Thermo-physical, Electrical and Mechanical Characterizations of Normal and Special Concretes: A Holistic-Empirical Investigation for Pre-qualification and Quality-Control of Concrete

Osagie Ibhadode¹*, A. A. Adekunle¹, Solomon O. Banjo² and O. D. Atakpu¹

¹Nigerian Building and Road Research Institute (NBRRI), Abuja, Nigeria.
²Covenant University (CU), Km 10 Idiroko Road, Ota, Ogun State, Nigeria
Corresponding Author: osagie.ibhadode@gmail.com

Abstract-
Nine (9) Concrete specimens (Concrete test-materials) [comprising of 3 ‘Portland Cement Normal Concrete specimens’, 3 ‘Portland Slag Special Concrete specimens’ and 3 ‘Silica-fume Slag Special Concrete specimens’] were designed-for in accordance with ACI 211.1-91, cast in accordance with ASTM C 127 and cured for three (3) Curing-ages of 28 days, 56 days and 90 days. Each was subjected to eleven (11) Quality (Strength, Durability & Workability)-evaluation experimental-tests in accordance with the relevant ASTM, BSI and other scientifically-established standard procedures, so as to empirically determine their Thermo-physical, Electrical & Mechanical characterizations (behavioural-changes) and the various determining (influencing) factors (variables). Summarily, it was experimentally discovered that, Supplementary Cementitious Material (SCM) content and Maturity (Curing-age) significantly influenced (affected) five (5) conducted Thermo-physical characterization-tests of ‘Specific Heat Capacity ($C_p$)’, ‘Thermal diffusivity ($\delta_{\text{Thermal}}$)’, ‘Thermal Conductivity ($K_{\text{Thermal}}$)’, ‘Dry bulk density ($\rho_{\text{bulk,dry}}$)’ and ‘Water sorptivity ($S$)’ of Concrete. Also, it was observed that the five (5) conducted Electrical characterization-tests i.e. ‘RCPT Total Electric Charge passed ($\sum Q_1$)’, ‘Chloride-ion Penetrability’, ‘Initial 5 minutes RCPT Electricity Resistivity ($\rho_{E(RCPT)}$)’, ‘Chloride-ion Penetration-depth ($C_{pd}$)’ and ‘Non-steady state migration coefficient ($D_{\text{nonMC}}$)’ of Concrete largely depended on the Water/Cement (w/c) ratio, Maturity (Curing-age) and SCM content. Furthermore, it was noticed that Mechanical characterization-test i.e. “Average Compressive-strength” and ‘Slump’ of Concrete is primarily a function of w/c ratio, SCM content, Maturity (Curing-age) and several other factors. Consequently, it has been experimentally revealed that amongst other things, the four (4) critical determinants of Concrete quality are the Concrete’s Water/Cement (w/c) ratio, Maturity (Curing-age), Supplementary Cementitious Material (SCM) content and Bulk density.

Keywords: Concrete, Concrete-quality, Compressive-strength, ASTM, ACI.

1. Introduction
The current global push for the transformation of existing ‘Megacities’ into new ‘Global (World)-cities’, coupled with the sustained (continuous) infrastructural development of the existing ‘Global (World)-cities’ in both developed (first-world) and developing (second- and third-world) countries, have continued to raise the stakes in the progressively-rising global
demand for ‘Concrete’ annually. Be that as it may, it is evident that, from ['New-York', 'Washington', 'Toronto' & ‘Montreal’] in North-America to ['London', 'Berlin', 'Hamburg', ‘Paris’ & ‘Stockholm’] in Europe to ['Tokyo', ‘Shanghai’, ‘Beijing’, ‘Hongkong’ & ‘Singapore’] in Asia, all the way down to ['Sydney'] in Oceania etc.; there is candidly no accurate quantification of the countless metric tons of ‘Concrete’ that have been used to construct critical infrastructure [such as bridges, flyovers, roads, platforms, buildings and dams etc.] in these Global (World)-cities that posit as ‘global economic Nerve-centers’. Actually, the above is but a conservatively-stated estimate of the importance and indispensable nature of ‘Concrete’ in construction, and the present over-dependence of the global construction industry on ‘Concrete’—judging from the upsurge in its use (applications) annually.

Concrete is unmistakably ranked second-place on the list of the most commonly-used materials globally, trailing behind ‘Water’, which predominantly occupies the first place on this list [1], [2], [3], [4]. Presently, the worldwide annual concrete production capacity is conservatively estimated to be ten billion metric tons. In the year 2012, the Concrete sub-sector of the US economy was single-handedly worth over US$37 billion and simultaneously provided employment for well over two million Americans [5]. In the year 2014, the net worth of the global concrete production capacity was US$53.9 billion [6]. In the year 2015, alone 214.8 metric tons of Ready-mix concrete were produced in sixteen (16) EU countries, while 353.0 metric tons of Ready-mix concrete were cumulatively produced in the twenty (20) countries officially registered with the European Ready-Mix Concrete Organization (ERMCO), as against the 40.5 metric tons, 99.0 metric tons and 260.0 metric tons of Ready-mix concrete respectively produced in Russia, Japan and USA within the same year [7]. However, in the year 2016, the net worth of the global concrete production capacity sky-rocketed by 13.6% of its year 2014 value to hit a whopping US$1,104 billion [6].

Concrete is an artificial, composite engineering-material which is often used in the construction industry, and is produced by the hardening (solidification) of a mixture of predetermined quantities of binder (cement, supplementary cementitious material(s)), water, air and embedded fragments of fillers (fine aggregate and coarse aggregate) with/without admixture(s). According to [8], ‘Good Concrete’ is concrete which performs satisfactorily in both its plastic (fresh) and hardened states, by virtue of the facts that, it is compacted and cohesive enough to be transported and placed (cast) [in/outside a formwork] without undergoing segregation. Now, aside the choice of the Curing method adopted, which goes a long way to ensuring that certain design requirements are met (satisfied), the quality (i.e. ‘Workability’) of Concrete in its fresh state [which is determined by the ‘Slump test’] is also of vital importance, since it plays a major role in determining the properties of the cast and cured Concrete, after it sets to its hardened state [9]. Over the years, certain advantages associated with the use (application) of concrete, that have unarguably earned it its place of preference amongst engineers and builders include: durability, strength, aesthetics, energy-efficiency, plastic-state workability, relative ease of on-site handling (mixing, casting & curing), good fire-resistance and affordability [10]. Three critically important properties that collectively define the quality of concrete are its ‘strength’, ‘durability’ and ‘workability’. The strength of concrete is simply the inherent ability of concrete to withstand (resist) [one or more combinations of compressive, tensile, torsional & shear] stress. On the other hand, the durability of concrete is defined by the American Concrete Institute (ACI) as “the inherent ability of concrete to withstand (resist) weathering-action,
abrasion chemical-attack and other field-application conditions” [11], [12]. A highly durable concrete is one with a high degree of impermeability (fluid-tightness).

Actually, when concrete is used under typical field (service) conditions, such as for the construction of engineering structures [bridges, fly-overs, roads, platforms, buildings and dams etc.], it will most certainly be exposed to harsh environmental conditions [such as temperature & pressure changes (thawing & freezing), chemical attacks, fluids (liquids and/or gases) flow (entry) into its pore structure, and variations in moisture content etc.] which might result in a deterioration of its strength and eventually a reduction of its durability during the service life of the concrete-structure. For instance, invisible faults or cracks within the concrete’s microstructure could be initiated by one or more combinations of excessive structural loads, mechanical stresses, excessive, adverse environmental exposures and chemical attacks; and then, if left unchecked (uncontrolled), may gradually escalate to the level of visible cracks—which sadly enough may result in a decrease in the concrete’s permeability (fluid-tightness)—by implication, a reduction in the concrete’s quality (strength and durability).

Now, the obvious undesirable consequences of a gradual decline in the durability of a concrete structure [e.g. an inhabited building or a bridge/flyover with peak traffic load is best imagined than experienced. This is because of its dreaded consequences—especially ‘structural failures’ which oftentimes are fatal i.e. resulting in the loss of human lives, with high fatalities particularly in highly congested and built-up megacities/Global (World)-cities with their characteristically high human population densities. It, therefore, becomes critically important to regularly embark on new (fresh) studies on the quality (durability and strength) of concretes that: (1.) were used to construct existing (old) public infrastructure in the past, and (2.) will be used to construct new public infrastructure in the future; in view of the currently adopted evolutionary trend in the design of concrete structures i.e. “Load and Resistance Factor Design (LRFD)”.

Moreover, the rampant cases of Building fires incidences [caused by a number of reasons including electricity, domestic activities, & uncontrolled bush burning etc.] commonly occurring in Africa & poor Asian countries coupled with the instances of wild forest fires [sometimes occurring in the North-America, Europe, Latin-America & Oceania] around concrete structures; it has become vitally important for Civil/Electrical/Mechanical Engineers, Architects, Building-services Experts and the Built-environment professionals etc., to factor-in the necessary considerations for the thermal behaviour of concrete.

More so, it is pertinent to mention that, while predesign conditions consideration and post-design testing of concrete specimens to ascertain their quality (durability & strengths) [prior to the construction of new concrete-structures] is encouraged as standard practice, there still remains the critical need to (concern of) evaluating and continuously validating the quality (durability & strength) of existing (old) concrete structures. Ironically, most of the conventional (traditional) methods of evaluating concrete durability usually involve a considerable time-interval between the casting of the to-be tested concrete specimens/specimens within the mould/form-work and the release of the experimental test results. Hence, in order to evaluate the potential durability indices of concrete, it has become necessary to apply a rapid result-generation and easy-to-conduct test method called the ‘Rapid Chloride Permeability (RCP)
Electrical test’—which was initially proposed by Sir. D. Whiting and then, was standardized as the ‘ASTM C 1202’.

Thus, from the foregoing, “the dire need to carry-out a holistic-study that takes into cognizance (consideration) the various performance-based behavioural patterns (characterizations) of concrete when subjected to service conditions that are similar conditions which are obtainable during real-time field exposures”, was the major motivation for embarking on this timeless and exhaustive research project.

Consequently, the aim of this research work is “to conduct a critical-empirical investigation of the thermo-physical characterizations (behavioural-changes) [Bulk density, Water-sorptivity, Specific heat capacity, Thermal conductivity & Thermal diffusivity], Electrical characterizations ['Total electric-charge passed/Chloride-ion penetrability', 'Initial 5 minute Rapid Chloride Permeability electrical-resistivity' & 'Chloride-ion penetration depth'] and Mechanical characterizations [Slump (Workability) & Compressive-strength] for the performance-based quality (durability & strength) evaluation of some normal and special concretes; while identifying & analyzing some of the factors (variables & conditions) that influence these characterizations (behavioural-changes) of concrete”.

2. **Methodology**

The materials (ingredients) used for this experimental research were: Binders ['ASTM type I Ordinary Portland Cement (OPC)’ with a density of 3134Kg/m³ & Blaine fineness of 350m³/Kg, ‘Type II Ground-granulated Blast-furnace Slag (GGBFS)’ with a density of 2854Kg/m³ & Blaine fineness of 425 m³/Kg and ‘Type GU--8SF Silica-fume blended cement (SFBC)’ with a density of 3080Kg/m³ & Blaine fineness of 337m³/Kg]; Fillers [washed & oven-dried Natural Siliceous ‘River-bank Sand’ with a Specific gravity of 2.63 (as Fine Aggregate) and washed & oven-dried 20mm nominal maximum-sized quarried angular-shaped ‘Granite-chippings’ with a dry-rodded density of 1638Kg/m³ & Specific gravity of 2.65]; Chemical Admixtures ['Glenium 7700’ Polycarboxylate-based Superplasticizer with a density of 1.06Kg/m³, ‘Pozzolith 210’ and Water-reducer with a density of 1138Kg/m³]; and potable (drinkable) Water with a PH of 7.

In order to determine the Particle Size Distribution (PSD), Sieve Analyses of both the Fine Aggregate (River sand) and Coarse Aggregate (Granite Chippings) were carried out in accordance with ASTM C 136 standard method\(^{[13]}\), by differently separating the washed, oven-dried, weighed specimens of fine and coarse aggregates through a ten(10)-minute mechanical agitation of sieves of standard recommended sizes [with progressively smaller & equally spaced regular holes (openings)], which were nested in a decreasing order from top to bottom, with a pan to collect the aggregates passing through the holes, while the top sieve was covered with a lid. For the fine aggregate, the weight retained on each sieve was ascertained by measurement, then the percentages passing and the total percentages retained were calculated to the nearest 0.1% of the initial ‘fine aggregate specimen dry weight’ and tabulated in ‘Table 1’, and then, the ‘Fineness Modulus of the Fine Aggregate \((FM_{FA})\)’ was computed as the quotient obtained when a dividend (i.e. ‘the sum of the cumulative percentages of fine aggregate masses retained on all sieves’) was divided by the divisor of ‘100’. A similar procedure was carried out for the Coarse Aggregate, as shown in ‘Table 2’. The above obtained percentages were then used to
generate (plot) the ‘Aggregate Grading (Particle size Distribution) curves’ for both the fine and coarse aggregates [as shown in ‘Figure 1’ and ‘Figure 2’] to determine if aggregates conformed with the standard grading requirements for fine and coarse aggregates specified by ‘ASTM C 33’ [14]. Also, The Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV) of the Coarse Aggregate were determined using an ACV machine and an AIV machine in accordance with standard test methods/procedures specified in the BS 812-110 [15] and BS 812-112 [16] Standards respectively.

Table 1: Sieve Analysis Data for Fine Aggregates (FA)

| Number | Size (mm) | Mass Retained (g) | Percentage Retained (%) | Passing (%) | Retained Percentage (%) | Passing Percentage (%) |
|--------|-----------|-------------------|-------------------------|-------------|------------------------|------------------------|
| 4      | 4.57      | 0.00              | 0.00                    | 100.0       | 0.00                   | 0.00                   |
| 8      | 2.36      | 197.90            | 16.85                   | 82.36       | 16.85                  | 82.36                  |
| 16     | 1.18      | 310.20            | 31.11                   | 48.28       | 47.96                  | 130.64                 |
| 30     | 0.60      | 305.60            | 27.06                   | 72.94       | 75.02                  | 151.05                 |
| 50     | 0.30      | 102.40            | 9.42                    | 90.58       | 84.44                  | 161.37                 |
| 100    | 0.15      | 51.10             | 2.73                    | 97.27       | 87.17                  | 168.52                 |

Sum (\(\sum\)) = 311.44

Fineness Modulus of Fine Aggregates

\[
(FM_{FA}) = \frac{\sum}{100} - - - - 1 \tag{13}
\]

\[
FM_{FA} = \frac{311.44}{100}
\]

\[
FM_{FA} = 3.144
\]

\[
FM_{FA} \approx 3.1
\]

NOTE:
The above FM-value satisfies the ASTM C33 / C33M -18 recommended limit range of 3.1 \(\geq FM_{FA} \geq 2.3\)

Table 2: Sieve Analysis Data for Coarse Aggregates (CA)

| Number or Size (mm) | Mass Retained (g) | Cumulative Mass Retained (g) | Percentage Retained (%) | Passing (%) | Cumulative Percentage |
|---------------------|-------------------|------------------------------|-------------------------|-------------|----------------------|

Figure 1: Aggregate Grading Curve for Fine Aggregates
Table 3: Aggregate Crushing Value Data for Coarse Aggregates (CA)

| S/No. | Measured/Calculated Parameter | Obtained Values |
|-------|-------------------------------|-----------------|
|       |                               | Test No. 1 | Test No. 2 | Test No. 3 |
| 1     | Mass of Cylinder ‘M₁(g)’       | 1210.0     | 1210.0     | 1210.0     |
| 2     | Mass of Cylinder and Sample ‘M₂(g)’ | 3897.0     | 3879.0     | 3885.0     |
| 3     | Mass of Sample ‘M₃(g)’ = M₂ − M₁ | 2687.0     | 2669.0     | 2675.0     |
| 4     | Mass of Sample passing the 5.00mm separating Sieve ‘M₄(g)’ | 715.2      | 711.4      | 713.9      |
Aggregate Crushing Value of Coarse Aggregates ($ACV_{CA}$) = \[
\frac{(%Fines_{test1} + %Fines_{test2} + %Fines_{test3})}{3}
\] 
\[
ACV_{CA} = \frac{26.6 + 26.7 + 26.7}{3} = \frac{80}{3}
\] 
\[
ACV_{CA} \approx 26.7
\]

NOTE: The above ‘ACV’ value conforms to the BS 812-110 specified requirement of ‘ACV values for Coarse aggregates which are suitable for the production of Concrete.

Table 4: Aggregate Impact Value Data for Coarse Aggregates (CA)

| S/No | Measured/Calculated Parameter | Obtained Values |
|------|------------------------------|-----------------|
|      |                              | Test No. 1  | Test No. 2  | Test No. 3  |
| 1    | Mass of Cylinder ‘M₁(g)’     | 2.35         | 2.35         | 2.35         |
| 2    | Mass of Cylinder and Sample ‘M₂(g)’ | 266.75       | 269.55       | 267.75       |
| 3    | Mass of Sample \(M₃(g) = M₂ - M₁\) | 264.40       | 267.20       | 265.40       |
| 4    | Mass of Sample retained on the 2.36mm separating Sieve ‘M₄(g)’ | 211.0         | 219.00       | 216.00       |
| 5    | Mass of Sample passing the 2.36mm separating Sieve ‘M₅(g)’   | 50.7          | 54.2         | 52.5         |
| 6    | Percentage of Fines ‘%Fines’ = \(\frac{M₄}{M₃} \times 100\)% | 19.2          | 20.3         | 19.8         |

Aggregate Impact Value of Coarse Aggregates ($AIV_{CA}$) = \[
\frac{(%Fines_{test1} + %Fines_{test2} + %Fines_{test3})}{3}
\] 
\[
AIV_{CA} = \frac{19.2 + 20.3 + 19.8}{3} = \frac{59.3}{3}
\] 
\[
AIV_{CA} \approx 19.8
\]

NOTE: The above ‘AIV’ value conforms to the BS 812-112 specified requirement of ‘AIV values for Coarse aggregates which are suitable for the production of Concrete.

During the course of this study, laboratory experiments were performed on single-batch mixes of nine (9) different non-air entrained Concrete specimens/test-materials [i.e. three Concrete specimens/test-materials from each of three Concrete-groups] consisting of:

a) Three (3) Concrete specimens/test-materials that comprise the ‘Portland Cement Normal Concrete-group’ (PCC):

I. ‘Maximally-mixed Portland Cement Normal Concrete (PCCₘₐₓ)’ produced with Ordinary Portland Cement, Aggregates and a maximum water content as determined by the expected field exposure conditions w/c ratio requirements and ‘ACI 211.1-91’ [17]
II. ‘Optimally-mixed Portland Cement Normal Concrete (\( PCC_{\text{opt}} \))’ produced with Ordinary Portland Cement, Aggregates and an optimal water content as determined by pre-design compressive strength \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

III. ‘Minimally-mixed Portland Cement Normal Concrete (\( PCC_{\text{min}} \))’ produced with Ordinary Portland Cement, Aggregates and a minimal water content as determined by pre-design compressive strength \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

b) Three (3) Concrete specimens/test-materials that comprise the ‘Portland Slag Special Concrete-group: (\( PSC \))’:

IV. ‘Maximally-mixed Portland Slag Special Concrete (\( PSC_{\text{max}} \))’ produced with 25% Ground-granulated Blast-furnace Slag [which is a pozzolana], Aggregates, a Water-reducing admixture and a maximum water content as determined by the expected field exposure conditions \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

V. ‘Optimally-mixed Portland Slag Special Concrete (\( PSC_{\text{opt}} \))’ produced with 25% Ground-granulated Blast-furnace Slag, Aggregates, a Water-reducing admixture and an optimum water content as determined by pre-design compressive strength \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

VI. ‘Minimally-mixed Portland Slag Special Concrete (\( PSC_{\text{min}} \))’ produced with 25% Ground-granulated Blast-furnace Slag, Aggregates, a Water-reducing admixture and a minimum water content as determined by pre-design compressive strength \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

c) Three (3) Concrete specimens/test-materials that comprise the ‘Silica-fume Slag special Concrete-group: (\( SSC \))’:

VII. ‘Maximally-mixed Silica-fume Slag Special Concrete (\( SSC_{\text{max}} \))’ produced with Silica-fume blended Cement, 25% Ground-granulated Blast-furnace Slag, Aggregates, a Super-plasticizer admixture and a maximum water content as determined by the expected field exposure conditions \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

VIII. ‘Optimally-mixed Silica-fume Slag Special Concrete (\( SSC_{\text{opt}} \))’ produced with Silica-fume blended Cement, 25% Ground-granulated Blast-furnace Slag, Aggregates, a Super-plasticizer admixture and an optimal water content as determined by pre-design compressive strength \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

IX. ‘Minimally-mixed Silica-fume Slag Special Concrete (\( SSC_{\text{min}} \))’ produced with Silica-fume blended Cement, 25% Ground-granulated Blast-furnace Slag, Aggregates, a Super-plasticizer admixture and an optimal water content as determined by pre-design compressive strength \( w/c \) ratio requirements and ‘ACI 211.1-91’ [17]

2.1 Concrete-Mix Designs

For each of these aforementioned nine (9) Concrete specimens/test-materials [3 Normal Concretes (‘\( PCC_{\text{max}} \)’, ‘\( PCC_{\text{opt}} \)’, ‘\( PCC_{\text{min}} \)’) and 6 Special Concretes (‘\( PSC_{\text{max}} \)’, ‘\( PSC_{\text{opt}} \)’, ‘\( PSC_{\text{min}} \)’, ‘\( SSC_{\text{max}} \)’, ‘\( SSC_{\text{opt}} \)’, ‘\( SSC_{\text{min}} \)’)], a unique Concrete-mix formulation was designed-for
in accordance with the ‘American Concrete Institute Standard Practice for selecting proportions for Normal, Heavy-weight and Mass Concrete (ACI 211.1-91)’, as are summarily presented in ‘Tables 5-14’. Prior to this, the ‘28-day Design-required (Target) Average Compressive Strengths \[ f_{m} \]’ were obtained in accordance with the British Standards Institute’s equation stated below:

\[
f_{m} = f_{\text{min}} + K \times S \tag{18}
\]

Where:
- \( f_{m} \) is the 28-day Design-required (Target) Mean Compressive Strength expressed in ‘MPa’
- \( f_{\text{min}} \) is the 28-day Specified Characteristic (Minimum) Compressive Strength expressed in ‘MPa’
- \( K \) is ‘Himsworth coefficient’, a statistical-factor (constant) which depends on the proportion (percentage) of defectives [also called ‘failure-probability’], and assumes a value of ‘1.65’ at a failure-probability of 5% when the curing-age is ‘28 days’
- \( S \) is the Standard deviation of the 28-day Expected Characteristic Compressive Strengths, from which the degree (level) of control can be inferred.

