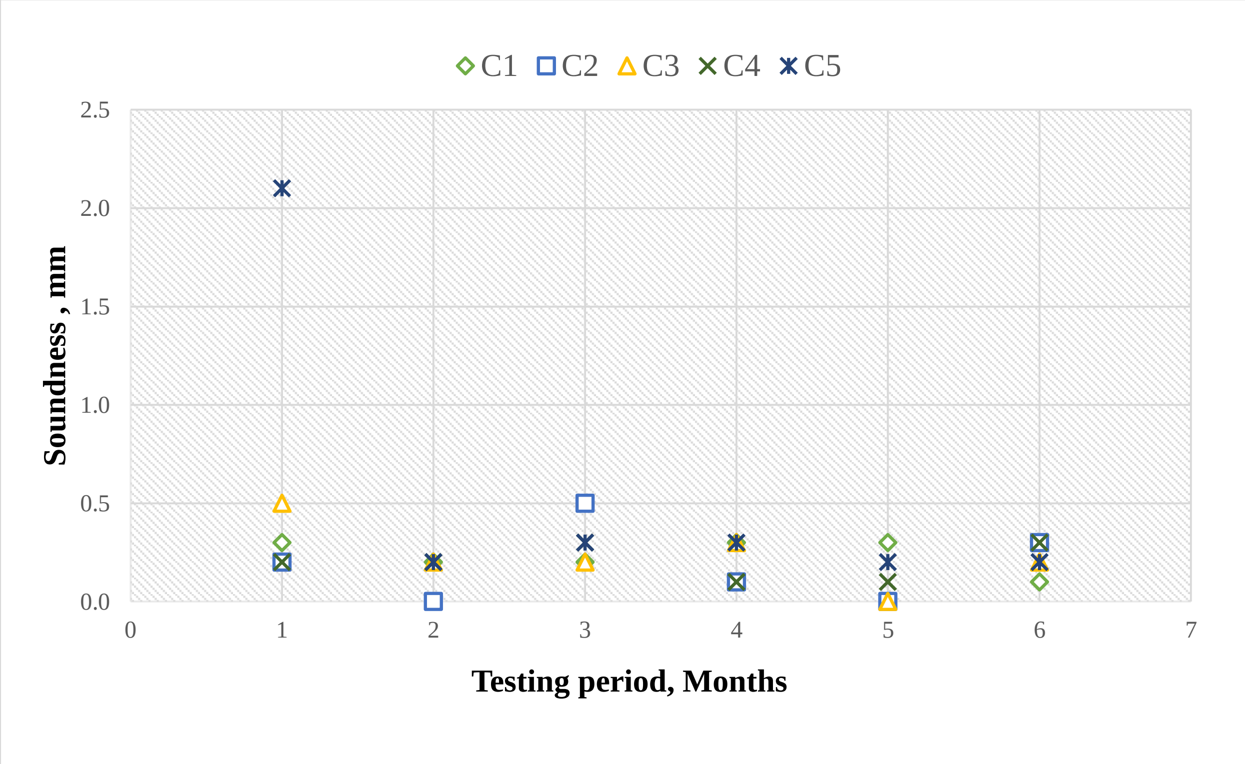


Figure 4-6 Soundness

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions are derived in line with the objective of this research.

In this research 2nd day compressive strength, 28th day compressive strength, initial setting time, final setting time, consistency, and soundness tests were conducted for five cement brands for six months. Based on the test results the following conclusions are made.

1. 40% of the studied cement brands do not fulfill the 2nd day compressive strength requirement of CES 28. Moreover, the variability of 2nd day compressive strength results showed high variability within the same brand ranging from 5% to 20% over the study period.
2. 20% of the studied cement brands do not fulfill the 28th day compressive strength requirement of CES 28. Additionally, 60% of the studied cement brands have high variability ranging from 6% to 8%. Nevertheless, 40% of the studied cement types have acceptable variability of about 3 - 4%.
3. All brands of the cements studied conform to the initial setting time and soundness requirements of CES 28. However, the results show that all cement brands had high variability in initial setting time (9% to 25%), final setting time (8% to 21%), and soundness (50% to 133%) over the study period.

Generally, all these variations cause an undesirable outcome in the overall properties of concrete and other cement products. To overcome this problem users might use additional cement, to compensate for variation, which increases the cost of the final product.

