## PROJECT No – CON 16

# Fresh, Hardened and Durability Performance Evaluation of Concrete made with PLC

Date of Commencement :April 2019
Target Date of Completion :March 2021


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# Project Background

- CON-16 is an extension of study carried on PLC in the COB 07 (2018) in which investigations on performance characteristics of PLC compositions using **one clinker and three grade of limestone (cement, low & dolomitic grade)** were carried out. The investigations indicated that compressive strength equivalent to OPC 43 grade could be achieved by addition of up to 15% of low, cement and dolomitic grade limestone in PLC.
- Based on the findings of the project, it was decided in RAC , to take up a comprehensive study on PLC covering material variation of clinker and limestone from different regions of the country. It was also decided to carry our fresh, hardened and durability performance evaluation of concrete made with PLC at 15% replacement along with study on PLC compositions by varying limestone from 0-30%.
- As a result CON-16 project commenced in April 2019.

# Assured End Product

Use of limestone of low grade and dolomitic limestone for manufacturing of Portland Limestone Cement and its application in production of durable concrete

# Expected benefits

- Reduction in Clinker Content
- Energy & natural resources conservation
- Waste utilization
- Reduced emission of GHG

# Objectives of the Project

- To produce Portland Limestone Cement (PLC) blends using OPC clinker, limestone (cement, low grade and dolomitic grade) and gypsum by **intergrinding** (varying the quantity of limestone from **0-30%)**
- To carry performance evaluation of PLC blends (0-30%) on the basis of chemical composition, physical properties, calorimetry and XRD **(to verify the conclusion of % addition of limestone in earlier work)**
- To carry out fresh, hardened and durability performance evaluation of concrete made with PLC with 15% replacement by limestone **(for conclusion about application of PLC)**
- **To draw recommendations for specifications of Portland Limestone Cement**

# Material Procurement

5 different clinker and 8 different limestone samples were obtained from different cement plants of the country. The details are given below

| Sl. No | Cement Plant | Location | Material | Terminology | |
|---|---|---|---|---|---|
| | | | | Clinker | LS |
| **Plant 1** | Nirma Cements Limited | District Pali, Rajasthan | Clinker, Limestone and Gypsum | **C1** | **L1, L2** |
| **Plant 2** | Ambuja Cements Limited | Bhatapara, Raipur, Chhattisgarh | Clinker, Limestone and Gypsum | **C2** | **L3, L4** |
| **Plant 3** | Ambuja Cements Limited | Rabariyawas, District Pali, Rajasthan | Clinker, Limestone and Gypsum | **C3** | **L5, L6** |
| **Plant 4** | My Home Industries Pvt. Ltd. | Mella Chervu, Telangana | Clinker, Limestone and Gypsum | **C4** | **L7** |
| **Plant 5** | UltraTech, Gujarat Cements | Kovaya, District Amreli, Gujarat | Clinker, Limestone and Gypsum | **C5** | **L8** |