2.2 Calculation of Concrete-yields

Following the nine (9) Concrete mix-designs, the expected ‘Concrete-yield’ for each of the nine Concrete specimen/test-material, was obtained in accordance with the ‘Absolute Volume method’ from ‘Equation 6’, [and presented in ‘Tables 5-13’] as follows:

\[
V_{C} = \frac{M_{w}}{1000} + \frac{M_{C}}{1000 \times S_{C}} + \frac{M_{FA}}{1000 \times S_{FA}} + \frac{M_{CA}}{1000 \times S_{CA}} \tag{19, 20, 21}
\]

Where:
- \( V_{C} \) is the Absolute Volume [or Yield] of fully compacted fresh Concrete expressed in ‘m^3’
- \( M_{w} \) is the Mass of Mixing-Water expressed in ‘Kg’
- \( M_{C} \) is the Mass of Binder (Cement/Cementitious-material) expressed in ‘Kg’
- \( M_{FA} \) is the Mass of Fine Aggregate expressed in ‘Kg’
- \( M_{CA} \) is the Mass of Coarse Aggregate expressed in ‘Kg’
- \( S_{C} \) is the Specific-gravity of Binder (Cement/Cementitious-material) without units
- \( S_{FA} \) is the Specific-gravity of Fine Aggregate without units
- \( S_{CA} \) is the Specific-gravity of Coarse Aggregate without units.

Table 14: Tabular Summary of Concrete Mix-designs, showing the Actual Mix-proportions (Batched Quantities of Ingredients) Per Cubic-meter of Concrete, for Nine (9) distinctly designed Concrete Specimens (Test-materials)

| SN | Concrete-group | Concrete-specimen | Binders’ Contents (Kg) | Aggregates’ Content (Kg) | Free Mixing- | Admixtures’ Content (mL./100Kg of Cement) |
|----|----------------|-------------------|------------------------|-------------------------|-------------|------------------------------------------|

9
Furthermore, it is important to note that, prior to casting, the ‘Actual volume of each prepared concrete-mix’ [per specimen/test-material] of 0.1m³ (100l), was slightly below (less than) twice the ‘Net Volume of the to-be prepared Concrete-mix’ of 0.057m³ (57l), and which based on the respectively determined (calculated) Concrete-yields [of: ‘0.976m³ for the \( PCC_{max} \) Concrete-mix design’, ‘0.977m³ for the \( PCC_{opt} \) Concrete-mix design’, ‘0.978m³ for the \( PCC_{min} \) Concrete-mix design’, ‘0.980m³ for the \( PSC_{max} \) Concrete-mix design’, ‘0.978m³ for the \( PSC_{opt} \) Concrete-mix design’, ‘0.978m³ for the \( PSC_{min} \) Concrete-mix design’, ‘0.978m³ for the \( SSC_{max} \) Concrete-mix design’, ‘0.978m³ for the \( SSC_{opt} \) Concrete-mix design’, and ‘0.979m³ for the \( SSC_{min} \) Concrete-mix design’] were adequate (sufficient/enough) in quantity (by volume) to cast all thirty-six (36) numbers of Ø (100mm) by H (200mm) [(4ft) by H (8ft)] cylindrical Concrete specimens/test-material per Concrete-group.

### 2.3 Preparation of the Concrete Trial-mix

For each concrete-mix prepared per Concrete specimen/test-material, a 0.01m³ (10l) trial-mix was also prepared to obtain the satisfactory (optimum) dosages (applied quantities) of the various admixtures required to ensure that the slump-values of the fresh concrete test-materials were duly maintained. This was done alongside the use of the relevant technical standard literature ‘ASTM C 494’ [22] and the application ranges specified in the admixtures’ manufacturers’ manual/instructions, as guides to determine the required dosages of admixtures expressed in ‘mL/100Kg’ of the binder (cement/cementitious material), as tabulated in ‘Table 14’.

|      | Cement (OPC) | Supplementary Cementitious Materials (SCMs) | Fine Aggregate (River sand) | Coarse Aggregate (Quarried Granite) | Water Content (Kg) | Water-reducer | Super-plasticizer |
|------|--------------|---------------------------------------------|-----------------------------|-------------------------------------|-------------------|--------------|------------------|
| 1    | Plain Cement [Normal] Concrete | \( PCC_{max} \) | 323 | - | - | 812 | 982 | 194 | - | - |
| 2    | \( PCC_{opt} \) | | 364 | - | - | 776 | 982 | 195 | - | - |
| 3    | \( PCC_{min} \) | | 417 | - | - | 732 | 982 | 196 | - | - |
| 4    | Portland Slag [Special] Concrete | \( PSC_{max} \) | 242 | 81 | - | 868 | 982 | 193 | 335 | - |
| 5    | \( PSC_{opt} \) | | 313 | 104 | - | 723 | 982 | 196 | 335 | - |
| 6    | \( PSC_{min} \) | | 349 | 116 | - | 680 | 982 | 197 | 335 | - |
| 7    | Silica-fume Slag [Special] Concrete | \( SSC_{max} \) | 244 | 91 | 29 | 754 | 982 | 195 | - | 590 |
| 8    | \( SSC_{opt} \) | | 312 | 116 | 37 | 680 | 982 | 197 | - | 590 |
| 9    | \( SSC_{min} \) | | 353 | 132 | 42 | 626 | 982 | 198 | - | 590 |
Table 15: Slump and Five (5) Other Characteristics of Nine (9) Fresh Concrete Specimens (Test-Materials/Design-mixes)

| SN | Concrete-group | Concrete-Specimen/Test-material/Design-mix | Binder(s) | Admixture | Temperature (°C) | Design Air-content (%) | Design 'w/c' ratio | Actual (True) 'w/c' ratio | Density of fresh Concrete (kg / m₃) | Slump (mm) |
|----|----------------|------------------------------------------|----------|-----------|----------------|----------------------|---------------------|-----------------------|---------------------------------|----------|
| 1  | Plain Cement [Normal] Concrete | $PCC_{\text{max}}$ OPC | - | 23 | 2 | 0.62 | 0.60 | 2383 | 95 |
| 2  | | $PCC_{\text{opt}}$ OPC | - | 24 | 2 | 0.55 | 0.54 | 2411 | 90 |
| 3  | | $PCC_{\text{min}}$ OPC | - | 23 | 2 | 0.48 | 0.47 | 2417 | 85 |
| 4  | Portland Slag [Special] Concrete | $PSC_{\text{max}}$ OPC, GGBFS | Water-reducer | 24 | 2 | 0.62 | 0.80 | 2428 | 95 |
| 5  | | $PSC_{\text{opt}}$ OPC, GGBFS | Water-reducer | 24 | 2 | 0.48 | 0.63 | 2446 | 85 |
| 6  | | $PSC_{\text{min}}$ OPC, GGBFS | Water-reducer | 25 | 2 | 0.43 | 0.56 | 2492 | 80 |
| 7  | Silica-fume Slag [Special] Concrete | $SSC_{\text{max}}$ OPC, Si-fume, GGBFS | Super-plasticizer | 25 | 2 | 0.55 | 0.80 | 2569 | 90 |
| 8  | | $SSC_{\text{opt}}$ OPC, Si-fume, GGBFS | Super-plasticizer | 24 | 2 | 0.43 | 0.63 | 2617 | 85 |
| 9  | | $SSC_{\text{min}}$ OPC, Si-fume, GGBFS | Super-plasticizer | 26 | 2 | 0.38 | 0.56 | 2665 | 80 |

2.4 Pre-casting Activities and Batching of Ingredients

For each of the nine Concrete specimens [yet-to-be produced], thrice the quantity the quantity of 20mm nominal maximum-sized quarried angular-shaped granite chippings required as coarse aggregate for this experimental programme was collected, washed [with water to make it free of any deleterious substance and/or impurity such as clay/clayey matter & dust etc..] and drained on clean, large flat inert pans, three days before the commencement of the Concrete specimens’ casting schedule. Then, a direct visual sorting was carried-out based on the individual size fractions of the chippings to avoid segregation, and in order to prevent variations in the moisture content of the discrete granite chippings, they were packed and sealed in clean, inert containers the very next day.

On the day of casting, this already mashed, drained & sealed coarse aggregate was equally divided into three portions. Each of which was subjected to testing in order to obtain its Specific gravity (Relative density) in accordance with ASTM C 127 [23]. weighed [using a digital weighing scale/balance], oven-dried at 110°C (383K) for a day-long period of twenty-four (24) hours, and then, re-weighed after oven-drying. The ‘Total moisture content of coarse aggregate’ [expressed as a percentage] was determined as follows:
Where: 

\[ MC_{CA} = \frac{M_{1,CA} - M_{2,CA}}{M_{2,CA}} \times 100 \quad - \quad - \quad - \quad - \quad 7 \]

A similar application of the above steps (procedures) of aggregate preparation and Total moisture content determination was applied to the fine aggregate—whose Specific gravity (Relative density) was obtained in accordance with ASTM C 128 [24]. Consequently, the ‘Total moisture content of fine aggregate’ [expressed as a percentage] was determined as follows:

\[ MC_{FA} = \frac{M_{1,FA} - M_{2,FA}}{M_{2,FA}} \times 100 \quad - \quad - \quad - \quad - \quad 8 \]

Also, it was ensured that the binders i.e. Cement [Ordinary Portland Cement (OPC)] and Cementitious materials/Pozzolanas [Ground-granulated Blast-furnace Slag (GGBFS) & Silica-fume blended cement (SFBC)] were stored under clean, inert & dry (moisture-free) laboratory conditions; while the water to be used for mixing the other ingredients (materials) was tested to be potable (drinkable) and have a pH value of ‘7’. Furthermore, just before the commencement of the actual physical mixing of the ingredients (materials) that were used to produce the nine Concrete specimens, there arose the critical need to make certain necessary adjustments on the design-obtained quantities (masses) of the Fine aggregate and Coarse aggregate, based on the previously obtained ‘Total Moisture Contents’ now being accommodated, which then gave rise to their respective batched quantities (masses), which will be ideal for practical field applications, [unlike the near-perfect experimental conditions within the laboratory].

2.5 Conduct of Slump (Workability) Test

Fresh Concrete was used for the ‘Slump test’, which was actually the first (1st) test performed and one of the six (6) fresh concrete characteristics [Temperature, Design Air-content, Design Water/Cement (w/c) ratio, Actual Water/Cement (w/c) ratio, Density, and Slump shown in ‘Table 15’] determined during this study. The Slump (Workability) test is a characteristic (property) of fresh concrete, which gives a measure of the concrete’s consistency, was ascertained in accordance with ASTM C 143-08 standard method/procedures [25], as is now explained. A Slump-cone was placed on a smooth, non-absorbent, inert & moist level surface; after which a dampening/wetting of its interior surface with water was carried out. The Slump-cone was then filled to one-third (1/3) of its entire volume with fresh concrete, followed by
twenty-five (25) evenly distributed rodding strokes over this first layer of the entire fresh concrete cross-section using a 5/8” by 2” (15.9 mm by 50.8 mm) tamping-rod. For a second time, the Slump-cone filled to two-thirds (2/3) of its entire volume with fresh concrete from the same batch, which was again followed by twenty-five (25) evenly distributed strokes over the second layer of the entire fresh concrete cross-section using the same tamping-rod, but this time care was taken to ensure that the 25 rodding-strokes penetrated into but not through the first rodded layer.

Later, the cone was filled to the point of overflow with fresh concrete from the very same batch. Similarly, this was followed by a third and final set of twenty-five (25) evenly distributed rodding-strokes over this third layer of the entire fresh concrete cross-section with the same tamping-rod. However, during this third and final rodding process, care was taken to ensure that the 25 rodding-strokes penetrated into but not through the second rodded-layer. Consequent upon the completion of the third & final rodding, with the aid of the tamping-rod, the excess concrete was removed (cleared-off) from the top of the Slump-cone, and the fallen (removed) excess concrete was cleaned from the bottom (base) of the Slump-cone.

Then, without delay, the Slump-cone was slowly but gently raised (lifted) in an even (regular) vertical motion—this was done in a very careful manner, such that the cone was not tilted nor did it touch/strike the already ‘slumped Concrete’ in the process. Also, the removed Slump-cone was carefully inverted and placed beside the ‘slumped Concrete’, but not touching (not making contact with) the ‘slumped Concrete’. The tamping-rod was finally placed horizontally across the top of the now inverted Slump-cone, and then, the ‘Slump’ [i.e. the downward vertical depression] from the bottom of the tamping-rod to the top of the ‘slumped Concrete’ at the point that coincides with the initial (original) centre of the base was measured. Amongst other things, it might be important to mention as one of the experimental precautions observed that, the feet of the human investigator were not removed from the sides of the Slump-cone until the Slump tests which did not exceed a maximum experimentation time of 2 minutes 30 seconds were completed. The results (data) of the Slump test and five other fresh concrete characteristics (properties) are presented under the ‘Results and Discussion section’ in ‘Table 15’.

2.6 Casting of Concrete Specimens (Concrete Test-materials)

ASTM C 192- 18 Standard Method/Procedure was strictly adhered to while preparing all the materials (ingredients) [as previously noted], mixing batched quantities of the materials (ingredients) using a high capacity (large volume) mechanized mixing machine (mechanical mixer), casting of all three hundred and twenty four (324) Concrete specimens [i.e. 36 Specimens per Concrete-group], and curing of the de-moulded cast Concrete specimens for three curing-ages, as is summarily explained [26]. First and foremost, in an attempt to reduce the absorption of the mixing-water by the mixing machine/mechanical mixer which was used, its blades and interior surfaces were carefully buttered (wetted/dampened) by applying wet burlap on them, and then, the dry-batched ingredients (materials) were placed inside the mixing-drum in accordance with the order specified in the ‘ACI Guide 304R- 89’ [27] as follows: first of all, ‘Coarse aggregate [crushed granite chippings]’, secondly ‘binders(s) [Cement (‘OPC’) and/or
Supplementary Cementitious Material (‘GGBFS’, ‘GUb-8SF’), and thirdly ‘Fine aggregate [Natural Siliceous river-bed sand].

The mixing machine was started (turned-on) and allowed to run for half a minute, mixing the above contained ingredients before the swift (quick) addition of batched quantities (masses) of water and admixtures [Super-plasticizer and Water-reducer], after which the mixer continued to run for another two and a half minutes, making a cumulative initial run (mixing operation) time of 3 minutes. The mixer was then covered and stopped (turned-off), allowing it to rest for 3 minutes, which was then followed by a re-starting (turning-on) of the mixer to allow for a final run (mixing operation) time of 2 minutes. Upon completion of the mixing, the fresh concrete still inside the mixer was immediately emptied to a clean inert, water-buttered (wetted/dampened) pan and quickly remixed using a shovel or spade to reduce the chances (probability) of segregation occurring.

Casting was performed in a laboratory using standard cylindrical steel moulds of dimensions [Diameter (100mm) by Height (200mm)] placed on a rigid vibration-free surface which were covered using Poly(ethene) caps. The short-distance transportation of the cast Concrete test-materials (Concrete specimens) was carried out in accordance with the ‘ACI Guide 304R- 89’ [24]. After an interval (time duration) of 24±8 hours, the cast Concrete specimens or test-materials were then de-moulded and cured by wholly immersing them in water-filled curing tanks for three curing-ages of 28 days, 56 days and 90 days, until they were each subjected to the nine (9) understated characterization-tests which give a measure of the quality (strength and durability characteristics/properties) of hardened concrete. This is aside from the already determined Slump-test which gives a measure of the quality (workability characteristic/property) of fresh (plastic) concrete.

It should be noted that, in addition to the Slump test [conducted using fresh concrete], for the ten (10) different [hardened concrete] characterization tests [which indicate the quality (durability, strength & workability) of Concrete] were conducted as explained below. For each of the three (3) Concrete-groups [Portland Cement Normal Concrete (‘PCC' max', ‘PCC opt', ‘PCC min'), Portland Slag Special Concrete (‘PSC' max', ‘PSC opt', ‘PSC min’) and Silica-fume Slag Special Concrete (‘SSC' max', ‘SSC opt', ‘SSC min')], twelve (12) [numbers of 100mm diameter by 200mm height] cylindrical Concrete specimens/test-materials required for various Thermo-physical, Electrical and Mechanical characterization-tests [comprising of a first (1st) set of three (3) concrete specimens/test-materials for ‘Specific Heat Capacity (C)’ test; a second (2nd) set of three (3) concrete specimens/test-materials for, ‘Thermal Conductivity (K)’ & ‘Thermal Diffusivity (D)’; a third (3rd) set of three (3) concrete specimens/test-materials for ‘RCPT Total Charge passed (Q)’, ‘Initial 5 minutes RCPT Electrical Resistivity (ρ)' /Chloride-ion Penetrability’, ‘Chloride-ion penetration depth (C)' & ‘Non-steady-state Migration coefficient (D)’; and a fourth (4th) set of three (3) concrete specimens/test-materials for ‘Water sorptivity (S)', & ‘Actual Mean (Average) Compressive Strength (f_c)’], were cast [and cured for each of three (3) curing-ages of ‘28 days’, ‘56 days’ & ‘90 days’], for every phase of the four(4)-phase testing regime, amounting
to: 12 Specimens/Test-materials per Concrete-group per Curing-age, 36 Specimens/Test-materials per Concrete-group, and a total of 324 concrete specimens/test-materials for the entire experimental programme, as shown in the “Concrete specimens’ Casting Schedule” in ‘Table 16’.

2.7 Determination of ‘Specific Heat Capacity ($C_p$)’

Specific Heat Capacity ($C_p$) of the cast and cured Concrete specimens were determined by the method of ‘Semi-adiabatic Calorimetry’, as is summarily explained below. Prior to the commencement of the actual calorimetry, the initial weight of each hardened Concrete specimen was measured to be ‘$W_i$’ Newton(N) using a digital weighing scale. At the attainment of each curing-age, three (3) Concrete specimens cast per test-material were retrieved from the curing-tank. An electric drilling machine fitted with a drill-bit of 0.53mm diameter was used to drill two (2) holes on the top surface of each of the Concrete specimens. A temperature-sensor was inserted into one hole of each Ø (100mm) by H (200mm) cylindrical Concrete specimen. An immersion heater [of technical specifications: $V_{rms} = 220 - 240V$, $f = 50 / 60Hz$, Rated Electric-power ($P_E = 1KW$)] was inserted into the second drilled hole.