5.2 Recommendations

Recommendations for cement users

Before cement purchase, a decision made by cement users such as contractors, concrete suppliers, and technical officers, cement variability shall be considered. Apart from the description on cement bags, cement users should request to see third party test reports over the past months. Everything else being equal, the cement that has a lower coefficient of variation (or low standard deviation) will be uniform and will generally result in a lower concrete property standard deviation. This can result in a lower target average concrete strength variations with a lower cement content for a given strength level, finally leading to the economical mix design.

With a complex interdependence of cement and concrete properties, it is important to analyze and evaluate variations in cement properties and its effect on the performance of concrete before choosing a supplier for economical concrete construction.

Recommendations for Ethiopian Standard Agency

Ethiopian Standard Agency (ESA) is a national standarda body in Ethiopia, ESA as a national standard body that develops and implements national standards. It has been noted that there is no standard for the variability of cement properties so far. Therefore, it is recommended that Ethiopian Standard Agency to set standard for variability of cement properties.

Areas of further studies

The following points are proposed for further studies, to researchers who are interested to study, on the locally produced cement.

- Study of the variability of Portland cement chemical properties
- The fineness of cement and its effect on various properties of cement & concrete.
- The main causes of cement properties variability.

References

1. **Kosmatka, Steven H., Kerkhoff, Beatrix, and Panarese, William C.,** *Design and Control of Concrete Mixtures, 14th Edition.* Portland Cement Association : Skokie, Illinois, USA, 2003.
2. **Lamond, Joseph F. and Pieler, James H.,** *Significance of Tests and Properties of Concrete and Concrete Making Materials, STP169D, 5th Edition.* ASTM International : Bridgeport, New Jersey, USA, 2006.
3. **Thushara Priyadarshana and Ranjith Dissanayake,** *Importance of Consistent Cement Quality for a Sustainable Construction, Vol 1, No 4.* International Journal of Material : Paradeniya, Sri Lanka, 2013.
4. **Nigus G/Egziabhere,** *Comparison of Concrete Properties using Mugher, Messebo and Dire Dawa Cements.* Addis Ababa University MSc Thesis : Addis Ababa, Ethiopia, 2005.
5. **Mindess, Sidney and Francis, J.,** *Concrete, 2nd Edition.* Pearson Education Inc. : Upper Saddle River, New Jersey, USA, 2003.
6. **ASTM C 917-98.** *Standard test Method Evaluation of Cement Strength Uniformity From a Single Source.* ASTM International : West Conshohocken, Pennsylvania, USA, 1998.
7. **Compulsory Ethiopian Standard, CES 28,** *Cement - Part 1: Composition Specification and Conformity Criteria for Common Cements.* Ethiopian Standard Agency : Addis Ababa, Ethiopia, 2013.
8. **Neville, A. M.,** *Properties of Concrete, 4th Edition.* Pearson Education Limited : Edinburgh Gate, Harlow, UK, 2004.
9. **Winter, Nicholas B.,** *Understanding Cement, 1st Edition.* WHD Microanalysis Consultants Ltd : Suffolk, UK, 2009.
10. **Brandt, Andrzej M.,** *Cement Based Composites - Material, Mechanical Properties and Performance, 2nd Edition.* Tylor & Francis e-Library : New York City, New York, USA, 2009.
11. **European Standard, EN 197-1:2011,** *Cement - Part 1: Composition, specifications and conformity criteria for common cements.* European Committee for Standardization : Brussels, Belgium, 2011.
12. **ASTM C150 - 2011,** *Standard Specification for Portland Cement.* ASTM International : West Conshohocken, Pennsylvania, USA, 2011.
13. **Goncalves, M. Clara, Margarido, Fernanda,** *Materials for Construction and Civil Engineering : Science, Processing and Design, 1st Edition.* Springer International Publishing : Lisbon, Portugal, 2015.
14. **Taylor, H.F.W.,** *Cement Chemistry, 2nd Edition.* Thomas Tolford Publishing : London, UK, 1997.