# CLINKER CHARACTERIZATION

# Clinker – Chemical Composition

| Test Parameter | Plant 1 | Plant 2 | Plant 3 | Plant 4 | Plant 5 | Range |
|---|---|---|---|---|---|---|
| Loss on Ignition% | 0.42 | 0.68 | 0.95 | 0.86 | 1.35 | 0.42-1.35 |
| Silica ($SiO_2$)% | 20.63 | 20.82 | 21.42 | 21.49 | 21.01 | 20.63-21.49 |
| Iron oxide ($Fe_2O_3$)% | 4.34 | 3.63 | 3.68 | 3.45 | 4.38 | 3.45-4.38 |
| Alumina ($Al_2O_3$)% | 5.49 | 5.29 | 5.13 | 5.30 | 6.22 | 5.13-6.22 |
| Calcium oxide (CaO)% | 62.70 | 63.87 | 63.96 | 65.20 | 63.90 | 62.70-65.20 |
| Magnesium oxide (MgO)% | 3.62 | 1.93 | 1.76 | 2.24 | 0.74 | 0.74-3.62 |
| Sulphur Anhydride ($SO_3$)% | 1.62 | 1.41 | 1.05 | 0.31 | 1.45 | 0.31-1.62 |
| Insoluble Residue | 0.32 | 0.90 | 0.12 | 1.2 | 0.65 | 0.12-1.2 |
| $Na_2O$% | 0.18 | 0.36 | 0.59 | 0.21 | 0.16 | 0.16-0.59 |
| $K_2O$% | 0.22 | 1.29 | 0.96 | 0.53 | 0.33 | 0.22-1.29 |
| $Na_2O$% Equivalent | 0.32 | 1.21 | 1.22 | 0.56 | 0.38 | 0.32-1.22 |
| Chloride % | 0.057 | 0.031 | 0.019 | 0.015 | 0.022 | 0.015-0.057 |
| Free Lime | 1.09 | 1.22 | 1.41 | 1.50 | 1.38 | 1.09-1.50 |
| Lime saturation factor (LSF) | 0.92 | 0.94 | 0.92 | 0.95 | 0.91 | 0.92-0.95 |
| Silica Ratio (SR) | 2.10 | 2.33 | 2.43 | 2.46 | 1.98 | 1.98-2.46 |
| Alumina to Iron Oxide Ratio | 1.26 | 1.46 | 1.39 | 1.54 | 1.42 | 1.26-1.54 |
| $C_3A$ | 7.29 | 7.95 | 7.44 | 8.28 | 9.16 | 7.29-9.16 |
| $C_4AF$ | 13.21 | 11.05 | 11.20 | 10.50 | 13.33 | 11.05-13.33 |
| $C_3S$ | 50.70 | 56.97 | 54.81 | 60.62 | 48.22 | 48.22-60.62 |
| $C_2S$ | 21.18 | 17.02 | 20.37 | 16.21 | 24.14 | 16.21-24.14 |
| $C_3S + C_2S$ | 71.88 | 74.00 | 75.18 | 76.83 | 72.35 | 71.88-76.83 |
| Grindability, kwh/Ton | 14.00 | 13.00 | 13.10 | 11.70 | 15.10 | 13-15.1 |

# Clinker - Phases

Clinker Phases were quantified using three methods – Bogues Equations, XRD and Optical Microscopy (OM)

| Plant Name | Using Bogue Calculation | | | | Using XRD | | | | Using OM | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $C_3S$ | $C_2S$ | $C_3A$ | $C_4AF$ | $C_3S$ | $C_2S$ | $C_3A$ | $C_4AF$ | $C_3S$ | $C_2S$ | $C_3A$ +C4AF |
| Plant 1 Nirma Pali Rajasthan | 50.70 | 21.18 | 7.29 | 13.21 | 45.00 | 31.50 | 3.50 | 13.00 | 54.00 | 31.00 | 15.00 |
| Plant 2 Ambuja Bhatapara | 56.97 | 17.02 | 7.95 | 11.05 | 58.00 | 19.80 | 7.20 | 11.10 | 57.00 | 21.00 | 22.00 |
| Plant 3 Ambuja Rabariyawas | 54.81 | 20.37 | 7.44 | 11.20 | 54.00 | 25.50 | 7.40 | 9.70 | 53.00 | 31.00 | 16.00 |
| Plant 4 My Home Telangana | 60.62 | 16.21 | 8.28 | 10.50 | 57.00 | 21.00 | 8.00 | 11.50 | 54.00 | 28.00 | 18.00 |
| Plant 5 Ultratech Cements Gujrat | 48.22 | 24.14 | 9.16 | 13.33 | 51.00 | 26.50 | 3.50 | 13.00 | 48.00 | 32.00 | 20.00 |

# Observations on Chemical Properties of Clinker

- LSF, Alumina to Silica ratio, $C_3S$, $C_2S$, $C_3S + C_2S$, $SO_3$, Free Lime, Chloride Content, Magnesia and LOI are within the limit for Portland Cement Clinker as per Table-01, IS 16353:2015
- Insoluble Residue is more than the limit of 1.0% for Clinker C4