The Concrete specimen in which was inserted the temperature-sensor and immersion-heater was placed inside a semi-adiabatic calorimeter consisting of two wooden boxes/chambers—a larger box with interior dimensions [L(457.2mm) * B(330.2mm) * H(660.4mm)] lined with 25.40mm thick layer of Cork-sheet, and a smaller box with interior dimensions [L(228.6mm) * B(228.6mm) * H(508.0mm)] covered with mild steel plate, while its exterior was lined with 25.40mm thick layer of Cork-sheet & 12.70mm thick layer of Glass-wool. The wires (cables) of both the immersion-heater and temperature-sensor were let-out (passed) through a hole inserted at the top of the larger box, with care taken to ensure that both wires/cables were separated with an appropriate electro-thermal insulative material to prevent direct physical contact.
Figure 3: Semi-adiabatic Calorimetric Setup for Experimental Determination of Specific Heat Capacity of Concrete

With the experimental set-up in place and the necessary precautions ensured, 'I' Ampere (A) of electric-current was passed through the immersion-heater at 'V' Volts (V) for a period (time-duration) of 'T' seconds (s), while the initial absolute temperature of 'θ₁' Kelvin (K) and final absolute temperature of 'θ₂' Kelvin (K) were sensed (measured) by the temperature-sensor. After completion of the calorimetry, the final weight of the Concrete specimen was measured to be 'W₂' Newton (N) using the digital weighing scale. Then, the Specific Heat Capacity of the Concrete specimen was obtained as follows:

\[
C_p = \frac{Q_2 - Q_1}{[(M_2 - M_1) \cdot (\theta_2 - \theta_1)]}
\]

Where:

'Cₚ' is the Specific Heat Capacity of the Concrete specimen in expressed in 'J / Kg - K'

'M₁' is mass of the Concrete specimen at 1st experiment = \(\frac{W_1(N)}{g(m/s^2)}\) Kg = \(\frac{W_1'N}{9.81m/s^2}\) Kg

'M₂' is mass of the Concrete specimen at 2nd experiment = \(\frac{W_2(N)}{g(m/s^2)}\) Kg = \(\frac{W_2'N}{9.81m/s^2}\) Kg

'θ₁' is the initial absolute temperature of the Concrete specimen expressed in 'K'

'θ₂' is the final absolute temperature of the Concrete specimen expressed in 'K'

'Q₁' is the Heat (Thermal) Energy of the Concrete specimen at 1st calorimetry expressed in 'J' ; and it is calculated as being = \(I \cdot V \cdot t₁\)
2.8 Determination of ‘Thermal Conductivity (K_{\text{thermal}})’

In accordance with the ASTM C 236-89 and ACI 122 R-02, the “Guarded Hot Box method” was used to obtain values for some understated parameters, based on which the ‘Thermal Conductivity (K_{\text{thermal}})’ values of each Concrete specimen was calculated using the German scientists’ (Poensgen’s and Jakob’s) modified version of the famous ‘Fourier’s Equation of One-dimensional Thermal Conduction’, as is summarily explained below.

With the aid of a ‘Universal Asphalt & Concrete Multi-saw’, each of three cylindrical Concrete specimens (test-materials) [from each of the three Concrete-groups (‘PCC’, ‘PSC’ and ‘SSC’)] at all three Curing-ages of 28 days, 56 days & 90 days] were vertically sliced [from its circular top-surface to its bottom-surface] at two parallel chord (lines) which were at an equal distance from the marked-out diameter (symmetric-line) [through the midpoint of the circular top-surface]. It should be noted that, these two chords through which the cylindrical Concrete specimens were sliced, were also parallel to the diameter; and were drawn inside the two semi-circles that make-up its circular top-surface. This was done in order to cut-out a representative concrete test-panel, which will be used for experimental testing at a temperature-differential which was kept at a minimum value of 25 K (−228°C) throughout the experimentation.

Table 16: Concrete Specimens’ Casting Schedule

| S/N | Characteristics/Properties of Concrete to be tested for | Shape and Size of Concrete specimen/Test-material | Number of Concrete Specimens required for testing |
|-----|--------------------------------------------------------|--------------------------------------------------|-----------------------------------------------|
|     |                                                        |                                                  | Per Curing-age | Total for three Curing-ages of: 28 days, 56 days & 90 days | Per Concrete-group | Total for nine Concrete Specimens/Test-materials/Design-mixes |
|     |                                                        |                                                  | Per Curing-age | &quot;28 days&quot; | &quot;56 days&quot; and &quot;90 days&quot; | Per Concrete-group | Total for nine Concrete Specimens/Test-materials/Design-mixes |
|       |                                      | Ø(H(200mm)) Cylinder | 3   | 9   | 9   | 81 |
|-------|--------------------------------------|----------------------|-----|-----|-----|----|
| 1     | Specific Heat Capacity                | C_p                  | 3   | 9   | 9   | 81 |
| 2     | Thermal Conductivity                  | K_thermal            | 3   | 9   | 9   | 81 |
| 3     | Thermal Diffusivity                   | δ_thermal            | 3   | 9   | 9   | 81 |
| 4     | Dry Bulk Density                      | D_d                  | 3   | 9   | 9   | 81 |
| 5     | RCPT Total Electric Charge passed     | ΣQ_p                 | 3   | 9   | 9   | 81 |
| 6     | Initial 5-minute Rapid Chloride       | ρ_{E1,RCL}            | 3   | 9   | 9   | 81 |
|       | Permeability Electrical Resistivity   |                     |     |     |     |    |
| 7     | Chloride ion penetration depth        | S_ion                | 3   | 9   | 9   | 81 |
| 8     | Non-steady-state Migration Coefficient| D_nonde              | 3   | 9   | 9   | 81 |
| 9     | Mean (Average) Compressive Strength   | f_{w,c}              | 3   | 9   | 9   | 81 |
| 10    |                                      |                      |     |     |     |    |

**TOTAL NUMBER REQUIRED**

|       |                                      |                      | 12  | 36  | 36  | 324|

Four (4) hours before the measurement of values of five (5) related parameters (‘Q’, ‘L’, ‘A’, ‘θ_1’, and ‘θ_2’) [related to the unknown Thermal Conductivity (K_thermal)] began, steady-state thermal conditions were imposed until these three understated conditional requirements were met:

I. The Average surface temperature variation did not exceed ±273.06K (±0.06°C, ±0.10°F),

II. The Metering-area’s power variation did not exceed ±1%, and

III. The obtained values of the aforementioned related parameters did not experience a Unidirectional change.

Now, with these and other procedural steps exhaustively explained in ASTM C 236 standard method, the Thermal Conductivity of each Concrete specimen (test-material) was calculated after substituting the obtained parameter-values into the modified Fourier’s equation below:

\[ K_{\text{thermal}} = \frac{Q \cdot L}{A(\theta_1 - \theta_2)} \]

Where:

‘Q’ is the ‘Total power input to the metering box’ i.e. the ‘Time-rate of Heat flow’ expressed in ‘W’

‘L’ is the ‘thickness of the Concrete specimen’ i.e. the ‘Length of the Heat path’


‘A’ is the Metering-area normal to the direction of the Heat flow’ expressed in ‘m²’
‘QA’ is the ‘Hot-surface’s area-weighted mean absolute temperature’ expressed in ‘K’, and
‘Q2’ is the ‘Cold-surface’s area-weighted mean absolute temperature expressed in ‘K’ [26],[27]

2.9 Determination of ‘Thermal Diffusivity (δThermal)’

The Thermal diffusivity values were computed using the empirical model below: kg/m³

\[
\delta_{Thermal} = \frac{K_{Thermal}}{C_\theta \cdot \rho_{bulk,dry}} \quad - \quad - \quad - 11 \quad [29],[30],[31],[32]
\]

Where:
‘δThermal’ is the Thermal diffusivity of the cylindrical Concrete specimen expressed in ‘m²/Sec’,
‘KThermal’ is the Thermal conductivity of the cylindrical Concrete specimen expressed in ‘W/m·K’,
‘C_\theta’ is the Specific Heat Capacity of the Concrete specimen in expressed in ‘J/Kg·K’, and
‘ρbulk,dry’ is the Dry bulk density of the cylindrical Concrete specimen expressed in ‘Kg/m³’.

2.10 Determination of ‘Dry Bulk Density (ρbulk,dry)’

Each hardened cylindrical Concrete specimen whose volume was about 0.001571m³ [having thus satisfied the standard test requirement of a minimum volume of 350cm³] was carefully inspected to ensure that it had no crack or broken edge. First of all, the oven-dried mass of each Concrete specimen (Concrete test-material) was determined, which was followed by several other procedural steps, and then, its immersed apparent mass was ascertained by immersing and boiling in water, and then, holding-up (suspending) the it (the Concrete specimen) with the aid of a wire. After which, the actual calculation of the Concrete specimen’s ‘Dry bulk density (ρbulk,dry)’ was carried out in accordance with the detailed standard test procedures (method) of ASTM C-642 [33].

2.11 Determination of ‘Water Sorptivity (S)’

The ‘Laboratory Sorptivity (S)’ of the Concrete specimens expressed in ‘mm/sec⁰.⁵’ was obtained in accordance with the ‘ASTM C 1585-04’ as summarily explained below. Three (3) Concrete-disc [of dimensions: diameter (D) = 100 ± 6mm and height (H) = 50 ± 3mm, whose cross-sectional area variations must not exceed 1% from each other when view/checked from top to bottom]; were sliced (cut-out) from along the length of each hardened, compressively-loaded cylindrical Concrete specimen of the three (3) Concrete test-materials, and set-apart for this test.
In order for each Concrete-disc to achieve an internal relative humidity ranging from 50% - 70%, [which is similar to field environmental conditions identified around some in-situ concrete structures], the Concrete-disc was conditioned by subjecting it to three (3) days of oven-drying at a temperature of 50°C(323K). Now, the essence of the conditioning process was to quickly and easily achieve the three-fold goal of: (i) a surface relative humidity ranging from 50% - 70%, (ii) a uniformly distributed moisture content, and (iii) a moisture content value in excess of 1% [34],[35],[36].

Also, as is procedurally required in ASTM C 1585-04 standard method, at an experimental temperature of 23 ± 2°C, one surface [i.e. the top surface] of the Concrete specimen disc was placed in contact with tap water for a time-period for a time-duration (period) of eight (8) days, the masses of the sealed & later inverted Concrete specimen disc were measured & recorded to the nearest 0.01g, and measurements of the various quantities (amounts) of water absorbed by the Concrete-specimen disc [due to capillary suction] were carried-out at the standard’s stipulated time interval.

Then, the incremental water absorption was computed as follows:

\[ I_{WA} = \frac{\Delta m}{A_{cd} \cdot \rho_w} \]  \hspace{1cm} - - - - 12 \[37\]

Where:

- \( I_{WA} \) is the incremental water absorption of the Concrete specimen disc expressed in ‘mm’
- \( \Delta m \) is the change in mass of the Concrete specimen disc expressed in ‘g’, at time ‘t’ seconds
- \( A_{cd} \) is the exposed cross-sectional area of the Concrete specimen disc expressed in ‘mm²’
- \( \rho_w \) is the mass density of water expressed in ‘g/mm³’.

However, from the research works (findings) of Philip (1957), Nokken et al., (2002) and ASTM C 1585 (2004); the Water Sorptivity [sometimes referred to as ‘Rate of water absorption’] (S) values expressed in ‘mm/sec⁰.⁵’, were obtained as the gradients (slopes) when the graph of \( I_{WA} \) (mm) was plotted against ‘Time⁰.⁵’(Sec⁰.⁵) in ‘Figures 7a to 7h’ based on their respective values tabulated in ‘Table 21’, with an arbitrary linear regression coefficient (r) value of 0.99 adopted. Then, both the initial (primary) and final (secondary) Water Absorption rates were empirically modelled to be analogous to the equation of a straight line, as follows:

\[ I_{WA} = S_i \sqrt{t} + n \] (Points measured up to the six experimental hours used) - - - - 13 \[37\]

\[ I_{WA} = S_f \sqrt{t} + n \] (Points measured after the first experimental day elapsed) - - - - 14 \[37\]

Where:

- \( S_i \) is the initial (primary) water absorption rate obtained by calculation to the nearest 0.1*10⁻⁴ mm/sec⁰.⁵, and
‘$S_f$’ is the final (secondary) water absorption rate obtained by calculation to the nearest $0.1 \times 10^{-4}\ mm/sec^{0.5}$ [37],[38],[39]

2.12 Determination of ‘RCPT Total Electric-Charge Passed ($\sum Q_p$)’

Also, in accordance with ASTM C 1202, the Rapid Chloride Permeability Test (RCPT) was performed for a time duration of six (6) hours on three [i.e. the middle & bottom] Ø(100mm) by Thickness (50mm) Concrete-discs which were sliced (cut-out) from each Ø(100mm) by Height (200mm) cylindrical Concrete specimen, by ensuring amongst other things that:

a) The applied Voltage value of the Electric-power supply system was $60 \pm 0.1\ Volts\ (V)$,

b) The experimental temperatures of the ambient air, the 3.0% $NaCl_{(aq)}$ solution, the 0.3$M\ NaOH_{(aq)}$ solution, the Concrete-discs & the Electric (applied voltage) cell were within a range of $20–25^\circ C\ (293–298\ K)$ and

c) The Electric current value was recorded at time intervals of 30 minutes;

\[
\sum Q_{p(95mm)} = 900(I_0 + 2I_{30} + 2I_{60} + ... + 2I_{300} + 2I_{330} + I_{360}) \quad - \quad 15^{[40]}
\]

Where:

‘$\sum Q_{p(95mm)}$’ is the Total Electric charge that passed through a standard 95mm diameter (£) Concrete-disc, which is expressed in Coulombs (C)
\[ I_0 \] is the Electric current that flowed immediately after the voltage of \( 60 \pm 0.1V \) was applied, which is expressed in Amperes (\( A \)).

\[ I_t \] is the Electric current that flowed at a time \( t \) minutes after the voltage of \( 60 \pm 0.1V \) was applied, which is expressed in Amperes (\( A \)).

However, since the Concrete-disc has an actual diameter \( (\Omega) \) of 100mm which exceeds the standard diameter of 95mm, then, a proportional adjustment of the ‘Standard specimen cross-sectional area’ to the ‘Actual specimen cross-sectional area’ must be factored-in as follows:

\[
\sum Q_P = \sum Q_{P(95mm)} \times \left( \frac{\Omega}{95} \right)^2 - 16^{[40]}
\]

Where:

\[ \sum Q_P \] is the Total Electric charge that passed through the Concrete-discs expressed in Coulombs (\( C \)).

\[ \Omega \] is the actual diameter of the Concrete-disc = 100mm

### 2.13 Determination of ‘Chloride-ion Penetrability’ Levels

Then, based on the research findings (works) of Whiting, D. (1981), Whiting, D. (1988) and ASTM C 1202-12 \[^{[40]},[41],[42]^{}\], the Chloride ion penetrability which is a function of the ‘RCPT Total Electric charge (\( \sum Q_P \)) that passed through the Concrete-disc’ was ascertained from ‘Table 22’ below:

**Table 22: Chloride Ion Penetrability of Concrete obtained as a function of the RCPT Total Electric Charge Passed ‘\( \sum Q_P \)’**

| S/No. | RCPT Total Electric charge passed [Coulombs (\( C \))] | Chloride-ion Penetrability |
|-------|------------------------------------------------------|---------------------------|
| 1     | \( > 4,000 \)                                       | High                      |
| 2     | \( 2,000 - 4,000 \)                                 | Moderate                  |
| 3     | \( 1,000 - 2,000 \)                                 | Low                       |
| 4     | \( 100 - 1,000 \)                                   | Very low                  |
| 5     | \( < 100 \)                                         | Negligible                |

### 2.14 Determination of ‘Initial 5-minute RCPT Electrical Resistivity (\( \rho_{E(RCPT)} \))’

The ‘Initial 5 minutes RCPT Electricity Resistivity (\( \rho_{E(RCPT)} \))’ was obtained from ‘Equation 17’ below:

\[
\rho_{E(RCPT)} = R \times \left( \frac{A_{opt,CS}}{L_{opt,CS}} \right) - 17^{[37]}
\]

Where:
‘$R$’ is Electrical resistance expressed in ‘Ω’, [which according to Ohm’s law] $= \frac{V}{I}$

‘$A_{cyl,CS}$’ is Cross-sectional area of Concrete-disc expressed in ‘$m^2$’, [which from Mensuration]

$$= \frac{\pi d^2}{4}$$

‘$L_{cyl,CS}$’ is the thickness of the Concrete-disc = 50mm

‘$V$’ is the applied voltage of the Electric-power supply system = 60.0 ± 0.1 V

‘$I$’ is the electric current that flowed through the Concrete-disc within the Concrete-disc within the initial [first] five (5) minutes of setting-up the electrical circuit, in Amperes (A).

‘$d$’ is the mean diameter computed after measuring the diameters of three (3) cylindrical Concrete specimens from which the Concrete-discs were sliced (cut) expressed in ‘mm’

$$= \frac{d_1 + d_2 + d_3}{3}$$

‘$d_1$’ is the diameter of the 1st cylindrical Concrete specimen expressed in ‘mm’

‘$d_2$’ is the diameter of the 2nd cylindrical Concrete specimen expressed in ‘mm’, and

‘$d_3$’ is the diameter of the 3rd cylindrical Concrete specimen expressed in ‘mm’

### 2.15 Determination of ‘Chloride-Ion Penetration Depth ($Cl_{pd}$)’

Consequent upon the completion of the Rapid Chloride Penetration Test (RCPT), the Chloride Ion Penetration Depth was calorimetrically determined as summarily explained. The Concrete-disc was split open into two (2) halves along its longest symmetrical line with the aid of a universal Asphalt & Concrete Multi-saw. The flat fractured (split) surfaces of both Concrete discs halves were then carefully sprayed with a 0.1 M (0.1 /mol /dm concentrated) aqueous solution of Silver trioxonitrate (V) [IUPAC nomenclature: ‘$AgNO_3(aq)$’] which is naturally colourless or crystalline white. Twenty minutes later, the extent (length) to which ionic chlorine penetrated across the width of each half of the split Concrete-disc at ten (10) different locations on each Concrete-disc half was identified by direct measurements in ‘mm’. Then, the Chloride ion penetration depth ($Cl_{pd}$) was calculated as the average value of all ten (10) Chloride ion penetration lengths [measured at the ten (10) different locations on the Concrete-disc] expressed in ‘mm’. However, there was some split Concrete-cone half surfaces in which the opaque white Silver Chloride [ $AgCl(s)$ precipitates were not visible (i.e. not observed to be present)]

### 2.16 Determination of ‘Non-steady-state Migration Coefficient ($D_{nss,MC}$)’ as a function of ‘Chloride-Ion Penetration Depth’

The values of Chloride ion penetration depth ($Cl_{pd}$) obtained as summarily explained above, were substituted into the understated 1991 approved ‘Nordtest method NT build 492’ equation [40], and other parameters were inputted, so as to determine the Non-steady-state Migration Coefficient of the Concrete specimens/test-materials.
$D_{nssMC} = \frac{0.0239(273 + T)L}{(V - 2)t} \left[ x_d - 0.0238 \sqrt{\frac{(273 + T)Lx_d}{V - 2}} \right] - - - - - - - 18$ [40]

Where:

- $D_{nssMC}$ is the non-steady-state migration coefficient, multiplied by a contact factor $10^{-12}$, and is expressed in $m^2/s$.
- $V$ is the applied voltage of 60 Volts.
- $T$ is the average value of the initial and final temperatures of the anolyte solution expressed in $\degree C$.
- $L$ is the thickness of the Concrete specimen/test-material expressed in $mm$.
- $t$ is the experimental time duration, which is usually taken as 6 hours (21,600 s).
- $x_d$ is Chloride-Ion penetration depth expressed in $mm$, and is also symbolized as $CI_{pd}$.

### 2.17 Determination of ‘Average Compressive-strength ($f_{ckf}$)’

In accordance with the standard test procedures comprehensively explained in ASTM C 39-12, the compressive strength testing of the moist-cured hardened Concrete specimens was carried-out as briefly explained. Before the commencement of this testing process, the three Concrete specimens of each Concrete test-material were examined to ensure that the variations in the diametrical dimensions were $\leq 2\%$, and that the deviation of both ends of the Concrete specimens from the perpendicular alignment of the axes did not exceed $0.5^\circ$ in every $100 mm$, after which the Concrete specimens were gently wiped to get rid of moisture on its surface.

The bearing blocks and other necessary testing fixtures of the compression testing machine were put in place (appropriately arranged), after which it (the compression testing machine) was turned-on for a fifteen (15) minute stabilization (balancing/equalization) of its hydraulic and electrical systems. Compressive axial load was continuously applied at a movement rate which corresponded to the stress rate of $0.25 \pm 0.05$ MPa/s ($35 \pm 7 psi$) and a loading rate of $199.6 \pm 40.82Kg/S (440 \pm 90lb/S)$ for 100mm ($4'$) diameter cylindrical Concrete specimen, until the point at which it experienced either a failure-induced fracture (crushing fragmentation) [to produce cone-like shaped objects/pieces] or a shear fracture. Thus, as one of experimental precautions observed, the results of all cylindrical Concrete specimens which experienced a non-shear fracture or were not fractured into cone-like shaped objects/pieces were discarded (rejected) in accordance with ASTM C39-12. Then, the maximum (ultimate) compressive axial load borne (overcome) by the Concrete specimen was recorded and divided by the Cross-sectional area of the cylindrical Concrete specimen to obtain its actual Compressive strength.