15. **Mamlouk, Michael S. and Zaniewski, John P.,** *Materials for Civil and Construction Engineers, 3rd Edition.* Pearson Education, Inc. : Upper Saddle River, New Jersey, USA, 2011.
16. **Itzhak Soroka,** *Portland Cement Paste and Concrete, 1st Edition.* The Macmillan Press LTD : London, UK, 1979.
17. **Mehta, P. Kumar and Monteiro, Paulo J. M.,** *Concrete - Microstructure, Properties, and Materials, 3rd Edition.* McGraw-Hill Companies : New York City, New York, USA, 2006.
18. **Neville, A.M. and Brooks J.J.,** *Concrete Technology, 2nd Edition.* Pearson Eduction Limited : Edinburgh Gate, Harlow, UK, 2010.
19. **Hewlett, Peter C.,** *Lea's Chemistry of Cement and Concrete, 4th Edition.* Elsevier Science & Technology Books : Amsterdam, Netherlands, 2004.
20. **Labahn, Otto,** *Cement Engineers Handbook, 4th Edition.* Wiesbadener Graphische Bertriebe : Berlin, Germany, 1983.
21. **Abebe Dinku,** *Construction Materials Laboratory Manual, 1st Edition.* Addis Ababa University Printing Press : Addis Ababa, Ethiopia, 2002.
22. **ASTM C 187-98,** *Standard Test Method for Normal Consistency of Hydraulic Cement.* ASTM International : West Conshohocken, Pennsylvania, USA, 1998.
23. **Bye, G.C.,** *Portland Cement - Composition, Production and Properties, 2nd Edition.* Thomas Telford Publishing : London, UK, 1999.
24. **ACI 214R-11,** *Guide to Evaluation of Strength Test Results of Concrete.* American Concrete Institute : Farmington Hills, Michigan, USA, 2011.
25. **ASTM C 39-03,** *Standard test method for compressive strength of cylinderical concrete specimens.* West Conshohocken, Pennsylvania, USA : ASTM Internaltional, 2003.
26. **Birhanu Bogale,** *Comparison of Concrete Durability as Produced by Varies Cements Manufactured in Ethiopia.* Addis Ababa University MSc Thesis : Addis Ababa, Ethiopia, 2007.
27. **Mark Bediako, Eric Opoku Amankwah.** *Analysis of Chemical Composition of Portland Cement in Ghana.* Hindawi Publishing Corporation : Kumasi, Ghana, 2015.
28. **Chemical and Construction Inputs Industry Development Institute.** *Cement Production of Ethiopian Cement Factories.* Unpublished Report : Addis Ababa, Ethiopia, 2018.
29. **ES 1176-1:2005.** *Method of Testing Cement Part 1 - Determination of Strength.* Quality and Standards Authority of Ethiopia : Addis Ababa, Ethiopia, 2005.
30. **ES 1176-3:2005.** *Method of Testing Cement Part 3 - Designation of Setting Time and Soundness.* Quality and Standards Authority of Ethiopia : Addis Ababa, Ethiopia, 2005.
31. **Bluman, Allan G.,** *Elementary Statistics: Step by Step Approach, 7th Edition.* McGraw-Hill : New York City, New York, USA, 2009.

Appendix A

1st-month compressive strength, setting time, consistency, and soundness test results of cement samples.

Cement	2nd day compressive strength (MPa)	28th day compressive strength (MPa)	Consistency (ml)	Initial setting time (min)	Final setting time (min)	Soundness (mm)
1C1N	23.1	51.6	132.5	187.32	236.62	0.325
	23.8	52.0				
	22.3	50.4				
	22.4	52.6				
	22.5	51.0				
	22.8	50.4				
1C2N	15.3	48.9	131	180.27	220.22	0.185
	15.8	45.0				
	16.4	46.4				
	16.2	48.7				
	15.6	43.2				
	16.0	45.0				
1C3R	20.9	53.8	131	207.05	248.83	0.535
	21.2	53.0				
	21.0	49.8				
	20.8	52.1				
	21.3	53.0				
	22.1	53.9				
1C4R	23.5	49.8	133	167.98	218.38	0.195
	24.1	52.9				
	23.3	49.6				
	23.7	52.8				
	23.9	49.8				
	24.3	52.0				
1C5R	21.7	53.9	132	122.02	153.57	2.05
	20.9	47.0				
	20.8	48.6				
	20.5	52.6				
	20.6	49.8				
	20.8	51.4				

Appendix B

2nd-month compressive strength, setting time, consistency, and soundness test results of cement samples.