# LIMESTONE CHARACTERIZATION

# Limestone – Chemical Composition

| Test Parameter | Plant 1 | | Plant 2 | | Plant 3 | | Plant 4 | Plant 5 | Range |
|---|---|---|---|---|---|---|---|---|---|
| | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | |
| LOI% | 35.46 | 40.91 | 36.33 | 38.17 | 23.49 | 46.08 | 33.39 | 36.26 | 23.49-46.08 |
| $SiO_2$% | 16.22 | 6.72 | 11.96 | 8.83 | 31.88 | 12.40 | 21.95 | 12.75 | 6.72-31.88 |
| $Fe_2O_3$% | 1.16 | 0.41 | 1.80 | 1.08 | 3.08 | 0.09 | 0.59 | 2.07 | 0.09-3.08 |
| $Al_2O_3$% | 2.86 | 0.76 | 3.46 | 2.84 | 8.26 | 0.16 | 0.90 | 2.69 | 0.16-8.26 |
| CaO% | 39.30 | 44.83 | 43.20 | 46.37 | 28.74 | 37.79 | 42.30 | 45.10 | 28.74-46.37 |
| MgO% | 4.00 | 5.98 | 1.45 | 1.15 | 1.04 | 15.37 | 0.30 | 0.62 | 0.30-15.37 |
| $SO_3$% | 0.10 | 0.08 | 0.10 | 0.14 | 0.12 | 0.07 | 0.05 | 0.14 | 0.05-0.14 |
| Insoluble Residue | 20.51 | 7.58 | 17.85 | 13.20 | 43.05 | 0.59 | 23.23 | 15.42 | 0.59-43.05 |
| Alkali ($Na_2O$ Equi.) | 0.40 | 0.22 | 0.72 | 0.59 | 2.27 | 0.20 | 0.22 | 0.21 | 0.20-2.27 |
| Chloride % | 0.04 | 0.03 | 0.02 | 0.04 | 0.01 | 0.07 | 0.01 | 0.01 | 0.01-0.07 |
| Grindability, kWhr/T | Fine | 7.00 | 11.80 | 12.00 | 9.20 | 4.10 | 6.80 | 5.70 | 4.10-12.00 |
| $CaCO_3$(%) | 70.18 | 80.05 | 77.14 | 82.80 | 51.32 | 67.48 | 75.54 | 80.54 | 51.32-82.80 |
| Dolomite (%) | 18.40 | 27.51 | 6.67 | 5.29 | 4.78 | 70.70 | 1.38 | 2.85 | 1.38-70.70 |

CaO content varying from 28.74 % ( L5) to 46.37% ((L4)

$CaCO_3$ content varying from 51.32 % ( L5) to 82.80% ((L4)

MgO content varying from 0.30 (L4) to 15.37% (L6)

Grindability varies from 4.1 (L6) to -12 (L4) kWhr/T

# Limestone – Classification

## I. Based on the CaO content

| Category | %CaO | Conventional term used | Limestone classification |
|---|---|---|---|
| I | 48 – 52 | High Grade | - |
| II | 44 – 48 | Cement Grade | L2, L4, L8 |
| III | 40 – 44 | Marginal Grade | L3,L7 |
| IV | 36 – 40 | Low grade | L1, L6 |

NOTE: L5 does not fall under any of the above category since the CaO content is 28.74% only. It is referred to as VERY LOW GRADE limestone in this study

**REF-** "Marginal grade limestone resource Upgradation – A challenge for Indian cement industry", D.K. Panda, S.K. Gotecha & B.S. Roy, NCCBM, 'Mineral Processing Technology' edited by G.V. Rao & Vibhuti N Misra, published from international seminar on mineral processing technology by RRL Bhubaneswar % Indian Institute of Mineral Engineers

## II. Based on the MgO content

| Type | % of Dolomite | Approximate MgO Equivalent | Limestone classification |
|---|---|---|---|
| High calcium limestone | Upto 10* | 0 – 2.1 | L3, L4, L5, L7, L8 |
| Dolomitic limestone | 10 – 50 | 2.1 – 10.8 | L1, L2 |
| Calcic dolomite | 50 – 90 | 10.8 – 19.5 | L6 |
| Dolomite | 90 – 100 | 19.5 – 21.6 | - |