Thus,
Where:

\[ f_{ck(cyl,CS)} = \frac{F_{\text{max}}}{A_{\text{cyl,CS}}} \]  

Where:

\[ 'f_{ck(cyl,CS)}' \] is the Characteristic Compressive strength of a particular cylindrical Concrete specimen expressed in ‘MPa’

\[ 'F_{\text{max}}' \] is the Maximum (ultimate) Compressive axial load borne (overcome) by the cylindrical Concrete specimen expressed in ‘N’

\[ 'A_{\text{cyl,CS}}' \] is the Cross-sectional area of the cylindrical Concrete specimen expressed in ‘mm^2’

\[ 'r' \] is the radius of the cylindrical Concrete specimen expressed in ‘mm’

However,

\[ \overline{f_{ck}} = \frac{f_{ck(cyl,CS1)} + f_{ck(cyl,CS2)} + f_{ck(cyl,CS3)}}{3} \]

Where:

\[ '\overline{f_{ck}}' \] is the Average compressive strength of a particular Concrete test-material, expressed in ‘MPa’

\[ 'f_{ck(cyl,CS1)}' \] is the Characteristic compressive strength of the 1st of three cylindrical Concrete specimens produced from a particular Concrete test-material, expressed in ‘MPa’

\[ 'f_{ck(cyl,CS2)}' \] is the Characteristic compressive strength of the 2nd of three cylindrical Concrete specimens produced from a particular Concrete test-material, expressed in ‘MPa’

\[ 'f_{ck(cyl,CS3)}' \] is the Characteristic compressive strength of the 3rd of three cylindrical Concrete specimens produced from a particular Concrete test-material, expressed in ‘MPa’

Finally, the values of the various Thermo-physical (Specific heat capacity, Thermal conductivity, Thermal diffusivity, Dry bulk density & Water sorptivity); Electrical (RCPT Total electric-charge passed, Chloride-ion penetrability, Initial 5-minute RCPT Electrical resistivity, Chloride-ion penetration depth & Non-steady-state migration coefficient); and Mechanical (Slump & Average Compressive-strength) characteristics/test results so obtained, were consequently tabulated, graphically illustrated, analyzed and discussed.

3. Results and Discussion

3.1 Thermo-physical Characterization Tests results

3.1.1 Specific Heat Capacity \((C_\theta)\) result:
The Specific Heat Capacity (C₂₈) of Concrete is the quantity (amount) of heat (thermal) energy that is absorbed (required) by concrete to raise the temperature of its unit mass [1Kg] of concrete through a temperature change of 1K (1°C). As an important thermal (heat) property of concrete, which plays a significant role in determining the quantity (amount) of heat (thermal) energy that a particular Concrete-material can store (absorb) before cracking (failing) [i.e. the concrete’s ‘thermal mass’], it is measured calorimetrically in the unit of ‘J / Kg – K’ or ‘J / Kg – °C’.

From ‘Table 17’ and ‘Figures 5a to 5d’, it was noted within each of the three Concrete-groups (i.e. PCC, PSC and SSC) that, apart from two Concrete test-materials [i.e. ‘max’ PSC and ‘min’ SSC], the specific heat capacity ‘C₂₈’ kept decreasing as Bulk density ‘Dd’ was decreasing at all three curing-ages. This proposition (statement) is summarily corroborated by the following understated observations:

Table 17: ‘Specific Heat Capacity (C₂₈)’ of Nine (9) Hardened Concrete-Specimens/Test-Materials

| S/N | Concrete- group | Concrete-Specimen/ Test-material/ Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | Concrete’s Maturity-level (Curing-age) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) |
|-----|-----------------|---------------------------------------------|-----------|--------------------------|---------------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|---------------------------------|-----------------|
| 1   | Plain Cement [Normal] | PCCmax | OPC | 0.62 | 28 days | 1299 | 2400 | 1304 | 2427 | 1309 | 2446 |
| 2   |                             | PCCopt | OPC | 0.55 | 56 days | 1297 | 2438 | 1302 | 2459 | 1308 | 2488 |
| 3   |                             | PCCmin | OPC | 0.48 | 90 days | 1289 | 2445 | 1295 | 2472 | 1299 | 2495 |
| 4   | Portland Slag [Special] | PSCmax | OPC, GGBFS | 0.62 | 28 days | 1300 | 2449 | 1305 | 2477 | 1312 | 2508 |
| 5   |                             | PSCopt | OPC, GGBFS | 0.48 | 56 days | 1319 | 2483 | 1323 | 2500 | 1351 | 2527 |
| 6   |                             | PSCmin | OPC, GGBFS | 0.43 | 90 days | 1307 | 2541 | 1310 | 2565 | 1316 | 2700 |
| 7   | Silica-fume Slag [Special] | SSCmax | OPC, Si-fume, GGBFS | 0.55 | 28 days | 1342 | 2620 | 1348 | 2656 | 1355 | 2677 |
| 8   |                             | SSCopt | OPC, Si-fume, GGBFS | 0.43 | 56 days | 1335 | 2653 | 1328 | 2686 | 1346 | 2719 |
| 9   |                             | SSCmin | OPC, Si-fume, GGBFS | 0.38 | 90 days | 1351 | 2702 | 1359 | 2740 | 1371 | 2796 |

For Plain Cement Normal Concrete (PCC): At 28 days of curing-age, while Bulk density steadily increased from “2400Kg / m³ (PCCmax) through 2438Kg / m³ (PCCopt) to 2445Kg / m³ (PCCmin)”; the Specific Heat Capacity randomly decreased from “1299J / Kg – K (PCCmax) through 1297J / Kg – K (PCCopt) to 1289J / Kg – K (PCCmin)”.

Table 17: ‘Specific Heat Capacity (C₂₈)’ of Nine (9) Hardened Concrete-Specimens/Test-Materials

| S/N | Concrete- group | Concrete-Specimen/ Test-material/ Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | Concrete’s Maturity-level (Curing-age) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) |
|-----|-----------------|---------------------------------------------|-----------|--------------------------|---------------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|---------------------------------|-----------------|
| 1   | Plain Cement [Normal] | PCCmax | OPC | 0.62 | 28 days | 1299 | 2400 | 1304 | 2427 | 1309 | 2446 |
| 2   |                             | PCCopt | OPC | 0.55 | 56 days | 1297 | 2438 | 1302 | 2459 | 1308 | 2488 |
| 3   |                             | PCCmin | OPC | 0.48 | 90 days | 1289 | 2445 | 1295 | 2472 | 1299 | 2495 |
| 4   | Portland Slag [Special] | PSCmax | OPC, GGBFS | 0.62 | 28 days | 1300 | 2449 | 1305 | 2477 | 1312 | 2508 |
| 5   |                             | PSCopt | OPC, GGBFS | 0.48 | 56 days | 1319 | 2483 | 1323 | 2500 | 1351 | 2527 |
| 6   |                             | PSCmin | OPC, GGBFS | 0.43 | 90 days | 1307 | 2541 | 1310 | 2565 | 1316 | 2700 |
| 7   | Silica-fume Slag [Special] | SSCmax | OPC, Si-fume, GGBFS | 0.55 | 28 days | 1342 | 2620 | 1348 | 2656 | 1355 | 2677 |
| 8   |                             | SSCopt | OPC, Si-fume, GGBFS | 0.43 | 56 days | 1335 | 2653 | 1328 | 2686 | 1346 | 2719 |
| 9   |                             | SSCmin | OPC, Si-fume, GGBFS | 0.38 | 90 days | 1351 | 2702 | 1359 | 2740 | 1371 | 2796 |

For Plain Cement Normal Concrete (PCC): At 28 days of curing-age, while Bulk density steadily increased from “2400Kg / m³ (PCCmax) through 2438Kg / m³ (PCCopt) to 2445Kg / m³ (PCCmin)”; the Specific Heat Capacity randomly decreased from “1299J / Kg – K (PCCmax) through 1297J / Kg – K (PCCopt) to 1289J / Kg – K (PCCmin)”.

Table 17: ‘Specific Heat Capacity (C₂₈)’ of Nine (9) Hardened Concrete-Specimens/Test-Materials

| S/N | Concrete- group | Concrete-Specimen/ Test-material/ Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | Concrete’s Maturity-level (Curing-age) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) | Specific Heat Capacity (J / KgK) | Dry Bulk Density (Kg / m³) |
|-----|-----------------|---------------------------------------------|-----------|--------------------------|---------------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|---------------------------------|-----------------|
| 1   | Plain Cement [Normal] | PCCmax | OPC | 0.62 | 28 days | 1299 | 2400 | 1304 | 2427 | 1309 | 2446 |
| 2   |                             | PCCopt | OPC | 0.55 | 56 days | 1297 | 2438 | 1302 | 2459 | 1308 | 2488 |
| 3   |                             | PCCmin | OPC | 0.48 | 90 days | 1289 | 2445 | 1295 | 2472 | 1299 | 2495 |
| 4   | Portland Slag [Special] | PSCmax | OPC, GGBFS | 0.62 | 28 days | 1300 | 2449 | 1305 | 2477 | 1312 | 2508 |
| 5   |                             | PSCopt | OPC, GGBFS | 0.48 | 56 days | 1319 | 2483 | 1323 | 2500 | 1351 | 2527 |
| 6   |                             | PSCmin | OPC, GGBFS | 0.43 | 90 days | 1307 | 2541 | 1310 | 2565 | 1316 | 2700 |
| 7   | Silica-fume Slag [Special] | SSCmax | OPC, Si-fume, GGBFS | 0.55 | 28 days | 1342 | 2620 | 1348 | 2656 | 1355 | 2677 |
| 8   |                             | SSCopt | OPC, Si-fume, GGBFS | 0.43 | 56 days | 1335 | 2653 | 1328 | 2686 | 1346 | 2719 |
| 9   |                             | SSCmin | OPC, Si-fume, GGBFS | 0.38 | 90 days | 1351 | 2702 | 1359 | 2740 | 1371 | 2796 |
This was followed by similar observations at subsequent curing-ages of 56 days and 90 days respectively.

For Portland Slag Special Concrete (PSC): At 56 days of curing-age, as Bulk density steadily rose from $2500 \text{Kg} / \text{m}^3 (PSC_{opt})$ to $2565 \text{Kg} / \text{m}^3 (PSC_{min})$, its Specific Heat Capacity dropped from $1323 \text{J/K g K} (PSC_{opt})$ to $1310 \text{J/K g K} (PSC_{min})$, with the exception of $PSC_{max}$. This was followed by similar observations at subsequent curing-ages of 28 days and 90 days.

For Silica-fume Slag Special Concrete (SSC): At 90 days of curing-age, when Bulk density climbed from $2677 \text{Kg} / \text{m}^3 (SSC_{max})$ to $2719 \text{Kg} / \text{m}^3 (SSC_{opt})$, the Specific Heat Capacity fell from $1355 \text{J/K g K} (SSC_{max})$ to $1346 \text{J/K g K} (SSC_{opt})$. However, this was not the case with $SSC_{min}$. Again, this variation pattern of both parameters [i.e. Bulk density and Specific heat capacity] was noticed after curing for 28 days and 56 days.

![Figure 5a: Graph of ‘Specific heat capacity’ versus ‘Curing-age’ for Nine (9) Concrete-specimens](image-url)
Thus, from the foregoing, it could be summarily said that: “for majority [i.e. 7 out of 9] of the Concrete test-materials experimented upon, as Bulk density [which is directly dependent on the SCM content amongst other factors] increases, the Specific heat capacity decreases and vice versa.

Figure 5c: Graph of ‘Specific Heat Capacity’ versus ‘Dry bulk density’ for three (3) Concrete-specimens in the Portland Slag [Special] Concrete-group (PSC)
3.1.2 Thermal Diffusivity ($\delta_{\text{thermal}}$) result:

The Thermal Diffusivity of Concrete is summarily defined as the rate at which temperature variations (changes) take place (occur) within a defined mass (quantity) of the Concrete-material. It is actually an index that simply determines (influences) the speed (rate) at which heat (thermal energy) is transferred along a temperature gradient from the hot (high temperature) region to the cold (low temperature) or from the outer layer to the inner layer of a Concrete-material. As an important thermal property of Concrete which is measured in ‘$m/\text{s}$’, it has an established mathematical relationship with the Thermal conductivity, Specific heat capacity and Bulk density of the Concrete-material.
Based on the results displayed in ‘Table 18’ and ‘Figure 6’, at a curing-age of 28 days, the highest values of Thermal diffusivity (9.89*10^{-7} \, m^2/\, Sec, 8.90*10^{-7} \, m^2/\, Sec, and 8.83*10^{-7} \, m^2/\, Sec) were respectively recorded for Silica-fume Slag Special Concrete test-materials (‘SSC_{max}’, ‘SSC_{opt}’ and ‘SSC_{min}’); followed by the medial (in-between maximum and minimum) Thermal diffusivity values of (7.22*10^{-7} \, m^2/\, Sec, 7.96*10^{-7} \, m^2/\, Sec, and 6.81*10^{-7} \, m^2/\, Sec) respectively recorded for Portland Slag Special Concrete test-materials materials (‘PSC_{max}’, ‘PSC_{opt}’ and ‘PSC_{min}’); while the lowest values of Thermal diffusivity (5.94*10^{-7} \, m^2/\, Sec, 6.37*10^{-7} \, m^2/\, Sec, and 5.81*10^{-7} \, m^2/\, Sec) were respectively recorded for Plain Cement Normal Concrete test-materials (‘PCC_{max}’, ‘PCC_{opt}’ and ‘PCC_{min}’). Similar trends were observed after curing for 56 days and 90 days. These therefore suggest that, the presence (addition) and/or increase of Supplementary Cementitious Materials (SCMs) [such as Ground-granulated Blast-furnace Slag (GGBFS) and Silica-fume blended cement (GUb-8SF) which consequently result in an increase in ‘Bulk Density’] of Concrete, is likely to result in an increase in its Thermal diffusivity.

| S/N | Concrete-group                      | Concrete-Specimen/Test-material/Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | Thermal Diffusivity of Concrete-Specimen at Curing-age of: |
|-----|-------------------------------------|------------------------------------------|----------|--------------------------|----------------------------------------------------------|
|     |                                      |                                          |          |                          | 28 days | 56 days | 90 days |
| 1   | Plain Cement [Normal] Concrete       | PCC_{max}                                | OPC      | 0.62                     | 5.94    | 5.76    | 5.59    |
| 2   |                                      | PCC_{opt}                                | OPC      | 0.55                     | 6.37    | 6.02    | 5.81    |
| 3   |                                      | PCC_{min}                                | OPC      | 0.48                     | 5.81    | 5.74    | 5.66    |
| 4   | Portland Slag [Special] Concrete     | PSC_{max}                                | OPC, GGBFS | 0.62                    | 7.2     | 6.98    | 6.22    |
| 5   |                                      | PSC_{opt}                                | OPC, GGBFS | 0.48                    | 7.96    | 7.37    | 6.65    |
| 6   |                                      | PSC_{min}                                | OPC, GGBFS | 0.43                    | 6.81    | 5.92    | 5.59    |
| 7   | Silica-fume Slag [Special] Concrete  | SSC_{max}                                | OPC, Si-fume, GGBFS | 0.55 | 9.87 | 7.95 | 7.12 |
| 8   |                                      | SSC_{opt}                                | OPC, Si-fume, GGBFS | 0.43 | 8.90 | 8.21 | 6.34 |
| 9   |                                      | SSC_{min}                                | OPC, Si-fume, GGBFS | 0.38 | 8.83 | 7.54 | 6.99 |

Furthermore, it could be seen from ‘Table 18’, that the Thermal diffusivity value of each Concrete test-material in all three Concrete-groups decreases [in the right direction] with
increasing curing-age from maximum values of \( [5.94 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{max}}), 6.37 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{opt}}) & 5.81 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{min}})] \) after 28 days curing; through medial values of \( [5.76 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{max}}), 6.02 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{opt}}) & 5.74 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{min}})] \) after 56 days curing; to minimal values of \( [5.59 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{max}}), 5.81 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{opt}}) & 5.66 \times 10^{-7} \text{ m}^2/\text{Sec} (PCC_{\text{min}})] \) after 90 days curing, for Plain Cement Normal concretes. Also, similar patterns of a decrease in the Thermal diffusivity values of Portland Slag Special Concretes (‘\( PSC_{\text{max}} \)’, ‘\( PSC_{\text{opt}} \)’ and ‘\( PSC_{\text{min}} \)’) and Silica-fume Slag Special Concretes (‘\( SSC_{\text{max}} \)’, ‘\( SSC_{\text{opt}} \)’ and ‘\( SSC_{\text{min}} \)’); summarily suggest that, the Thermal diffusivity of concrete decreases with increasing curing-age.

### 3.1.3 Thermal Conductivity (\( K_{\text{Thermal}} \)) result:

The Thermal conductivity (\( K_{\text{Thermal}} \)) of Concrete is actually the inherent ability of Concrete to transmit heat without undergoing bulk motion (movement), but simply through direct (physical) contact after its heterogenous components have been subjected to thermal agitation. Mathematically, it refers to the quotient (ratio) of heat flux [i.e. the amount (quantity) of thermal (heat) energy transferred per unit time (1 second) and per unit surface-area (1 square meter)] and temperature-change (gradient/difference) of the Concrete-material. As a very important thermal property of concrete, its S. I. unit of measurement is the ‘\( W/\text{m} - \text{K} \)’ or ‘\( W/\text{m} - \text{°C} \)’.

![Graph of 'Thermal conductivity' versus 'Curing-age' for Nine (9) Concrete-specimens](image)
‘Table 19’ and ‘Figures 7a to 7d’, showed that, within each of the three Concrete-groups (i.e. PCC, PSC and SSC), with the exception of three Concrete test-materials ['PCC', 'PSC' and 'SSC'], the values of Thermal conductivity ‘$K_{thermal}$’ reduced at the time that the value of Bulk density ‘$D_b$’ increased after measurement at curing-ages of 28 days, 56 days and 90 days respectively, as is summarily reported below.

After curing for 28 days, as the Bulk density of Plain Cement Normal Concrete (PCC) increased from “2438$\text{Kg/m}^3 (PCC_{opt})$” to 2445$\text{Kg/m}^3 (PCC_{min})”", while its Thermal conductivity decreased from “2.01$W/m-K (PCC_{opt})$” to 1.83$W/m-K (PCC_{min})””. Also, at other curing-ages of 56 days and 90 days, the same variation trend was noticed.

| SN | Concrete-group | Concrete-Specimen/Design-mix | Binder(s) | Actual (True) 'w/c' ratio | 28 days | 56 days | 90 days |
|---|---|---|---|---|---|---|---|
| 1 | Plain Cement [Normal ] Concrete | $PCC_{max}$ | OPC | 0.62 | 1.85 | 2400 | 1.82 | 2427 | 1.79 | 2446 |
| 2 | PCC | $PCC_{opt}$ | OPC | 0.55 | 2.01 | 2438 | 1.92 | 2459 | 1.89 | 2488 |
| 3 | $PCC_{min}$ | OPC | 0.48 | 1.83 | 2445 | 1.84 | 2472 | 1.83 | 2495 |
| 4 | Portland Slag [Special] Concrete | $PSC_{max}$ | OPC, GGBFS | 0.62 | 2.30 | 2449 | 2.23 | 2477 | 2.05 | 2508 |
| 5 | PSC | $PSC_{opt}$ | OPC, GGBFS | 0.48 | 2.61 | 2483 | 2.44 | 2500 | 2.27 | 2527 |
| 6 | $PSC_{min}$ | OPC, GGBFS | 0.43 | 2.26 | 2541 | 1.99 | 2565 | 1.98 | 2700 |
| 7 | Silica-fume Slag [Special] Concrete | $SSC_{max}$ | OPC, Si-fume, GGBFS | 0.55 | 3.47 | 2620 | 2.85 | 2656 | 2.58 | 2677 |
| 8 | SSC | $SSC_{opt}$ | OPC, Si-fume, GGBFS | 0.43 | 3.15 | 2653 | 2.93 | 2686 | 2.32 | 2719 |
| 9 | $SSC_{min}$ | OPC, Si-fume, GGBFS | 0.38 | 3.22 | 2702 | 2.81 | 2740 | 2.68 | 2796 |

After curing for 56 days, an increase in the Bulk density of Portland Slag Special Concrete (PSC) from “2500$\text{Kg/m}^3 (PSC_{opt})$” to 2565$\text{Kg/m}^3 (PSC_{min})””, was accompanied by a
decrease in its Thermal conductivity from “$2.61 \text{ W/mK} (PSC_{opt})$ to $2.26 \text{ W/mK} (PSC_{min})$”. Similar patterns were noted after curing for 28 days and 90 days.

After curing for 90 days, the Bulk density value of Silica-fume Slag Special Concrete (SSC) rose from “$32677 \text{ Kg/m}^3 (SSC_{max})$ to $32719 \text{ Kg/m}^3 (SSC_{opt})$”, at the same time that its Thermal conductivity value dropped from “$2.58 \text{ W/mK} (SSC_{max})$ to $2.32 \text{ W/mK} (SSC_{opt})$”. The results obtained after curing for previous curing-ages of 28 days & 56 days were not so different.
Thus, based on the above results, we may say that: “in a few (minority of the) of these experimental-cases [i.e. 3 out of 9 Concrete test-materials ‘$\text{PCC}_{\text{max}}$’, ‘$\text{PSC}_{\text{max}}$’ & ‘$\text{SSC}_{\text{min}}$’ investigated], the Thermal conductivity increased with increasing Bulk Density; while in most (majority of the) of these experimental-cases [i.e. 6 out of 9 Concrete test-materials’ $\text{PCC}_{\text{opt}}$, ‘$\text{PCC}_{\text{min}}$’, ‘$\text{PSC}_{\text{opt}}$’, ‘$\text{PSC}_{\text{min}}$’, ‘$\text{SSC}_{\text{max}}$’ & ‘$\text{SSC}_{\text{opt}}$’ investigated], the Thermal conductivity of Concrete decreased while it increasing Bulk density.