Cement	2nd day compressive strength (MPa)	28th day compressive strength (MPa)	Consistency (ml)	Initial setting time (min)	Final setting time (min)	Soundness (mm)
2C1N	32.45	57.06	145	144.08	205.02	0.16
	30.46	57.54				
	32.19	55.13				
	32.18	55.42				
	31.81	57.39				
	30.46	58.11				
2C2N	18.11	49.45	131	146.43	190.22	0
	19.75	43.77				
	17.53	47.51				
	19.46	42.54				
	17.12	48.26				
	18.06	46.51				
2C3R	19.23	51.71	137	179.23	256.2	0.24
	20.51	52.14				
	18.38	45.96				
	17.68	47.74				
	19.53	50.18				
	20.21					
2C4R	25.40	51.98	135	161.88	224.28	0.23
	24.84	54.85				
	25.57	55.27				
	23.79	52.29				
	24.18	50.09				
	25.47	55.18				
2C5R	22.45	53.11	134	124.42	163.85	0.22
	24.00	51.06				
	20.91	50.74				
	21.42	52.59				
	21.03	51.37				
	22.26	54.59				

Appendix C

3rd-month compressive strength, setting time, consistency, and soundness test results of cement samples.

Cement	2nd day compressive strength (MPa)	28th day compressive strength (MPa)	Consistency (ml)	Initial setting time (min)	Final setting time (min)	Soundness (mm)
3C1N	25.96	54.88	133	170.88	222.05	0.15
	26.93	55.13				
	24.62	54.06				
	26.54	51.29				
	26.13	57.94				
	25.45	52.11				
3C2N	11.79	38.75	116	123.08	157.33	0.5
	13.07	38.62				
	12.54	38.99				
	13.03	40.82				
	12.71	40.41				
	13.01	39.86				
3C3R	16.86	52.54	135	182.02	247.17	0.2
	17.12	49.79				
	18.79	50.92				
	18.44	50.15				
	17.14	55.33				
	17.83	51.64				
3C4R	18.80	46.38	131	136.82	183.2	0.295
	19.29	44.18				
	19.04	42.36				
	18.09	39.99				
	17.76	46.04				
	18.34	42.84				
3C5R	21.71	55.33	133	177.42	248.57	0.31
	22.85	55.48				
	21.16	53.83				
	22.29	50.14				
	22.31	56.69				
	22.65	50.18				

Appendix D

4th-month compressive strength, setting time, consistency, and soundness test results of cement samples.

Cement	2nd day compressive strength (MPa)	28th day compressive strength (MPa)	Consistency (ml)	Initial setting time (min)	Final setting time (min)	Soundness (mm)
4C1N	39.43	50.16	162	97.13	136.5	0.33
	39.22	52.28				
	36.43	51.22				
	39.32	50.02				
	41.59	53.08				
4C2N	14.94	41.56	128	131.97	163.23	0.12
	15.44	44.17				
	16.03	38.16				
	16.16	37.92				
	16.41	44.59				
	13.98	44.15				
4C3R	19.84	51.88	134	177.17	245.05	0.255
	20.67	51.74				
	22.06	49.61				
	20.94	46.23				
	21.73	45.10				
		46.37				
4C4R	20.44	49.24	130	131.9	178.05	0.05
	22.69	45.10				
	20.38	44.62				
	21.94	45.18				
	21.23	48.33				
	21.50	45.86				
4C5R	20.74	52.08	130	133.57	172.93	0.255
	21.07	55.21				
	19.93	56.64				
	20.36	53.72				
	21.50	59.97				
	20.29					

Appendix E

5th-month compressive strength, setting time, consistency, and soundness test results of cement samples.

Cement	2nd day compressive strength (MPa)	28th day compressive strength (MPa)	Consistency (ml)	Initial setting time (min)	Final setting time (min)	Soundness (mm)
5C1N	28.44	53.23	140	109.22	162.05	0.265
	27.81	53.11				
	29.06	52.13				
	28.33	54.56				
	28.89	49.26				
	30.58	47.92				
5C2N	16.30	41.58	129.5	117.08	144.65	0
	16.53	40.91				
	15.43	42.58				
	15.54	41.89				
	15.78	41.81				
	15.51					
5C3R	22.40	50.95	130	166.67	208.73	0
	24.06	51.94				
	23.49	54.11				
	21.29	52.73				
	22.79	53.93				
	22.67					
5C4R	21.31	46.86	136.6	136.02	165.2	0.13
	21.54	45.53				
	20.38	47.80				
	20.76	47.94				
	19.24	43.41				
	22.10	46.88				
5C5R	23.11	54.96	132.5	126.07	149.43	0.24
	23.90	53.19				
	22.37	46.86				
	22.04	48.56				
	22.40	49.95				
	23.28	51.92				

Appendix F

6th-month compressive strength, setting time, consistency, and soundness test results of cement samples.

Cement	2nd day compressive strength (MPa)	28th day compressive strength (MPa)	Consistency (ml)	Initial setting time (min)	Final setting time (min)	Soundness (mm)
6C1N	25.14	50.63	132.5	174.38	236.7	0.05
	25.31	51.68				
	26.37	51.34				
	24.18	51.57				
	24.66	53.83				
		55.64				
6C2N	17.56	48.63	128.5	132.75	174.63	0.32
	17.33	48.04				
	17.44	48.76				
	17.53	46.84				
	18.23	50.31				
	17.89	45.77				
6C3R	20.72	50.89	132.6	204.82	265.55	0.175
	20.59	52.74				
	21.66	50.83				
	21.31	51.80				
	20.37	51.68				
	20.28					
6C4R	21.29	47.19	127.7	140.57	192.08	0.34
	21.13	46.14				
	22.76	45.44				
	22.15	44.68				
	22.39	49.42				
	22.70	47.69				
6C5R	20.38	45.11	134.5	155.8	191.1	0.2
	21.09	47.70				
	19.93	46.75				
	19.86	44.00				
	21.28	46.01				
	20.50	47.21				

Appendix G

Student t distribution table

Degree of freedom	Confidence interval, α				
	80%	90%	95%	98%	99%
1	3.078	6.314	12.706	31.821	63.657
2	1.886	2.920	4.303	6.965	9.925
3	1.638	2.353	3.182	4.541	5.841
4	1.533	2.132	2.776	3.747	4.604
5	1.476	2.015	2.571	3.365	4.032
6	1.440	1.943	2.447	3.143	3.707
7	1.415	1.895	2.365	2.998	3.499
8	1.397	1.860	2.306	2.896	3.355
9	1.383	1.833	2.262	2.821	3.250
10	1.372	1.812	2.228	2.764	3.169
11	1.363	1.796	2.201	2.718	3.106
12	1.356	1.782	2.179	2.681	3.055
13	1.350	1.771	2.160	2.650	3.012
14	1.345	1.761	2.145	2.624	2.977
15	1.341	1.753	2.131	2.602	2.947
16	1.337	1.746	2.120	2.583	2.921
17	1.333	1.740	2.110	2.567	2.898
18	1.330	1.734	2.101	2.552	2.878
19	1.328	1.729	2.093	2.539	2.861
20	1.325	1.725	2.086	2.528	2.845
21	1.323	1.721	2.080	2.518	2.831
22	1.321	1.717	2.074	2.508	2.819
23	1.319	1.714	2.069	2.500	2.807
24	1.318	1.711	2.064	2.492	2.797
25	1.316	1.708	2.060	2.485	2.787
26	1.315	1.706	2.056	2.479	2.779
27	1.314	1.703	2.052	2.473	2.771
28	1.313	1.701	2.048	2.467	2.763
29	1.311	1.699	2.045	2.462	2.756
30	1.310	1.697	2.042	2.457	2.750
32	1.309	1.694	2.037	2.449	2.738
34	1.307	1.691	2.032	2.441	2.728
36	1.306	1.688	2.028	2.434	2.719
38	1.304	1.686	2.024	2.429	2.712
40	1.303	1.684	2.021	2.423	2.704
45	1.301	1.679	2.014	2.412	2.690
50	1.299	1.676	2.009	2.403	2.678
55	1.297	1.673	2.004	2.396	2.668
60	1.296	1.671	2.000	2.390	2.660
65	1.295	1.669	1.997	2.385	2.654
70	1.294	1.667	1.994	2.381	2.648
75	1.293	1.665	1.992	2.377	2.643
80	1.292	1.664	1.990	2.374	2.639
90	1.291	1.662	1.987	2.368	2.632
100	1.290	1.660	1.984	2.364	2.626
500	1.283	1.648	1.965	2.334	2.586
1000	1.282	1.646	1.962	2.330	2.581