3.1.4 **Dry Bulk Density ($\rho_{\text{bulk, dry}}$) result:**

Based on the results reported in ‘Table 20’ and ‘Figure 8’, it could be said that, at a Curing-age of 28 days, as the Supplementary Cementitious Material (SCM) content increased with decreasing Water/Cement (w/c) ratio, the Dry bulk density of the Concrete test-materials [in all
three (3) Concrete-groups] increased. This proposition is predicated on the following understated experimental observations below:

Table 20: ‘Dry Bulk Density \( (\rho_{\text{bulk,dry}}) \)’ of Nine (9) Hardened Concrete-Specimens/Test-Materials

| S/N | Concrete-group | Concrete-Specimen/Test-material /Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | Dry Bulk Density (Kg / m³) of Concrete-Specimen at Curing-age of |
|-----|----------------|-----------------------------------------------|-----------|--------------------------|---------------------------------------------------------------|
|     |                |                                               |           |                          | 28 days | 56 days | 90 days |
| 1   | Plain Cement [Normal] Concrete | \( \text{PCC}_{\text{max}} \) | OPC       | 0.62                     | 2400    | 2427    | 2446    |
| 2   |                | \( \text{PCC}_{\text{opt}} \) | OPC       | 0.55                     | 2438    | 2459    | 2488    |
| 3   |                | \( \text{PCC}_{\text{min}} \) | OPC       | 0.48                     | 2445    | 2472    | 2495    |
| 4   | Portland Slag [Special] Concrete | \( \text{PSC}_{\text{max}} \) | OPC, GGBFS | 0.62                     | 2449    | 2477    | 2508    |
| 5   |                | \( \text{PSC}_{\text{opt}} \) | OPC, GGBFS | 0.48                     | 2483    | 2500    | 2527    |
| 6   |                | \( \text{PSC}_{\text{min}} \) | OPC, GGBFS | 0.43                     | 2541    | 2565    | 2700    |
| 7   | Silica-fume Slag [Special] Concrete | \( \text{SSC}_{\text{max}} \) | OPC, Si-fume, GGBFS | 0.55                     | 2620    | 2656    | 2677    |
| 8   |                | \( \text{SSC}_{\text{opt}} \) | OPC, Si-fume, GGBFS | 0.43                     | 2653    | 2686    | 2719    |
| 9   |                | \( \text{SSC}_{\text{min}} \) | OPC, Si-fume, GGBFS | 0.38                     | 2702    | 2740    | 2796    |

First and foremost, the ‘28th-day Dry bulk density \( (\rho_{\text{bulk,dry}}) \)’ of the ‘Plain Cement Normal Concrete-group (PCC)’ increased from 2400 Kg / m³ \( (\text{PCC}_{\text{max}}) \) upward through 2438 Kg / m³ \( (\text{PCC}_{\text{opt}}) \) to 2445 Kg / m³ \( (\text{PCC}_{\text{min}}) \), as the SCM content increased with decreasing w/c ratio from 0.62 \( (\text{PCC}_{\text{max}}) \) downward through 0.55 \( (\text{PCC}_{\text{opt}}) \) to 0.48 \( (\text{PCC}_{\text{min}}) \). Secondly, at a Maturity (Curing-age) of 28 days, the Dry bulk density \( (\rho_{\text{bulk,dry}}) \) of the ‘Portland Slag Special Concrete-group (PSC)’ increased from 2449 Kg / m³ \( (\text{PSC}_{\text{max}}) \) upward through 2483 Kg / m³ \( (\text{PSC}_{\text{opt}}) \) to 2541 Kg / m³ \( (\text{PSC}_{\text{min}}) \), as the SCM content increased with decreasing w/c ratio from 0.62 \( (\text{PSC}_{\text{max}}) \) downward through 0.48 \( (\text{PSC}_{\text{opt}}) \) to 0.43 \( (\text{PSC}_{\text{min}}) \). Thirdly, after curing for a period of 28 days, the Dry bulk density \( (\rho_{\text{bulk,dry}}) \) of the ‘Silica-fume Slag Special Concrete-group (SSC)’ increased from 2620 Kg / m³ \( (\text{SSC}_{\text{max}}) \) upward through 2653 Kg / m³ \( (\text{SSC}_{\text{opt}}) \) to 2702 Kg / m³ \( (\text{SSC}_{\text{min}}) \), as the SCM content increased with decreasing w/c ratio...
from 0.55 ($SSC_{\text{max}}$) downward through 0.43 ($SSC_{\text{opt}}$) to 0.38 ($SSC_{\text{min}}$). It is important to note that, the same trend “of an increase in Dry bulk density as SCM content increased with decreasing w/c ratio” was observed at other Curing-ages of 56 days and 90 days.

Figure 8: Graph of ‘Dry bulk density’ versus ‘Curing-age’ for Nine (9) Concrete specimens

Also, another view of ‘Table 27’ reveals that, for the ‘Plain Cement Normal Concrete test-materials (PCC)’, as the Dry bulk density of $PCC_{\text{max}}$ increased from 2400 Kg/m$^3$ [at 28 days] upward through 2427 Kg/m$^3$ [at 56 days] to 2446 Kg/m$^3$ [at 90 days]; the Dry bulk density of $PCC_{\text{opt}}$ increased from 2438 Kg/m$^3$ [at 28 days] upward through 2459 Kg/m$^3$ [at 56 days] to 2488 Kg/m$^3$ [at 90 days]; and then, the Dry bulk density of $PCC_{\text{min}}$ increased from 2445 Kg/m$^3$ [at 28 days] upward through 2472 Kg/m$^3$ [at 56 days] to 2495 Kg/m$^3$ [at 90 days]. Thus, these and similar variation patterns noticed with test-materials from the two other Concrete-groups [i.e. ‘Portland Slag Special Concrete-group (PSC)’ and ‘Silica-fume Slag Special Concrete-group (SSC)’] summarily suggest that “the Dry bulk density of Concrete increases with increasing Maturity (Curing-age)”.

3.1.5 Water Sorptivity ($S$) result:

As an important physical property of Concrete, the ‘Water Sorptivity ($S$)’ of Concrete basically refers to the index of the ability of Concrete to either ‘absorb’ or ‘desorb’ water by capillary action. As was mentioned in the ‘Materials and Method’ section of this study, three [i.e. Top, middle & bottom] Concrete-discs obtained by slicing the cylindrical Concrete specimen were
subjected to this particular experimental analysis called the ‘Water Sorptivity’ test. However, the relatively higher average Water Sorptivity values [computed to the nearest \(0.1 \times 10^{-4}\ mm/\sec^{0.5}\)] were recorded for the bottom discs when compared with the corresponding values for both the top and bottom discs.

Also, based on the results shown in ‘Table 21’ and ‘Figures 9a to 9h’, at a Curing-age of 28 days, the highest values of ‘Initial Water Sorptivity \((S_i)\)’ [i.e. \(43.7 \times 10^{-4}\ mm/\sec^{0.5}\) \((PCC_{\text{max}})\), \(38.6 \times 10^{-4}\ mm/\sec^{0.5}\) \((PCC_{\text{opt}})\) & \(37.6 \times 10^{-4}\ mm/\sec^{0.5}\) \((PCC_{\text{min}})\)] and ‘Secondary Water Sorptivity \((S_{s})\)’ [i.e. \(16.5 \times 10^{-4}\ mm/\sec^{0.5}\) \((PCC_{\text{max}})\), \(11.7 \times 10^{-4}\ mm/\sec^{0.5}\) \((PCC_{\text{opt}})\) & \(10.6 \times 10^{-4}\ mm/\sec^{0.5}\) \((PCC_{\text{min}})\)] were recorded for the ‘Plain Cement Normal Concretes’; while the lowest values of ‘Initial Water Sorptivity \((S_i)\)’ [i.e. \(21.9 \times 10^{-4}\ mm/\sec^{0.5}\) \((SSC_{\text{max}})\), \(18.8 \times 10^{-4}\ mm/\sec^{0.5}\) \((SSC_{\text{opt}})\) & \(14.3 \times 10^{-4}\ mm/\sec^{0.5}\) \((SSC_{\text{min}})\)] and ‘Secondary Water Sorptivity \((S_{s})\)’ [i.e. \(5.4 \times 10^{-4}\ mm/\sec^{0.5}\) \((SSC_{\text{max}})\), \(3.9 \times 10^{-4}\ mm/\sec^{0.5}\) \((SSC_{\text{opt}})\) & \(2.6 \times 10^{-4}\ mm/\sec^{0.5}\) \((SSC_{\text{min}})\)] were recorded for the ‘Silica-fume Slag Special Concretes’. Similar trends were noticed at the other two Curing-ages of 56 days and 90 days.

Thus, from the foregoing, it could be inferred that the presence (addition) and/or increase of Supplementary Cementitious Materials (SCMs) such as ‘Ground-granulated Blast-furnace Slag (GGBFS)’ and ‘Silica-fume blended cement (GUb-8SF)’, would most likely result in an increase in the ‘Water Sorptivity \((S)\)’ of Concrete. However, this is particularly true with ‘GUb-8SF’ and other ‘Silica-fume based SCMs’ which inhibit the Water Sorptivity level of Concrete.
Figure 9b: Graph of ‘Final Water Sorptivity’ versus ‘Curing-age’ for Nine (9) Concrete specimens

Table 21: ‘Water Sorptivity (S)’ of Nine (9) Hardened Concrete-Specimens/Test-Materials/Design-mixes

| S/N | Concrete-group | Concrete-Specimen/Test-material/Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | Average Water Sorptivity (*10^-4 mm/sec^0.5) at Curing-age of: |
|-----|----------------|-------------------------------------------|-----------|---------------------------|---------------------------------------------------------------|
|     |                |                                           |           |                           | 28 days (mm) | 56 days (mm) | 90 days (mm) |
| 1   | Plain Cement   | PCC_max                                   | OPC       | 0.62                      | 43.7 | 16.5 | 39.0 | 13.2 | 37.4 | 11.1 |
| 2   | Normal Concrete| PCC_opt                                   | OPC       | 0.55                      | 38.6 | 11.7 | 28.9 | 4.7  | 30.6 | 6.0  |
| 3   |                | PCC_min                                   | OPC       | 0.48                      | 37.6 | 10.6 | 24.8 | 1.2  | 29.4 | 5.1  |
| 4   | Portland slag  | PSC_max                                   | OPC, GGBFS| 0.62                      | 32.8 | 8.3  | 28.9 | 6.2  | 22.2 | 5.0  |
| 5   | Special slag   | PSC_opt                                   | OPC, GGBFS| 0.48                      | 29.5 | 7.3  | 26.3 | 5.8  | 20.7 | 4.7  |
| 6   |                | PSC_min                                   | OPC, GGBFS| 0.43                      | 23.8 | 5.6  | 18.9 | 4.9  | 6.52 | 1.8  |
| 7   | Silica-fume    | SSC_max                                   | OPC, Si-fume, GGBFS | 0.55 | 21.9 | 5.4  | 20.4 | 3.5  | 13.7 | 3.5  |
| 8   | Special slag   | SSC_opt                                   | OPC, Si-fume, GGBFS | 0.43 | 18.8 | 3.9  | 15.6 | 3.2  | 12.5 | 3.1  |
In addition, an attempt was made to compare the magnitudes of Water Sorptivities (Rates of Water Absorption) within each of the three Concrete-groups as reported in ‘Table 21’. Thus, a particular trend was observed throughout irrespective of Curing-age and Concrete-group, which will now be portrayed by three representative instances below:

I. For Plain Cement Normal Concrete-group (PCC)
At 90 days curing-age, the High Water/Cement (w/c) ratio Concrete test-material [i.e. $PCC_{\text{max}}$ having the highest w/c ratio of 0.62] recorded the highest initial and Secondary Water Sorptivities of $37.4 \times 10^{-4} \text{mm/sec}^{0.5}$ and $11.1 \times 10^{-4} \text{mm/sec}^{0.5}$ respectively; while the Low Water/Cement (w/c) ratio Concrete test-material [i.e. $PCC_{\text{min}}$ having the lowest w/c ratio 0.48] recorded the lowest initial and Secondary Water Sorptivities of $29.4 \times 10^{-4} \text{mm/sec}^{0.5}$ and $5.1 \times 10^{-4} \text{mm/sec}^{0.5}$ respectively; with similar variation patterns noticed at 28 days and 56 days Curing-ages.

II. For Portland Slag Special Concrete-group (PSC):
At 56 days curing-age, the Concrete test-material ($PSC_{\text{max}}$) with the maximum w/c ratio of 0.62, was noted to have exhibited the maximum initial Water Sorptivity value of $28.9 \times 10^{-4} \text{mm/sec}^{0.5}$ and the maximum secondary Water Sorptivity value of $6.2 \times 10^{-4} \text{mm/sec}^{0.5}$. On the other hand, the Concrete test-material ($PSC_{\text{min}}$) with the least w/c ratio of 0.43, was noted to have exhibited the least initial Water Sorptivity value of $18.9 \times 10^{-4} \text{mm/sec}^{0.5}$ and the least secondary Water Sorptivity value of $4.9 \times 10^{-4} \text{mm/sec}^{0.5}$. Again, this trend was observed to have occurred at the curing-ages of 28 days and 90 days.

III. For Silica-fume Slag Special Concrete-group (SSC):
At 28 days curing-age, the High Water/Cement (w/c) ratio Concrete test-material [i.e. $SSC_{\text{max}}$ having the highest w/c ratio of 0.55] recorded the highest initial and Secondary Water Sorptivities of $21.9 \times 10^{-4} \text{mm/sec}^{0.5}$ and $14.3 \times 10^{-4} \text{mm/sec}^{0.5}$ respectively; while the Low Water/Cement (w/c) ratio Concrete test-material [i.e. $SSC_{\text{min}}$ having the lowest w/c ratio 0.38] recorded the lowest initial and Secondary Water Sorptivities of $5.4 \times 10^{-4} \text{mm/sec}^{0.5}$ and $2.6 \times 10^{-4} \text{mm/sec}^{0.5}$ respectively; with similar variation patterns noticed at 56 days and 90 days Curing-ages.

Thus, it could be inferred that, “the higher the w/c ratio, the higher the initial and secondary Water Sorptivity of Concrete, irrespective of its Curing-age”. This may be explained on the basis of the fact that both ‘a high porosity level’ and ‘a pore structure with a high degree (level) of continuity’ are the direct consequences of a high Water/Cement (w/c) ratio in Concrete.
Figure 9c: Graph of 'Initial Water Sorptivity' versus 'Water/Cement or Cementitious material (w/c) ratio' for Concrete-specimens in the Portland Cement [Normal] Concrete-group (PCC) at three Curing-ages

Figure 9d: Graph of 'Initial Water sorptivity' versus 'Water/Cement or Cementitous material (w/c) ratio' for Concrete-specimens in the Portland Slag [Special] Concrete-group (PSC) at three Curing-ages
Furthermore, looking at ‘Table 21’ horizontally from left to right shows that the following:

I. The $PCC_{\text{max}}$ ‘initial Water Sorptivity’ decreased from $43.7 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 28 days Curing-age] through $39.0 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 56 days Curing-age] to $37.4 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 90 days Curing-age]; and the $PCC_{\text{max}}$ ‘secondary Water Sorptivity’ also decreased from $16.5 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 28 days Curing-age] through $13.2 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 56 days Curing-age] to $11.1 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 90 days Curing-age]; followed by similar behaviours displayed by the other two Plain Cement Normal Concrete test-materials [i.e. $\text{PCC}_{\text{opt}}$ and $\text{PCC}_{\text{min}}$].
II. The $PSC_{max}$ ‘initial Water Sorptivity’ decreased from $32.8 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 28 days Curing-age] through $28.9 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 56 days Curing-age] to $22.2 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 90 days Curing-age]; and the $PSC_{max}$ ‘secondary Water Sorptivity’ also decreased from $8.3 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 28 days Curing-age] through $6.2 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 56 days Curing-age] to $5.0 \times 10^{-4} \text{ mm/sec}^{0.5}$ [at 90 days Curing-age]; followed by similar behaviours displayed by the other two Portland Slag Special Concrete test-materials [i.e. ‘$PSC_{opt}$’ and ‘$PSC_{min}$’].
III. The $SSC_{opt}$ 'initial Water Sorptivity' decreased from $18.8 \times 10^{-4} \, \text{mm} / \text{sec}^{0.5}$ [at 28 days Curing-age] through $15.6 \times 10^{-4} \, \text{mm} / \text{sec}^{0.5}$ [at 56 days Curing-age] to $12.5 \times 10^{-4} \, \text{mm} / \text{sec}^{0.5}$ [at 90 days Curing-age]; and the $SSC_{opt}$ 'secondary Water Sorptivity' also decreased from $3.9 \times 10^{-4} \, \text{mm} / \text{sec}^{0.5}$ [at 28 days Curing-age] through $3.2 \times 10^{-4} \, \text{mm} / \text{sec}^{0.5}$ [at 56 days Curing-age] to $3.1 \times 10^{-4} \, \text{mm} / \text{sec}^{0.5}$ [at 90 days Curing-age] This was followed by similar behaviours displayed by the other two Silica-fume Slag Special Concrete test-materials [i.e. $SSC_{max}$ and $SSC_{min}$]; however, $SSC_{max}$ exhibited a constant (the same) secondary Water Sorptivity value of $3.5 \times 10^{-4} \, \text{mm} / \text{sec}^{0.5}$ at 56 days and 90 days Curing-ages.

From the foregoing, it is therefore experimentally correct to conclude that, “the higher the Curing-age of Concrete, the lower its Water Sorptivity”. This may be explained on the basis of the fact that the greater the maturity (Curing-age) of Concrete, the greater the discontinuity of its pore system, and consequently, the lesser its Water Sorptivity (absorption) arising from the suction of its capillary pores.
Figure 9h: Graph of ‘Final Water sorptivity’ versus ‘Water/Cement or Cementitious material (w/c) ratio’ for Concrete-specimens in the Silica-fume Slag [Special] Concrete-group (SSC) at three Curing-ages

3.2 Electrical Characterization Tests results

3.2.1 RCPT Total Electric-charge Passed (\( \sum Q_p \)) and Chloride-ion Penetrability results:

A comparative assessment of the experimental results contained in ‘Table 23’ and graphically illustrated in ‘Figure 10; clearly reveals that, the ‘Plain Cement Concretes (\( PCC_{\text{max}} \), \( PCC_{\text{opt}} \) & \( PCC_{\text{min}} \))’ allowed the passage of the highest quantities [i.e. 5718 Coulombs, 4461 Coulombs & 3203 Coulombs]; followed by ‘Portland Slag Special Concrete (\( PSC_{\text{max}} \), \( PSC_{\text{opt}} \) & \( PSC_{\text{min}} \))’ which allowed the passage of 2278 Coulombs, 1378 Coulombs & 1057 Coulombs; and then, ‘Silica-fume Slag Special Concretes (\( SSC_{\text{max}} \), \( SSC_{\text{opt}} \) & \( SSC_{\text{min}} \))’ which allowed the passage of the lowest quantities [i.e. 454 Coulombs, 316 Coulombs & 259 Coulombs] of RCPT Electricity (Total Electric-charge) through them respectively at a curing-ages of 28 days. This suggests that, the presence and/or increase of Supplementary Cementitious Materials (SCMs) such as ‘Ground-granulated Blast-furnace Slag (GGBFS)’ and ‘Silica-fume blended cement (GUb-8SF)’ reduce the amount of ‘Total RCPT Electric-charge Passed.'
Table 23: ‘RCPT Total Electric-charge Passed \(\sum Q_p\)’ of Nine (9) Hardened Concrete-Specimens

| S/N | Concrete-group | Concrete-Specimen/Test-material/Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | RCPT Total Electric-charge passed (Coulombs) | Chloride-ion Penetrability | RCPT Total Electric-charge passed (Coulombs) | Chloride-ion Penetrability | RCPT Total Electric-charge passed (Coulombs) | Chloride-ion Penetrability |
|-----|----------------|--------------------------------------------|------------|---------------------------|---------------------------------------------|---------------------------|---------------------------------------------|---------------------------|---------------------------------------------|---------------------------|
|     |                |                                            |            |                           |                                             |                           |                                             |                           |                                             |                           |
| 1   | Plain Cement   | PCC\(_{\text{max}}\)                         | OPC        | 0.62                      | 5718                                        | High                      | 3162                                        | Moderate                   | 1061                                        | Low                       |
| 2   |                | PCC\(_{\text{opt}}\)                         | OPC        | 0.55                      | 4461                                        | High                      | 2645                                        | Moderate                   | 1414                                        | Low                       |
| 3   |                | PCC\(_{\text{min}}\)                         | OPC        | 0.48                      | 3203                                        | Moderate                  | 2128                                        | Moderate                   | 1767                                        | Low                       |
| 4   | Silica-fume    | PSC\(_{\text{max}}\)                         | OPC, GGBFS | 0.62                      | 2278                                        | Moderate                  | 1682                                        | Low                        | 206                                         | Very Low                  |
| 5   |                | PSC\(_{\text{opt}}\)                         | OPC, GGBFS | 0.48                      | 1378                                        | Low                       | 1017                                        | Low                        | 429                                         | Very Low                  |
| 6   |                | PSC\(_{\text{min}}\)                         | OPC, GGBFS | 0.43                      | 1057                                        | Very Low                  | 780                                         | Very Low                   | 656                                         | Very Low                  |
| 7   | Silica-fume    | SSC\(_{\text{max}}\)                         | OPC, Si-fume, GGBFS | 0.55                      | 454                                         | Very Low                  | 326                                         | Very Low                   | 101                                         | Very Low                  |
| 8   |                | SSC\(_{\text{opt}}\)                         | OPC, Si-fume, GGBFS | 0.43                      | 316                                         | Very Low                  | 261                                         | Very Low                   | 116                                         | Very Low                  |
| 9   |                | SSC\(_{\text{min}}\)                         | OPC, Si-fume, GGBFS | 0.38                      | 259                                         | Very Low                  | 233                                         | Very Low                   | 155                                         | Very Low                  |

Again, ‘Table 23’ shows that, there is a progressive reduction in the quantity of ‘Total RCPT Electric-charge Passed’ from the left (28 days Curing-age) through 56 days Curing-age to the right (90 days Curing-age), which is a clear indication that, ‘Total RCPT Electric-charge Passed \(\sum Q_p\)’ decreases with increasing Curing-age.

Also, within each of the three Concrete-groups, it was noticed that the Concrete test-material with the highest Water/Cement (w/c) ratio [which by implication had the highest porosity] recorded the highest ‘Total RCPT Electric-charge Passed’. This implies that the higher the Water/Cement (w/c) ratio, the higher the ‘Total RCPT Electric-charge Passed’ and vice versa. Now, this may not be unconnected with the fact that, the ‘Total RCPT Electric-charge Passed’ is largely dependent on the ‘relative ionic mobility of the concrete-matrix’, which itself is affected by the ‘Porosity of the binder (Cement/Cement + SCM) paste’—whose major determinant is the Water/Cement (w/c) ratio.

Similarly, from ‘Table 23’ and ‘Figure 10’, the ‘Chloride-ion Penetrability’ level decreased with increasing Curing-age as follows:
I. From ‘Highs’ & ‘Moderate’ [at 28 days Curing-age], through ‘all Moderate’ [at 56 days Curing-age] to ‘Lows’ [at 90 days Curing-age] for ‘Plain Cement Normal concretes \( \text{max} (PCC, PCC_{opt} \& PCC_{min}) \) respectively; and

II. From ‘Moderate’ & ‘Lows’ [at 28 days Curing-age] through ‘Lows’ & ‘very lows’ [at 56 days Curing-age] to ‘Very lows’ [at 90 days Curing-age] for ‘Portland Slag Special Concretes \( \text{max} (PSC, PSC_{opt} \& PSC_{min}) \) respectively.

However, it (Chloride-ion Penetrability) remained unchanged (constant) at ‘Very low’ all through the three Curing-ages of 28 days, 56 days & 90 days for ‘Silica-fume Slag Special Concretes \( \text{max} (SSC, SSC_{opt} \& SSC_{min}) \).

Again, within each of the three Concrete-groups \( (PCC, PSC \& SSC) \) & the ‘Chloride-ion Penetrability’ level was noticed to decrease with decreasing ‘Water/Cement (w/c) ratio’ and the presence and/or increase of Supplementary Cementitious Materials (SCMs) [such as ‘GGBFS’ and ‘GUb-8SF’], since it drops from ‘Highs’ [at w/c ratios of 0.62 and 0.55] to ‘Moderate’ [at a w/c ratio of 0.48] for ‘Plain Cement Normal concretes’ at 28 days Curing-age; and then, from ‘Moderate’ [at a w/c ratio of 0.62] to ‘Lows’ [at w/c ratios of 0.48 and 0.43] at 28 days Curing-age for ‘Portland Slag special Concrete’; followed by ‘Lows’ [at w/c ratios of 0.62 and 0.48] to ‘Very low’ [at w/c ratio of 0.43] at 56 days Curing-age also for ‘Portland Slag special Concrete’. However, it i.e. ‘Chloride-ion Penetrability’ remained unchanged (constant) at all other w/c ratios and Curing-ages.

3.2.2 Initial 5-minute RCPT Electrical-resistivity \( (\rho_{RCPT}) \) result
For all three Curing-ages (28 days, 56 days & 90 days), both Concrete-groups containing Supplementary Cementitious Materials (SCMs) i.e. ‘Portland Slag Special Concretes (PSC)’ and ‘Silica-fume Slag Special Concretes (SSC)’ had ‘Initial 5-minute RCPT Electrical Resistivity ($\rho_{ERCPT}$)’ values which were higher than those without i.e. ‘Plain Cement Normal Concretes (PCC)’. This is because, as could be seen in ‘Table 24’, and ‘Figures 11a to 11c’, the ‘28 day Initial 5-minute RCPT Electrical Resistivity’ value of [8.9KΩ – cm] for ‘Portland Slag Special Concrete ($PSC_{\text{max}}$)’ with a w/c ratio of 0.62, is nearly three and a half ($\approx 3.5$) times the value of [2.6KΩ – cm] for its counterpart test-material i.e. ‘Plain Cement Normal Concrete ($PCC_{\text{max}}$)’ of the same Curing-age of 28 days and having the same w/c ratio of 0.62.

Table 24: ‘Initial 5-Minute RCPT Electrical Resistivity [$\rho_{ERCPT}$]’ of Nine (9) Hardened Concrete-Specimens/Test-Materials

| S/N | Concrete-group | Concrete-Specimen/Test-material/Design-mix | Binder(s) | Actual (True) ‘w/c’ ratio | Initial 5-Minute RCPT Electrical Resistivity (KΩ – cm) of Concrete-Specimen at Curing-age of
|     |               |                                   |          |                         | 28 days | 56 days | 90 days |
|-----|---------------|-------------------------------------|----------|--------------------------|---------|---------|---------|
| 1   | Plain Cement [Normal] Concrete | $PCC_{\text{max}}$ | OPC      | 0.62                     | 2.6     | 6.0     | 8.5     |
| 2   |               | $PCC_{\text{opt}}$                | OPC      | 0.55                     | 4.6     | 7.5     | 9.7     |
| 3   |               | $PCC_{\text{min}}$                | OPC      | 0.48                     | 6.6     | 9.0     | 10.9    |
| 4   | Portland Slag [Special] Concrete | $PSC_{\text{max}}$ | OPC, GGBFS | 0.62                   | 8.9     | 14.6    | 18.4    |
| 5   |               | $PSC_{\text{opt}}$                | OPC, GGBFS | 0.48                  | 11.8    | 16.8    | 19.9    |
| 6   |               | $PSC_{\text{min}}$                | OPC, GGBFS | 0.43                  | 16.1    | 22.2    | 29.3    |
| 7   | Silica-fume Slag [Special] Concrete | $SSC_{\text{max}}$   | OPC, Si-fume, GGBFS | 0.55             | 22.4    | 51.3    | 58.8    |
| 8   |               | $SSC_{\text{opt}}$                | OPC, Si-fume, GGBFS | 0.43             | 52.4    | 66.7    | 74.0    |
| 9   |               | $SSC_{\text{min}}$                | OPC, Si-fume, GGBFS | 0.38             | 64.9    | 73.1    | 80.3    |

Similar observations were recorded at subsequent Curing-ages of 56 days and 90 days, when:

I. The Initial 5-minute RCPT Electrical Resistivity value of 14.6KΩ – cm [for $PSC_{\text{max}}$ with w/c ratio of 0.62 at 56 days] is almost two and a half ($\approx 2.5$) times the value of 6.0KΩ – cm [for $PCC_{\text{max}}$ with the same w/c ratio of 0.62 at the same Curing-age of 56 days]; and
II. The Initial 5-minute RCPT Electrical Resistivity value of 18.4\(K\Omega \cdot cm\) [for \(PSC_{\text{max}}\) with w/c ratio of 0.62 at 90 days] is roughly twice (\(\approx 2.0\) times) the value of 8.5\(K\Omega \cdot cm\) [for \(PCC_{\text{max}}\) with the same w/c ratio of 0.62 at the same Curing-age of 90 days].

![Graph of Initial 5-minute RCPT Electrical-resistivity versus Water/Cement or Cementitious material (w/c) ratio for Concrete-specimens in the Portland Cement (Normal) Concrete-group (PCC) at 3 Curing-ages](image)

Figure 11a: Graph of 'Initial 5-minute RCPT Electrical-resistivity' versus 'Water/Cement or Cementitious material (w/c) ratio' for Concrete-specimens in the Portland Cement [Normal] Concrete-group (PCC) at 3 Curing-ages

Also, ‘Table 24’ shows that, with a w/c ratio of 0.43, and:

I. At a Curing-age of 28 days, a ‘Silica-fume Slag Special Concrete (\(SSC_{\text{max}}\))’ has an ‘Initial 5-minute RCPT Electrical Resistivity’ of 52.4\(K\Omega \cdot cm\), which is greater than thrice (\(\approx 3.3\) times) the resistivity of 16.1\(K\Omega \cdot cm\) for a ‘Portland Slag Special Concrete (\(PSC_{\text{min}}\))’ with the very same values of w/c ratio and Curing-age.

II. At a Curing-age of 56 days, \(SSC_{\text{max}}\) has an ‘Initial 5-minute RCPT Electrical Resistivity’ of 66.7\(K\Omega \cdot cm\), which is exactly thrice (\(\approx 3.0\) times) the resistivity of 22.2\(K\Omega \cdot cm\) for \(PSC_{\text{min}}\) having the same w/c ratio and Curing-age.
From the foregoing, it is clear that ‘Initial 5-minute RCPT Electrical Resistivity’ increases with the presence (addition) and/or increase in Supplementary Cementitious Material (SCM) such as ‘GGBFS’ and ‘GUb-8SF’.

Furthermore, a comparative-assessment of the Concrete test-materials within each Concrete-group indicates that the ‘Initial 5-minute RCPT Electrical Resistivity’ increases with a decrease in w/c ratio, and vice versa irrespective of the Curing-ages considered during this study. This is in view of the results presented ‘Table 24’, in which for illustrative examples:

I. At 28 days Curing-age, the ‘Initial 5-minute RCPT Electrical Resistivity’ values of ‘Plain Cement Normal Concretes (PCC)’ increased with decreasing w/c ratio, i.e. from $2.6\,\Omega\cdot\text{cm}$ [for $PCC_{\text{max}}$ with w/c ratio of 0.62], through $4.6\,\Omega\cdot\text{cm}$ [for $PCC_{\text{opt}}$ with w/c ratio of 0.55] to $6.6\,\Omega\cdot\text{cm}$ [for $PCC_{\text{min}}$ with w/c ratio of 0.48]; with similar behaviours at other Curing-ages of 56 days and 90 days.

II. At 56 days Curing-age, the ‘Initial 5-minute RCPT Electrical Resistivity’ values of ‘Portland Slag Special Concretes (PSC)’ increased with decreasing w/c ratio, i.e. from $14.6\,\Omega\cdot\text{cm}$ [for $PSC_{\text{max}}$ with w/c ratio of 0.62], through $16.8\,\Omega\cdot\text{cm}$ [for $PSC_{\text{opt}}$...
with w/c ratio of 0.48] to \(22.2 K\Omega - \text{cm}\) [for \(PSC_{\text{min}}\) with w/c ratio of 0.43]; with similar behaviours at other Curing-ages of 28 days and 90 days.

III. At 90 days Curing-age, the ‘Initial 5-minute RCPT Electrical Resistivity’ values of ‘Silica-fume Slag Special Concretes (SSC)’ increased with decreasing w/c ratio, i.e. from \(58.8 K\Omega - \text{cm}\) [for \(SSC_{\text{max}}\) with w/c ratio of 0.55], through \(74.0 K\Omega - \text{cm}\) [for \(SSC_{\text{opt}}\) with w/c ratio of 0.43] to \(80.3 K\Omega - \text{cm}\) [for \(SSC_{\text{min}}\) with w/c ratio of 0.38]; with similar behaviours at other Curing-ages of 28 days and 56 days.

![Graph of 'Initial 5 minute RCPT Electrical-resistivity' versus 'Water/Cement or Cementitious material (w/c) ratio' for Concrete-specimens in the Silica-fume Slag [Special] Concrete-group (SSC) at three Curing-ages](image)

In addition, it is pertinent to mention here and now that, the rebar corrosion risk level (magnitude) [which is a primary reason for both partial (local) and total (collapse) failures of a steel-reinforced Concrete structure] is inversely proportional to the ‘Bulk RCPT Electrical Resistivity’ of the Concrete.

\[3.2.3 \quad \text{Chloride-ion Penetration Depth} \ (C/p) \ \text{result}\]
From the results presented in ‘Table 25’ and ‘Figures 12a to 12c’, at a Curing-age of 28 days, it was observed that, the highest ‘Chloride-ion Penetration Depths’ ($Cl_{pd}$) of $29.4 \text{mm}$, $23.9 \text{mm}$ & $18.4 \text{mm}$ were respectively associated with the test-materials of ‘Plain Cement Normal Concretes’ i.e. ‘$PCC_{max}$’, ‘$PCC_{opt}$’ & ‘$PCC_{min}$’; and then, the medial ‘Chloride-ion Penetration Depths’ ($Cl_{pd}$) of $12.2 \text{mm}$, $9.1 \text{mm}$ & $6.6 \text{mm}$ were respectively associated with the test-materials of ‘Portland Slag Special Concretes’ i.e. ‘$PSC_{max}$’, ‘$PSC_{opt}$’ & ‘$PSC_{min}$’; while the lowest ‘Chloride-ion Penetration Depths’ ($Cl_{pd}$) of $3.3 \text{mm}$, $2.2 \text{mm}$ & $1.7 \text{mm}$ were respectively associated with the test-materials of ‘Silica-fume Slag Special Concretes’ i.e. ‘$SSC_{max}$’, ‘$SSC_{opt}$’ & ‘$SSC_{min}$’. Very similar results of a decrease in ‘Chloride-ion Penetration Depths’ ($Cl_{pd}$) with the presence (“addition) and/or increase of Supplementary Cementitious Materials (SCMs) [such as ‘GGBFS’ and ‘GUb-8SF’] at another Curing-age of 56 days.
Figure 12b: Graph of 'Initial Chloride-ion Penetration Depth' versus 'Water/Cement or Cementitious material (w/c) ratio' for Concrete-specimens in the Portland Slag [Special] Concrete-group (PSC) at three Curing-ages

Figure 12c: Graph of 'Initial Chloride-ion Penetration Depth' versus 'Water/Cement or Cementitious material (w/c) ratio' for Concrete-specimens in the Silica-fume Slag [Special] Concrete-group (SSC) at three Curing-ages
Furthermore, it is particularly important to notice from ‘Table 25’, that the presence (addition) of ‘Silica-fume’ as a Supplementary Cementitious Material (SCM) significantly reduces the ‘Chloride-ion Penetration Depth’ of Concrete, even as Curing-age increases, to the point where it is no longer visible [i.e. reduces to a value of 0.0\,mm] at a Curing-age of 90 days.

Also, within each Concrete-group [i.e. Concrete test-materials with the same Supplementary Cementitious Materials (SCMs)], the highest ‘Chloride-ion Penetration Depths’ were associated with the Concrete test-material that had the highest Water/Cement (w/c) ratio and vice versa. This obviously is an indication that ‘Chloride-ion Penetration Depth’ is primarily influenced by w/c ratio, the later which as a determinant is directly proportional to the porosity and pore-size distribution of the Concrete pore structure; since ‘Chloride-ion Penetration Depth’ has been proven to be a function of (directly dependent on) the Concrete’s pore structure, rather than the Concrete’s pore solution.

Table 25: ‘Chloride-ion Penetration depth \( [C_i] \)’ of Nine (9) Hardened Concrete-Specimens

| S/N | Concrete-group | Concrete-Specimen/Test-material/Design-mix | Binder(s) | Actual (True) \( w/c \) ratio | Chloride-ion Penetration depth (mm) of Concrete-Specimen at Curing-age of: |
|-----|----------------|------------------------------------------|-----------|------------------------------|--------------------------------------------------------------------------------|
|     |                |                                          |           |                              | 28 days  | 56 days  | 90 days  |
| 1   | Plain Cement [Normal] Concrete | \(PCC_{\text{max}}\) | OPC | 0.62 | 29.4 | 21.3 | 23.9 |
| 2   | \(PCC_{\text{opt}}\) | OPC | 0.55 | 23.9 | 18.3 | 18.4 |
| 3   | \(PCC_{\text{min}}\) | OPC | 0.48 | 18.4 | 15.3 | 12.9 |
| 4   | Portland Slag [Special] Concrete | \(PSC_{\text{max}}\) | OPC, GGBFS | 0.62 | 12.2 | 10.5 | 9.3 |
| 5   | \(PSC_{\text{opt}}\) | OPC, GGBFS | 0.48 | 9.1 | 7.9 | 7.2 |
| 6   | \(PSC_{\text{min}}\) | OPC, GGBFS | 0.43 | 6.6 | 6.1 | 5.1 |
| 7   | Silica-fume Slag [Special] Concrete | \(SSC_{\text{max}}\) | OPC, Si-fume, GGBFS | 0.55 | 3.3 | 4.4 | 0.0 |
| 8   | \(SSC_{\text{opt}}\) | OPC, Si-fume, GGBFS | 0.43 | 2.2 | 2.1 | 0.0 |
| 9   | \(SSC_{\text{min}}\) | OPC, Si-fume, GGBFS | 0.38 | 1.7 | 1.1 | 0.0 |
3.2.4 Non-steady state Migration Coefficient \( (D_{nssMC}) \) result

A careful consideration of the ‘Table 26’ and ‘Figure 13’, show that, within the Portland Cement [Normal] Concrete-group, the 28 day Non-steady-state Migration Coefficient decreased from \( 7.90 \times 10^{-12} \text{ m}^2 / \text{s} \) [‘\( PCC_{\text{max}} \)’] through \( 6.52 \times 10^{-12} \text{ m}^2 / \text{s} \) [‘\( PCC_{\text{opt}} \)’] to \( 4.83 \times 10^{-12} \text{ m}^2 / \text{s} \) [‘\( PCC_{\text{min}} \)’], as w/c ratio also decreased from 0.62 [‘\( PCC_{\text{max}} \)’] through 0.55 [‘\( PCC_{\text{opt}} \)’] to 0.48 [‘\( PCC_{\text{min}} \)’]. It should be noted that this trend was also observed at 56days and 90 days Curing-age. Thus, similar results noticed within other Concrete-groups at all three Curing-ages, justify the inference that Non-steady-state Migration Coefficient decreases with decreasing Water/Cement or Cementitious material (w/c) ratio. Also, it was generally observed that the Non-steady-state Migration Coefficient of the Concrete specimens/test-materials decreased with increasing Supplementary Cementitious Material (SCM) content and increasing Curing-age.

Figure 13: Graph of ‘Non-steady-state Migration Coefficient’ versus ‘Curing-age’ for Nine (9) Concrete-specimens
Table 26: ‘Non-steady-state Migration Coefficient [$D_{nssMC}$]’ of Nine (9) Hardened Concrete Specimens

| S/N | Concrete-group | Concrete Specimen | w/c ratio | Parameter | Curing-age |
|-----|----------------|-------------------|-----------|-----------|------------|
|     |                |                   |           |           | 28 days    | 56 days    | 90 days    |
| 1.  | Portland Cement [Normal] Concrete | $PCC_{max}$ | 0.62      | Specimen Thickness [L] (mm) | 50.74       | 50.81       | 51.42       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 25.61       | 25.49       | 25.32       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 29.40       | 21.30       | 23.90       |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 7.90        | 5.65        | 6.44        |
| 2.  | Portland Cement [Special] Concrete | $PCC_{opt}$ | 0.55      | Specimen Thickness [L] (mm) | 51.83       | 50.74       | 50.35       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 26.77       | 25.92       | 25.68       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 23.90       | 18.30       | 18.40       |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 6.52        | 4.82        | 4.81        |
| 3.  | Portland Cement [Special] Concrete | $PCC_{min}$ | 0.48      | Specimen Thickness [L] (mm) | 50.35       | 50.29       | 50.03       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 27.41       | 27.13       | 26.85       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 18.40       | 15.30       | 12.90       |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 4.83        | 3.97        | 3.36        |
| 4.  | Portland Slag [Special] Concrete | $PSC_{max}$ | 0.62      | Specimen Thickness [L] (mm) | 51.36       | 52.11       | 52.87       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 28.67       | 27.35       | 27.21       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 12.20       | 10.50       | 9.30        |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 3.20        | 2.76        | 2.45        |
| 5.  | Portland Slag [Special] Concrete | $PSC_{opt}$ | 0.48      | Specimen Thickness [L] (mm) | 52.66       | 51.89       | 51.95       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 28.92       | 28.74       | 28.35       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 9.10        | 7.90        | 7.20        |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 2.40        | 2.03        | 1.84        |
| 6.  | Portland Slag [Special] Concrete | $PSC_{min}$ | 0.43      | Specimen Thickness [L] (mm) | 53.02       | 52.91       | 53.00       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 29.88       | 29.37       | 29.04       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 6.60        | 6.10        | 5.10        |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 1.71        | 1.56        | 1.28        |
| 7.  | Silica-fume Slag [Special] Concrete | $SSC_{max}$ | 0.55      | Specimen Thickness [L] (mm) | 52.64       | 52.49       | 52.30       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 30.52       | 29.83       | 29.21       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 3.30        | 4.40        | 0.00        |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 7.87        | 1.08        | 0.00        |
| 8.  | Silica-fume Slag [Special] Concrete | $SSC_{opt}$ | 0.43      | Specimen Thickness [L] (mm) | 52.70       | 52.51       | 52.70       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 32.41       | 31.65       | 29.72       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 2.20        | 2.10        | 0.00        |
|     |                |                   |           | Migration Coefficient [$D_{nssMC}$](*10⁻¹² m²/S) | 4.95        | 4.66        | 0.00        |
| 9.  | Silica-fume Slag [Special] Concrete | $SSC_{min}$ | 0.38      | Specimen Thickness [L] (mm) | 52.87       | 52.51       | 52.36       |
|     |                |                   |           | Specimen Temperature [T] (°C) | 34.63       | 32.49       | 30.10       |
|     |                |                   |           | Chloride-ion Penetration depth [$C_{pd}$] (mm) | 1.70        | 1.10        | 0.00        |
3.3 Mechanical Characterization Test results

3.3.1 Average Compressive-strength (\(\bar{f}_{ck}\)) result:

Displayed in ‘Table 27’ and graphically illustrated in ‘Figures 14a to 14d’, are the results of the Average Compressive strength tests conducted for all nine Concrete test-materials that constitute the three Concrete-groups at three Curing-ages.