Appendix H

The 27 products in the family of common cement

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass[a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana natural	Pozzolana natural calcined	Fly ash siliceous	Fly ash calca-reous	Burnt shale	Limestone		
			K	S	D[b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	0-5
		CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	0-5
		CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	6-20	–	0-5
		CEM II/B-L	65-79	–	–	–	–	–	–	–	21-35	–	0-5
		CEM II/A-LL	80-94	–	–	–	–	–	–	–	–	6-20	0-5
		CEM II/B-LL	65-79	–	–	–	–	–	–	–	–	21-35	0-5
	Portland-composite cement[c]	CEM II/A-M	80-88	<------ 12-20 ------>									0-5
		CEM II/B-M	65-79	<------ 21-35 ------>									
CEM III	Blast furnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement[c]	CEM IV/A	65-89	–	<------ 11-35 ------>					–	–	–	0-5
		CEM IV/B	45-64	–	<------ 36-55 ------>					–	–	–	0-5
CEM V	Composite cement[c]	CEM V/A	40-64	18-30	–	<------ 18-30 ------>			–	–	–	–	0-5
		CEM V/B	20-38	31-49	–	<------ 31-49 ------>			–	–	–	–	0-5

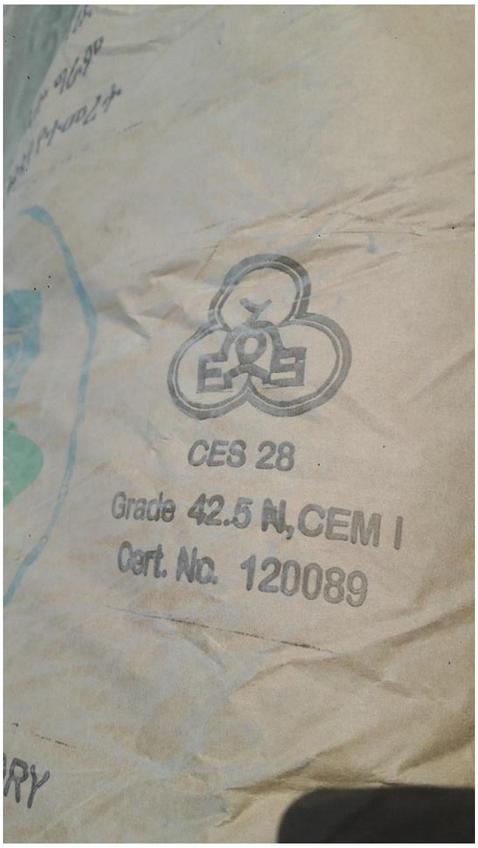
a The values in the table refer to the sum of the main and minor additional constituents.

b The proportion of silica fume is limited to 10 %.

c In Portland-composite cements CEM II/A-M and CEM II/B-M, in pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for examples, see Clause 8).

Appendix I

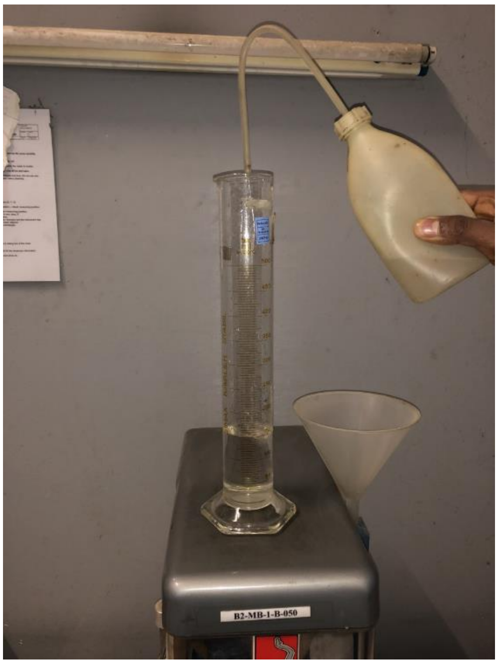
Laboratory photos



Cement sample

Cement weighing

Mortar mixer



Water measurement

Standard sand adding to paste

Casting mortar

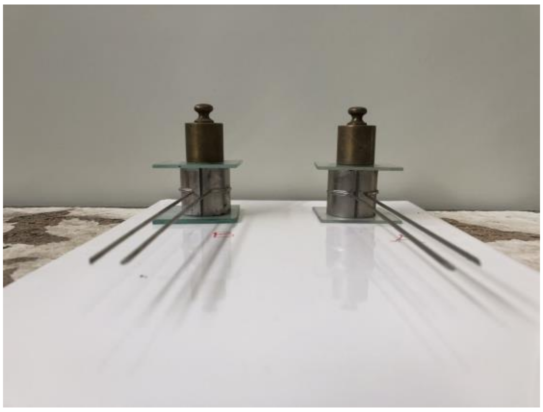
Humidity cabinet

Samples at Curing tank

Flexural strength test

Compressive strength test result

Specimen test for compressive strength



Soundness test

Setting time test

Oven for soundness