From ‘Table 27’, it could be seen that, at a uniform Water/Cement (w/c) ratio of 0.62 and an equal maturity (Curing-age) of 28 days, a ‘Portland Slag Special Concrete test-material (\(PSC_{\text{max}}\))’ [containing ‘GGBFS’ as a Supplementary Cementitious Material (SCM)] had an Average Compressive strength (\(\bar{f}_{ck}\)) of 39.98 MPa—which is higher than that of the corresponding ‘Plain Cement Normal Concrete test-material (\(PCC_{\text{max}}\))’ with an Average Compressive strength (\(\bar{f}_{ck}\)) of 34.26 MPa. Again, the \(PSC_{\text{opt}}\) [with a w/c ratio = 0.48] is Compressively stronger than \(PCC_{\text{min}}\) [with the same w/c ratio = 0.48], since the former [i.e. ‘\(PSC_{\text{opt}}\)’] gave a 28 day Average Compressive Strength of 44.06 MPa, as against the 39.51 MPa which was recorded for the latter [i.e. ‘\(PCC_{\text{min}}\)’] at the same Curing-age of 28 days.

Table 27: ‘Average Compressive-Strength [\(\bar{f}_{ck}\)]’ of Nine (9) Hardened Concrete-Specimens/Test-Materials

| S/N | Concrete-group | Concrete-Specimen/Test-material/Design-mix | Binder(s) | Actual (True) w/c’ ratio | 28 days | 56 days | 90 days |
|-----|----------------|------------------------------------------|-----------|-------------------------|---------|---------|---------|
| 1   | Plain Cement [Normal] Concrete | \(PCC_{\text{max}}\) | OPC | 0.62 | 34.26 | 37.41 | 39.74 |
| 2   |                      | \(PCC_{\text{opt}}\) | OPC | 0.55 | 38.73 | 41.21 | 44.62 |
| 3   |                      | \(PCC_{\text{min}}\) | OPC | 0.48 | 39.51 | 42.77 | 45.55 |
| 4   | Portland Slag [Special] Concrete | \(PSC_{\text{max}}\) | OPC, GGBFS | 0.62 | 39.98 | 43.37 | 46.90 |
| 5   |                      | \(PSC_{\text{opt}}\) | OPC, GGBFS | 0.48 | 44.06 | 46.13 | 49.29 |
| 6   |                      | \(PSC_{\text{min}}\) | OPC, GGBFS | 0.43 | 49.84 | 52.29 | 54.93 |
| 7   | Silica-fume Slag [Special] Concrete | \(SSC_{\text{max}}\) | OPC, Si-fume, GGBFS | 0.55 | 60.35 | 64.68 | 67.11 |
| 8   |                      | \(SSC_{\text{opt}}\) | OPC, Si-fume, GGBFS | 0.43 | 64.27 | 68.16 | 72.13 |
| 9   |                      | \(SSC_{\text{min}}\) | OPC | 0.38 | 70.10 | 74.66 | 77.16 |
Likewise, at a uniform maturity (Curing-age) of 28 days and the same w/c ratio of 0.43, a ‘Silica-fume Slag special Concrete test-material (SSC\text{opt})’ [Curing-age =28 days, w/c ratio=0.43, SCM = ‘GGBFS’] had an Average Compressive strength (\(f_{ck}\)) of 64.27 MPa, which was significantly higher than that of ‘Portland Slag special Concrete test-material (PSC\text{min})’ [Curing-age =28 days, w/c ratio= 0.43, SCMs = ‘GGBFS’ and ‘Silica-fume’] whose Average Compressive strength was 49.84 MPa. Thus, such vivid similarities in the Compressive-strength variation patterns at other Curing-ages [of 56 days and 90 days], experimentally establishes the fact that, ‘the presence (addition) and/or increase of Supplementary Cementitious Materials (SCMs) [such as ‘GGBFS’ and ‘Silica-fume’] improve the Compressive-strength of Concrete.

This may be attributed to the secondary hydration which ‘GGBFS’ and ‘Silica-fume’ each undergo as Supplementary binders Ordinary Portland Cement. However, at this point, it is pertinent to mention that, during this experimental programme, it was often observed among the two (2) Concrete-groups [i.e. ‘Portland Slag Special Concretes’ and ‘Silica-fume Slag Special Concretes’] that contained Supplementary Cementitious Materials (SCMs), that, at various Curing-ages, Compressive-strength gain rate was higher in ‘Silica-fume Slag Special Concrete test-materials/specimens [i.e. ‘SSC\text{max}’, ‘SSC\text{opt}’ and ‘SSC\text{min}’]’ than in ‘Portland Slag
Special Concrete test-materials/specimens [i.e. ‘$PSC_{\text{max}}$’, ‘$PSC_{\text{opt}}$’ and ‘$PSC_{\text{min}}$’] respectively.

This may be attributed to the slow rate of the hydration reaction between the Portlandite (Calcium hydroxide ‘$\text{Ca(OH)}_2$’) [present in Cement paste] and the Quartz/Silica (Silicon (IV) Oxide ‘$\text{SiO}_2$’) [present in Slag].

Also, based on the data displayed in ‘Table 27’ it is evident that, for the ‘Plain Cement Normal Concrete test-materials (PCC)’, just as the Average Compressive-strength of $PCC_{\text{max}}$ increased from 34.26 MPa [at 28 days] upward through 37.41 MPa [at 56 days] to 39.74 MPa [at 90 days]; the Average Compressive-strength of $PCC_{\text{opt}}$ increased from 38.73 MPa [at 28 days] upward through 41.21 MPa [at 56 days] to 44.62 MPa [at 90 days]; and likewise, the Average Compressive-strength of $PCC_{\text{min}}$ increased from 39.51 MPa [at 28 days] upward through 42.77 MPa [at 56 days] to 45.55 MPa [at 90 days]. Similar observations recorded with test-materials from the other Concrete-groups [i.e. ‘Portland Slag Special Concrete-group (PSC)’ and ‘Silica-fume Slag Special Concrete-group (SSC)’] clearly point to the fact that, the Average Compressive-strength of Concrete increases with increasing Maturity (Curing-age).
Finally, within each Concrete-group, it could be noticed from ‘Table 27’, that, the test-material/specimen with the highest Water/Cement (w/c) ratio had the lowest Average Compressive-strength and vice versa. The understated instances below buttress this point:

I. At a Curing-age of 28 days, while the Average Compressive-strengths of ‘Plain Cement Normal Concretes’ increased downward from a minimum value of $34.26\, MPa$ [$PCC_{\text{min}}$ with a maximum w/c ratio = 0.62], through a medial value of $38.73\, MPa$ [$PCC_{\text{opt}}$ with a medial w/c ratio = 0.55] to a maximum value of $35.91\, MPa$ [$PCC_{\text{max}}$ with a minimum w/c ratio = 0.48].

II. At a Curing-age of 28 days, while the Average Compressive-strengths of ‘Portland Slag Special Concretes’ increased downward from a minimum value of $39.98\, MPa$ [$PSC_{\text{min}}$ with a maximum w/c ratio = 0.62], through a medial value of $44.06\, MPa$ [$PSC_{\text{opt}}$ with a medial w/c ratio = 0.48] to a maximum value of $49.84\, MPa$ [$PSC_{\text{max}}$ with a minimum w/c ratio = 0.43].

III. At a Curing-age of 28 days, while the Average Compressive-strengths of ‘Silica-fume Slag Special Concretes’ increased downward from a minimum value of $60.35\, MPa$ [$SSC_{\text{min}}$ with a maximum w/c ratio = 0.55], through a medial value of $64.27\, MPa$ [$SSC_{\text{opt}}$ with a medial w/c ratio = 0.50] to a maximum value of $69.23\, MPa$ [$SSC_{\text{max}}$ with a minimum w/c ratio = 0.43].
SSC\textsubscript{opt} with a medial w/c ratio = 0.43] to a maximum value of 70.10 MPa [SSC\textsubscript{min} with a minimum w/c ratio = 0.38].

These and similar trends observed at other Curing-ages of 56 days and 90 days, clearly prove that the Compressive-strength of Concrete decreases with increasing Water/Cement (w/c) ratio. This may simply be attributed to the fact that the higher the free mixing water-content of Concrete, the higher the porosity of its capillary pore structure and consequently, the lower its Compressive-strength.

Furthermore, it is important to point out here and now, that, apart from the presence (addition) and/or increase of Supplementary Cementitious Material (SCM), Maturity (Curing-age) and Water/Cement (w/c) ratio which are critical parameters (variable) that significantly affect (influence) the Compressive-strength of Concrete—being the most important quality-evaluation property of ‘Concrete’ as an engineering material, some other determining (influence) factors of Concrete’s Compressive-strength include its Curing-type (method), Air-Void system nature (properties) and the Extent (degree/level) of Compaction (Consolidation).

4. Conclusion
Practically, while it has become an established fact in the fields of ‘Material Science & Engineering’ and ‘Construction’ that the ‘Strength of Concrete’ is by far the most important technical characteristic (property) of Concrete, it is also true that the ‘Durability of Concrete’ and the ‘Workability of Concrete’ are two equally important technical characteristics (properties) of Concrete, which together with its strength, collectively define (specify) the ‘Quality of Concrete’. This is because a ‘Strong concrete’ is not necessarily a ‘Durable Concrete’ and/or a ‘highly Workable concrete’. Realizing that the relevance of these three properties—strength, durability & workability of Concrete cannot be over-emphasized, ten (10) Performance-based Quality-evaluation Characterization-tests [i.e. 1 fresh-concrete test (‘Slump/Workability’) and nine hardened-concrete tests comprising of: 5 Thermo-physical tests (‘Specific heat Capacity’, ‘Thermal Diffusivity’, ‘Thermal Conductivity’, ‘Dry Bulk Density’ & ‘Water Sorptivity’); 3 Electrical tests (‘RCPT Total Electric-charge Passed’ with ‘Chloride-ion Penetrability’, ‘Initial 5-minute RCPT Electrical Resistivity’ & ‘Chloride-ion Penetration Depth’) and 1 Mechanical test (‘Average Compressive-strength’)] have been experimentally conducted on nine (9) Concrete test-materials [Comprising of: 3 Normal Concrete specimens and 6 Special Concrete specimens], leading to the following understated experimental conclusions:

I. Concrete Quality [which is collectively defined by its Strength, Durability & Workability] is directly affected (largely determined/greatly influenced) by the Concrete’s Water/Cement (w/c) ratio, but inversely affected (determined/influenced) by its Supplementary Cementitious Material (SCM) content, since:
   (a) The Strength (i.e. Average Compressive-strength) of the tested Concrete specimens/test-materials increased with decreasing w/c ratio, increasing SCM content and increasing maturity (Curing-age) etc.
   (b) The durability (i.e. impermeability/fluid-tightness) of the tested Concrete specimens also increased with decreasing w/c ratio and increasing SCM content.
   (c) The Workability (i.e. the ‘Slump’) of the tested fresh Concrete increased with increasing Cement content, increasing Water/Cement (w/c) ratio, increasing Admixture content and increasing Ground-granulated Blast-furnace slag (GGBFS) content [as an SCM]; but decreased with increasing ‘Aggregate/Cement ratio’ [which is determined from the Concrete’s Mix-ratio], and increasing Silica-fume content [as a SCM]; as is evident from ‘Table 25’ and ‘Table12’.

II. The Specific heat capacity of majority (7 out of 9) of the tested Concrete specimens/test-materials experimentally decreased with increasing Bulk density (SCM content), but increased with increasing maturity (Curing-age).

III. The Thermal diffusivity of the tested Concretes increases with increasing SCM content but decreases with increasing maturity (Curing-age).

IV. The Thermal conductivity of the tested Concrete specimens/test-materials increased with increasing Bulk density in minority of the experimental-cases (one-third ’33.3%’) [i.e. 3 out 9 Concrete specimens]; but decreased with increasing Bulk density in the majority of the experimental-cases (two-thirds ’66.6%’) [i.e. 6 out 9 Concrete specimens]. Also, the Thermal conductivity of all tested Concrete specimens increased with increasing maturity (Curing-age). It should be noted that ‘High Thermal conductivity Concrete’ has the advantage of accommodating a lower ‘Temperature gradient’, when compared with that of a ‘Low Thermal conductivity Concrete’. 
However, when the concept of ‘Thermal insulation of building structures’ is considered a matter of interest, the latter (‘Low Thermal conductivity Concrete’) performs better.

V. The Bulk density (‘Dry Bulk density’) increased with increasing SMC content and increasing maturity (Curing-age).

VI. The Water sorptivity (‘Initial Water sorptivity’ and ‘Secondary Water sorptivity’) of the tested Concrete specimens decreased with decreasing w/c ratio, increasing SCM content and increasing maturity (Curing-age).

VII. The ‘RCPT Total Electric-charge passed’ of the tested Concrete specimens decreased with increasing SCM content and increasing maturity (Curing-age).

VIII. The Chloride-ion penetrability of the tested concrete specimens generally (oftentimes) decreased with increasing maturity (Curing-age), decreasing w/c ratio and increasing SCM content.

IX. The ‘Initial 5-minute RCPT Electrical Resistivity’ of the tested Concrete specimens increased with increasing SCM content and decreasing w/c ratio.

X. The ‘Chloride-ion penetration depth’ of the tested Concrete specimens [which depends on the Concrete’s pore structure, and not its pore solution,] decreased with increasing SCM content [particularly the ‘Silica-fume’ content] but increased with increasing w/c ratio.

XI. The ‘Non-steady-state Migration Coefficient’ of the tested Concrete specimens [which is a function of their respective Chloride-ion penetration depths] increases with increasing w/c ratio but decreases with increasing SCM content and increasing Curing-age.

The Average Compressive-strength of the tested Concrete specimens increased with increasing SCM content and increasing maturity (Curing-age); but decreased with increasing w/c ratio—because a lower w/c ratio implies that there is a lower free-mixing water content leading to a lesser porosity of the concrete’s capillary pore structure, which in turn results in a higher Compressive-strength.

Acknowledgements

The authors will remain eternally indebted to GOD almighty, by whose grace, mercy and favour, it has become possible to contribute this considerable chunk of science-based empirical-research findings to the existing body of knowledge globally. Furthermore, time and space will fail us to mention every one of the numerous persons who have contributed in one way or the other to see that we had a smooth sail while attempting to achieve this herculean research feat. Moreover, some corporate bodies stand-out, as being worthy of mention in our crowded hall-of-fame, they are: the management and staff of ‘Hafalix Nigeria Limited (Engineering, Construction, Maritime & Logistics), Lagos, Nigeria’; ‘Redsav Limited, Lagos, Nigeria’; and ‘Cintojon Company Limited, Ota-Lagos, Nigeria’—sincerely we cannot thank you enough. Finally, this success story is incomplete without resounding thunderous ovations for several organizational contributors such as the American Society for Testing and Materials (ASTM), the American Concrete Institute (ACI) and the British Standards Institute (BSI)—the global relevance and timelessness of your Works/Standards have continued to speak volumes as some of the most profound documented fundamental contributions that drive (turn the wheel of) R&D (Research & Development) around the world.
Table 5: Concrete-mix Design summary for ‘Maximally-mixed Normal Cement Concrete ($PC_{max}$)* with w/c of 0.62

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|--------------------------------|--------------------------------|
| 1.    | Volume of Batch (m$^3$), (L)   | 1, 1000                        |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength [$f_{min}$] (MPa) | 20                             |
| 3.    | 28-day Required (Target) mean Compressive Strength [$f_{m}$] (MPa) | 25                             |
| 4.    | Expected Field-application Exposure-type | Mild                           |
| 5.    | Specific gravity (without units) |                                 |
| 6.    | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630                          |
| 7.    | Coarse Aggregate (20mm Quarried Granite Chippings) | 2.650                          |
| 8.    | Ordinary Portland Cement (OPC) | 3.134                          |
| 9.    | Silica-fume Blended Cement (SFBC) | -                              |
| 10.   | Ground granulated Blast furnace Slag (GGBFS) | -                              |
| 11.   | Nominal maximum size of Coarse Aggregate (mm) | 20                             |
| 12.   | Recommended (Target) Slump (mm) | 80-100                         |
| 13.   | Free water-Cement/Cementitious material ratio (w/c) | 0.62                           |
| 14.   | Water Content (Demand) per unit volume of Concrete (Kg/m$^3$) | 194                            |
| 15.   | Approximate entrapped Air Content (%) | 2                              |
| 16.   | Cement Content per unit volume of Concrete (Kg/m$^3$) | 323                            |
| 17.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m$^3$) | -                              |
| 18.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m$^3$) | -                              |
| 19.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m$^3$) | 812                            |
| 20.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m$^3$) | 982                            |
| 21.   | Calculated Concrete-yield (m$^3$), (L) | 0.976, 976                     |
| 22.   | Net Volume of to-be prepared Concrete-mix (m$^3$), (L) | 0.057, 57                      |
| 23.   | Actual Volume of prepared Concrete-mix (m$^3$), (L) | 0.100, 100                     |
Table 6: Concrete-mix Design summary for ‘Optimally-mixed Normal Cement Concrete ($PCC_{opt}$)’, with w/c of 0.55

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|-------------------------------|--------------------------------|
| 1.    | Volume of Batch (m$^3$), (L)  | 1                              |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength [ $f_{ceu}$ ] (MPa) | 25                             |
| 3.    | 28-day Required (Target) mean Compressive Strength [ $f_{ct}$ ] (MPa)  | 30                             |
| 4.    | Expected Field-application Exposure-type | Mild                           |
| 5.    | Specific gravity (without units) |                                |
|       | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630                          |
|       | Coarse Aggregate (20mm Quarried Granite Chippings) | 2.650                          |
|       | Ordinary Portland Cement (OPC) | 3.134                          |
|       | Supplementary Cementitious Material (SCM) |                              |
|       | Silica-fume Blended Cement (SFBC) | -                             |
|       | Ground granulated Blast furnace Slag (GGBFS) | -                             |
| 6.    | Nominal maximum size of Coarse Aggregate (mm) | 20                             |
| 7.    | Recommended (Target) Slump (mm) | 80-100                        |
| 8.    | Free water-Cement/Cementitious material ratio (w/c) | 0.55                          |
| 9.    | Water Content (Demand) per unit volume of Concrete (Kg/m$^3$) | 195                           |
| 10.   | Approximate entrapped Air Content (%) | 2                             |
| 11.   | Cement Content per unit volume of Concrete (Kg/m$^3$) | 364                           |
| 12.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m$^3$) | -                            |
| 13.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m$^3$) | -                            |
| 14.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m$^3$) | 776                           |
| 15.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m$^3$) | 982                           |
| 16.   | Calculated Concrete-yield (m$^3$), (L) | 0.977, 977                    |
| 17.   | Net Volume of to-be prepared Concrete-mix (m$^3$), (L) | 0.057, 57                     |
| 18.   | Actual Volume of prepared Concrete-mix (m$^3$), (L) | 0.100, 100                    |
Table 7: Concrete-mix Design summary for ‘Maximally-mixed Normal Cement Concrete (\(PCC_{\text{min}}\))’ with w/c of 0.62

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|--------------------------------|-------------------------------|
| 1.    | Volume of Batch (m³), (L)     | 1, 1000                       |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength [\(f_{\text{cm}}\)] (MPa) | 30                             |
| 3.    | 28-day Required (Target) mean Compressive Strength [\(f_{\text{m}}\)] (MPa) | 35                             |
| 4.    | Expected Field-application Exposure-type | Mild                          |
| 5.    | Specific gravity (without units) |                              |
|       | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630                         |
|       | Coarse Aggregate (20mm Quarried Granite Chippings) | 2.650                         |
|       | Ordinary Portland Cement (OPC) | 3.134                         |
|       | Silica-fume Blended Cement (SFBC) | -                             |
|       | Ground granulated Blast furnace Slag (GGBFS) | -                             |
| 6.    | Nominal maximum size of Coarse Aggregate (mm) | 20                            |
| 7.    | Recommended (Target) Slump (mm) | 80-100                        |
| 8.    | Free water-Cement/Cementitious material ratio (w/c) | 0.48                          |
| 9.    | Water Content (Demand) per unit volume of Concrete (Kg/m³) | 196                           |
| 10.   | Approximate entrapped Air Content (%) | 2                             |
| 11.   | Cement Content per unit volume of Concrete (Kg/m³) | 417                           |
| 12.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m³) | -                             |
| 13.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m³) | -                             |
| 14.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m³) | 732                           |
| 15.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m³) | 982                           |
| 16.   | Calculated Concrete-yield (m³), (L) | 0.978, 978                    |
| 17.   | Net Volume of to-be prepared Concrete-mix (m³), (L) | 0.057, 57                     |
| 18.   | Actual Volume of prepared Concrete-mix (m³), (L) | 0.100, 100                    |
Table 8: Concrete-mix Design summary for ‘Minimally-mixed Portland Slag Concrete (\(PSC_{\text{max}}\))’ with w/c of 0.62

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|--------------------------------|-------------------------------|
| 1.    | Volume of Batch (m³), (L)      | 1, 1000                       |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength \([f_{c_{\text{m}}}]\) (MPa) | 20                             |
| 3.    | 28-day Required (Target) mean Compressive Strength \([f_{c_{\text{m}}}]\) (MPa) | 25                             |
| 4.    | Expected Field-application Exposure-type | Medium                     |
| 5.    | Specific gravity (without units) |                                |
|       | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630                       |
|       | Coarse Aggregate (20mm Quarried Granite Chippings) | 2.650                       |
|       | Ordinary Portland Cement (OPC) | 3.134                       |
|       | Silica-fume Blended Cement (SFBC) | -                           |
|       | Ground granulated Blast furnace Slag (GGBFS) | 2.854                       |
| 6.    | Nominal maximum size of Coarse Aggregate (mm) | 20                           |
| 7.    | Recommended (Target) Slump (mm) | 80-100                       |
| 8.    | Free water-Cement/Cementitious material ratio (w/c) | 0.62                      |
| 9.    | Water Content (Demand) per unit volume of Concrete (Kg/m³) | 193                        |
| 10.   | Approximate entrapped Air Content (%) | 2                           |
| 11.   | Cement Content per unit volume of Concrete (Kg/m³) | 242                        |
| 12.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m³) | -                        |
| 13.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m³) | 81                        |
| 14.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m³) | 886                        |
| 15.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m³) | 982                        |
| 16.   | Calculated Concrete-yield (m³), (L) | 0.980, 980                  |
| 17.   | Net Volume of to-be prepared Concrete-mix (m³), (L) | 0.057, 57                   |
| 18.   | Actual Volume of prepared Concrete-mix (m³), (L) | 0.100, 100                  |
### Table 9: Concrete-mix Design summary for ‘Minimally-mixed Portland Slag Concrete (PSC\textsubscript{opt})’ with w/c of 0.48

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|--------------------------------|-------------------------------|
| 1.    | Volume of Batch (m\(^3\), (L)) | 1, 1000                       |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength \( f_{\text{min}} \) (MPa) | 30                           |
| 3.    | 28-day Required (Target) mean Compressive Strength \( f_{\text{m}} \) (MPa) | 35                           |
| 4.    | Expected Field-application Exposure-type | Medium                      |
| 5.    | Specific gravity (without units) |                              |
|       | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630                        |
|       | Coarse Aggregate (20mm Quarried Granite Chippings) | 2.650                        |
|       | Ordinary Portland Cement (OPC) | 3.134                        |
|       | Supplementary Cementitious Material (SCM) |                              |
|       | Silica-fume Blended Cement (SFBC) | -                            |
|       | Ground granulated Blast furnace Slag (GGBFS) | 2.854                        |
| 6.    | Nominal maximum size of Coarse Aggregate (mm) | 20                           |
| 7.    | Recommended (Target) Slump (mm) | 80-100                       |
| 8.    | Free water-Cement/Cementitious material ratio (w/c) | 0.48                         |
| 9.    | Water Content (Demand) per unit volume of Concrete (Kg/m\(^3\)) | 196                          |
| 10.   | Approximate entrapped Air Content (%) | 2                            |
| 11.   | Cement Content per unit volume of Concrete (Kg/m\(^3\)) | 313                          |
| 12.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m\(^3\)) | -                            |
| 13.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m\(^3\)) | 104                          |
| 14.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m\(^3\)) | 723                          |
| 15.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m\(^3\)) | 982                          |
| 16.   | Calculated Concrete-yield (m\(^3\), (L)) | 0.978, 978                   |
| 17.   | Net Volume of to-be prepared Concrete-mix (m\(^3\), (L)) | 0.057, 57                    |
| 18.   | Actual Volume of prepared Concrete-mix (m\(^3\), (L)) | 0.100, 100                   |
Table 10: Concrete-mix Design summary for ‘Minimally-mixed Portland Slag Concrete ($PSC_{\text{min}}$)’ with w/c of 0.43

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|--------------------------------|--------------------------------|
| 1.    | Volume of Batch (m$^3$), (L)   | 1, 1000                        |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength [$f_{\text{cm}}$] (MPa) | 35                             |
| 3.    | 28-day Required (Target) mean Compressive Strength [$f_{\text{c}}$] (MPa) | 40                             |

4. Expected Field-application Exposure-type

| Specific gravity (without units) | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630 |
|----------------------------------|-----------------------------------------------------|-------|
|                                  | Coarse Aggregate (20mm Quarried Granite Chippings)  | 2.650 |

| Ordinary Portland Cement (OPC) | 3.134 |
|--------------------------------|-------|

5. Supplementary Cementitious Material (SCM)

| Silica-fume Blended Cement (SFBC) | - |
|-----------------------------------|---|
| Ground granulated Blast furnace Slag (GGBFS) | 2.854 |

6. Nominal maximum size of Coarse Aggregate (mm)

7. Recommended (Target) Slump (mm)

8. Free water-Cement/Cementitious material ratio (w/c)

9. Water Content (Demand) per unit volume of Concrete (Kg/m$^3$)

10. Approximate entrapped Air Content (%) 2

11. Cement Content per unit volume of Concrete (Kg/m$^3$) 349

12. Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m$^3$) -

13. Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m$^3$) 116

14. Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m$^3$) 680

15. Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m$^3$) 982

16. Calculated Concrete-yield (m$^3$), (L) 0.978, 978

17. Net Volume of to-be prepared Concrete-mix (m$^3$), (L) 0.057, 57

18. Actual Volume of prepared Concrete-mix (m$^3$), (L) 0.100, 100
| S/No. | Mix Proportions/Mix Properties                                                                 | Batch-Quantity, level (degree) |
|-------|-----------------------------------------------------------------------------------------------|-------------------------------|
| 1.    | Volume of Batch (m³), (L)                                                                     | 1, 1000                       |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength \( f_{\text{min}} \) (MPa)               | 25                            |
| 3.    | 28-day Required (Target) mean Compressive Strength \( f_{\text{e}} \) (MPa)                  | 30                            |
| 4.    | Expected Field-application Exposure-type                                                      | Severe                        |
| 5.    | Specific gravity (without units)                                                             |                               |
|       | Fine Aggregates (Natural Siliceous River-bank Sand)                                          | 2.630                         |
|       | Coarse Aggregate (20mm Quarried Granite Chippings)                                           | 2.650                         |
|       | Ordinary Portland Cement (OPC)                                                               | 3.134                         |
|       | Supplementary Cementitious Material (SCM)                                                    |                               |
|       | Silica-fume Blended Cement (SFBC)                                                            | 3.080                         |
|       | Ground granulated Blast furnace Slag (GGBFS)                                                 | 2.854                         |
| 6.    | Nominal maximum size of Coarse Aggregate (mm)                                                | 20                            |
| 7.    | Recommended (Target) Slump (mm)                                                              | 80-100                        |
| 8.    | Free water-Cement/Cementitious material ratio (w/c)                                           | 0.55                          |
| 9.    | Water Content (Demand) per unit volume of Concrete (Kg/m³)                                  | 195                           |
| 10.   | Approximate entrapped Air Content (%)                                                        | 2                             |
| 11.   | Cement Content per unit volume of Concrete (Kg/m³)                                           | 244                           |
| 12.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m³)                | 29                            |
| 13.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m³)     | 91                            |
| 14.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m³)                               | 754                           |
| 15.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m³)                             | 982                           |
| 16.   | Calculated Concrete-yield (m³), (L)                                                          | 0.971, 971                    |
| 17.   | Net Volume of to-be prepared Concrete-mix (m³), (L)                                          | 0.057, 57                     |
| 18.   | Actual Volume of prepared Concrete-mix (m³), (L)                                             | 0.100, 100                    |
Table 12: Concrete-mix Design summary for ‘Maximally-mixed Silica-fume Slag Concrete ($SSC_{opt}$)’ with w/c of 0.43

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|-------------------------------|--------------------------------|
| 1.    | Volume of Batch (m$^3$), (L)  | 1, 1000                        |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength [$f_{cm}$] (MPa) | 35 |
| 3.    | 28-day Required (Target) mean Compressive Strength [$f_c$] (MPa) | 40 |
| 4.    | Expected Field-application Exposure-type | Severe |
| 5.    | Specific gravity (without units) |                           |
|       | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630 |
|       | Coarse Aggregate (20mm Quarried Granite Chippings) | 2.650 |
|       | Ordinary Portland Cement (OPC) | 3.134 |
|       | Silica-fume Blended Cement (SFBC) | 3.080 |
|       | Ground granulated Blast furnace Slag (GGBFS) | 2.854 |
| 6.    | Nominal maximum size of Coarse Aggregate (mm) | 20 |
| 7.    | Recommended (Target) Slump (mm) | 80-100 |
| 8.    | Free water-Cement/Cementitious material ratio (w/c) | 0.43 |
| 9.    | Water Content (Demand) per unit volume of Concrete (Kg/m$^3$) | 197 |
| 10.   | Approximate entrapped Air Content (%) | 2 |
| 11.   | Cement Content per unit volume of Concrete (Kg/m$^3$) | 312 |
| 12.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m$^3$) | 37 |
| 13.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m$^3$) | 116 |
| 14.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m$^3$) | 680 |
| 15.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m$^3$) | 982 |
| 16.   | Calculated Concrete-yield (m$^3$), (L) | 0.978, 978 |
| 17.   | Net Volume of to-be prepared Concrete-mix (m$^3$), (L) | 0.057, 57 |
| 18.   | Actual Volume of prepared Concrete-mix (m$^3$), (L) | 0.100, 100 |
Table 13: Concrete-mix Design summary for ‘Maximally-mixed Silica-fume Slag Concrete (SSC$_{\text{min}}$) with w/c of 0.38

| S/No. | Mix Proportions/Mix Properties | Batch-Quantity, level (degree) |
|-------|--------------------------------|-------------------------------|
| 1.    | Volume of Batch (m$^3$), (L)   | 1, 1000                       |
| 2.    | 28-day Characteristic (Minimum) Compressive Strength [$f_{\text{m}}$] (MPa) | 40 |
| 3.    | 28-day Required (Target) mean Compressive Strength [$f_{\text{c}}$] (MPa) | 45 |
| 4.    | Expected Field-application Exposure-type | Severe |
| 5.    | Specific gravity (without units) |                             |
|       | Fine Aggregates (Natural Siliceous River-bank Sand) | 2.630 |
|       | Coarse Aggregate (20mm Quarried Granite Chippings) | 2.650 |
|       | Ordinary Portland Cement (OPC) | 3.134 |
|       | Silica-fume Blended Cement (SFBC) | 3.080 |
|       | Ground granulated Blast furnace Slag (GGBFS) | 2.854 |
| 6.    | Nominal maximum size of Coarse Aggregate (mm) | 20 |
| 7.    | Recommended (Target) Slump (mm) | 80-100 |
| 8.    | Free water-Cement/Cementitious material ratio (w/c) | 0.38 |
| 9.    | Water Content (Demand) per unit volume of Concrete (Kg/m$^3$) | 198 |
| 10.   | Approximate entrapped Air Content (%) | 2 |
| 11.   | Cement Content per unit volume of Concrete (Kg/m$^3$) | 353 |
| 12.   | Silica-fume Blended Cement (SFBC) Content per unit volume of Concrete (Kg/m$^3$) | 42 |
| 13.   | Ground granulated Blast furnace Slag (GGBFS) Content per unit volume of Concrete (Kg/m$^3$) | 132 |
| 14.   | Wet Mass of Fine Aggregate per unit volume of Concrete (Kg/m$^3$) | 626 |
| 15.   | Wet Mass of Coarse Aggregate per unit volume of Concrete (Kg/m$^3$) | 982 |
| 16.   | Calculated Concrete-yield (m$^3$), (L) | 0.979, 979 |
| 17.   | Net Volume of to-be prepared Concrete-mix (m$^3$), (L) | 0.057, 57 |
| 18.   | Actual Volume of prepared Concrete-mix (m$^3$), (L) | 0.100, 100 |
References

[1] Ibhadode, O.; Bello, T.; Asuquo, A. E.; Idris, F. W.; Okougha, F. A.; Umanah, I. I.; Ugonna, M. C.; and Nwaigwe, D. N. (2017). Comparative-study of Compressive-strengths and densities of concrete produced with different brands of ordinary Portland cement in Nigeria. *International Journal of Scientific & Engineering Research*, 8(9): pp. 1260–1275. [https://www.ijser.org/onlineResearchPaperViewer.aspx](https://www.ijser.org/onlineResearchPaperViewer.aspx)

[2] Eseigbe, A. P.; Ibhadode, O.; Ayoola, A. R.; Sosanolu, O. M. (2018). An Experimental Determination of Drinking Water Quality in Abeokuta Metropolis, South-western Nigeria. *International Journal of Advances in Scientific Research and Engineering*, 4(12): pp. 241–256. DOI: 10.31695/IJASRE.2018.33035

[3] Damme, H. V. (2018). Concrete material science: Past, present, and future innovations. *Cement and Concrete Research*, Elsevier, vol. 112(1): pp. 5-24, DOI: [http://www.concretehelper.com/concrete-facts](http://www.concretehelper.com/concrete-facts), on 7th January 2013, 04:30am.

[4] Busari, A.; Akinmusuru, J.; Dahunsi, B. (2019). Strength and Durability Properties of Concrete Using Metakaolin as a Sustainable Material: Review of Literatures. *International Journal of Civil Engineering and Technology*, 10(1): pp. 1893-1902, DOI: [http://www.ermco.eu/publications/statistics](http://www.ermco.eu/publications/statistics), on 23rd March 2017, 08:00am.

[5] Neville, A. M. and Brooks, J. J. (2010). Concrete Technology, Pearson Educational Limited, 2nd ed., pp.1-189

[6] [Caltrans—California Department of Transportation (2015). Concrete Design Technology. *Bridge Design Practice: February 2015*, Retrieved online from [www.dot.ca.gov/des/techpubs/manuals/bridge-design-practice/page/bdp-5.pdf](http://www.dot.ca.gov/des/techpubs/manuals/bridge-design-practice/page/bdp-5.pdf), on 28th February 2015, 03:15am](http://www.dot.ca.gov/des/techpubs/manuals/bridge-design-practice/page/bdp-5.pdf)

[7] ASTM C136 / C136M -14: 2014 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp.1-8, DOI: 10.1520/C0136_C0136M-14
[14] ASTM C33 / C33M -18: 2018 Standard Specification for Concrete Aggregates, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp.1-8, DOI: 10.1520/C0033_C0033M-18

[15] BS 812-110: 1990 Method for determination of Aggregate crushing value, London, UK, pp. 1-2.

[16] BS 812-112: 1990 Method for determination of Aggregate impact value, London, UK, pp. 1-2.

[17] ACI 211.1-91: 1991 Standard Practice for Selecting Proportions for Normal, Heavy weight and Mass Concrete, American Concrete Institute, Michigan, USA, pp. 1-38 https://www.scribd.com/document/81595615/ACI-211-1

[18] BS EN 206-1:2000 Concrete: Specification, performance, production and conformity, British Standards Institute-European Ready-Mix Concrete Organization, London, UK, pp. 1-66, https://www.scribd.com/doc/52640170/readymix-concrete-BS-EN-206-1

[19] ASTM C138 / C138M – 17a: 2017 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp. 1-6, DOI: 10.1520/C0138_C0138M-17A

[20] Calculate Quantities of Materials for Concrete-Cement, Sand aggregates, Retrieved online from https://theconstructor.org/concrete/calculate-quantities-of-materials-for-concrete/10700/, on 21st April 2019, 06:00pm.

[21] How to Estimate Yield of Concrete for Volume batching, Retrieved online from https://civilblog.org/2015/08/12/how-to-estimate-yield-of-concrete-for-volume-batching/, on 21st April 2019, 06:30pm.

[22] ASTM C494 / C494M – 17: 2017 Standard Specification for Chemical Admixtures for Concrete, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp. 1-10, DOI: 10.1520/C0494_C0494M-17

[23] ASTM C127 - 15: 2015 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp. 1-5, DOI: 10.1520/C0127-15

[24] ASTM C128 - 15: 2015 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp. 1-6, DOI: 10.1520/C0128-15

[25] ASTM C143 / C143M - 15a: 2015, Standard Test Method for Slump of Hydraulic-Cement Concrete, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp. 1-4, DOI: 10.1520/C0143_C0143M-15A

[26] ASTM C192 / C192M - 18: 2018, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp. 1-4, DOI: 10.1520/C0192_C0192M-18

[27] ACI Guide 304R-89: 1989 Guide for Measuring, Mixing, Transporting and Placing Concrete, American Concrete Institute, Michigan, USA, pp. 1-54, https://www.scribd.com/.../ACI-304R-89-Guide-for-Measuring-Mixing-Transporting-...
[28] Salmon, D. R. (2001) Thermal conductivity of insulations using guarded hot plates, including recent developments and sources of reference materials. *Measurement Science and Technology*, IOP Publishing Ltd, Meas. Sci. Technol. 12 (2001) R89–R98, stacks.iop.org/MST/12/R89

[29] ASTM C 236 – 89: 1989 *Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box*, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp.1-12, DOI: 10.1520/C0236-89R93E01

[30] ACI-122R-02: 2002 *Guide to Thermal Properties of Concrete and Masonry Systems*, American Concrete Institute, Michigan, USA, pp. 1-21, https://www.scribd.com/document/392385374/ACI-122R-02

[31] Fuchs, S.; Balling, N.; Forster, A. (2015) Calculation of thermal conductivity, thermal diffusivity and specific heat capacity of sedimentary rocks using petrophysical well logs. *Geophysical Journal International*, Geophys. J. Int. 203, pp. 1977–2000. DOI: 10.1093/gji/ggv403

[32] Thermal Diffusivity, Internet document Retrieved online from https://en.wikipedia.org/wiki/Thermal_diffusivity, on 5th June 2019, 02:00am.

[33] ASTM C 642 – 13: 2013 *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp.1-3, DOI: 10.1520/C0642-13

[34] Sicakova, A.; Draganovska, M.; Kovac, M. (2017) Water absorption coefficient as a performance characteristic of building mixes containing fine particles of selected recycled materials. International High-Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016, *Procedia Engineering* 180, Elsevier, pp. 1256 – 1265, DOI: 10.1016/j.proeng.2017.04.287

[35] Parrott L. J. (1994) Moisture Conditioning and Transport Properties of Concrete Test Specimens, *Materials and Structures*, 27(8), pp. 460-468, DOI: 10.1007/BF02473450

[36] DeSouza, S.; Hooton, R.; Bickley, J. (1997) Evaluation of Laboratory Drying Procedures Relevant to Field Conditions for Concrete Sorptivity Measurements. *Cement, Concrete and Aggregates*, 19(2), ISSN 0149-6123, pp. 59-63, https://doi.org/10.1520/CCA10315J.

[37] ASTM C 1585 – 04: 2004 *Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes*, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp.1-6, DOI: 10.1520/C1585-04

[38] Philip, J. R. (1957). The Theory of Infiltration: Four Sorptivity and Algebraic Infiltration Equations. *Soil Science*, 84(1): pp. 257–264. DOI: 10.1097/00010694-195709000-00010

[39] Nokken, M. R. and Hooton R. D. (2002) Dependence of Rate of Absorption on Degree of Saturation of Concrete. *Cement, Concrete, and Aggregates*, 24(1), pp. 20-24, https://www.researchgate.net/publication/285727506

[40] ASTM C1202 - 19: 2019 *Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration*, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp.1-8, DOI: 10.1520/C1202-19
[41] Whiting, D. (1981) Rapid Determination of the Chloride Permeability of Concrete, *Final Report No. FHWA/RD-81/119*, Federal Highway Administration, USA, NTIS No. PB 82140724.

[42] Whiting, D. (1988) Permeability of Selected Concretes, *Permeability of Concrete*, SP-108, American Concrete Institute, Detroit, Michigan, pp. 195–222.

[43] ASTM C39 / C39M - 18: 2018 *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, American Society for Testing and Materials international, West Conshohocken, Philadelphia, USA, pp.1-8, DOI: 10.1520/C0039_C0039M-18