**REF-** Limestone and dolomitic resources of Karnataka book by NR Pattabhi Ramaiah, Geological Survey of India, Bengaluru 2003 (Page No 04)

# Gypsum – Chemical Composition

| S. No | Test Name | Gypsum |
|---|---|---|
| 1 | Loss on Ignition | 0.00 |
| 2 | Combined water | 17.55 |
| 3 | Silica | 0.36 |
| 4 | Silica + Acid Insoluble | 0.00 |
| 5 | Iron oxide | 0.08 |
| 6 | Combined Iron + Alumina | 0.00 |
| 7 | Alumina | 0.05 |
| 8 | Calcium oxide | 30.92 |
| 9 | Magnesium oxide | 1.36 |
| 10 | $SO_3$ | 44.33 |
| 11 | $CaSO_4.2H_2O$ | 95.31 |
| 12 | IR | 2.59 |
| 13 | $Na_2O$ | 0.04 |
| 14 | $K_2O$ | 0.01 |

- Mineral gypsum with 95.31 % purity was used for all PLC blends.

# PLC Blends

- 05 No. of OPC and 48 No of PLC blends were prepared with Limestone content varying from 0-30% using inter grinding method.
- $SO_3$ content was kept less that 3±0.2% and fineness was maintained between 380±20 $m^{2/}kg$.

| Cement Plant | Clinker | LS | PLC Blends | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Plant 1 | C1 | L1 | C1 CTL | C1-L1 5 | C1-L1 10 | C1-L1 15 | C1-L1 20 | C1-L1 25 | C1-L1 30 |
| | | L2 | C1 CTL | C1-L2 5 | C1-L2 10 | C1-L2 15 | C1-L2 20 | C1-L2 25 | C1-L2 30 |
| Plant 2 | C2 | L3 | C2 CTL | C2-L3 5 | C2-L3 10 | C2-L3 15 | C2-L3 20 | C2-L3 25 | C2-L3 30 |
| | | L4 | C2 CTL | C2-L4 5 | C2-L4 10 | C2-L4 15 | C2-L4 20 | C2-L4 25 | C2-L4 30 |
| Plant 3 | C3 | L5 | C3 CTL | C3-L5 5 | C3-L5 10 | C3-L5 15 | C3-L5 20 | C3-L5 25 | C3-L5 30 |
| | | L6 | C3 CTL | C3-L6 5 | C3-L6 10 | C3-L6 15 | C3-L6 20 | C3-L6 25 | C3-L6 30 |
| Plant 4 | C4 | L7 | C4 CTL | C4-L7 5 | C4-L7 10 | C4-L7 15 | C4-L7 20 | C4-L7 25 | C4-L7 30 |
| Plant 5 | C5 | L8 | C5 CTL | C5-L8 5 | C5-L8 10 | C5-L8 15 | C5-L8 20 | C5-L8 25 | C5-L8 30 |

# Chemical Composition of C1-CTL, C1L1 & C1L2

| PLC Blend | LOI | $SiO_2$% | $Fe_2O_3$% | $Al_2O_3$% | CaO% | MgO% | $SO_3$% | IR % | $Na_2O$% | $K_2O$% | Cl% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C1-CTL | 1.03 | 21.29 | 4.15 | 4.93 | 61.37 | 3.25 | 3.11 | 0.41 | 0.13 | 0.15 | 0.084 |
| C1-L1-5 | 3.17 | 19.80 | 4.40 | 4.53 | 61.36 | 3.64 | 2.87 | 2.30 | 0.19 | 0.150 | 0.062 |
| C1-L1-10 | 4.55 | 19.74 | 4.00 | 4.67 | 59.13 | 3.83 | 3.03 | 2.02 | 0.28 | 0.220 | 0.044 |
| C1-L1-15 | 6.57 | 19.85 | 3.65 | 4.81 | 57.29 | 3.90 | 3.02 | 3.48 | 0.03 | 0.250 | 0.057 |
| C1-L1-20 | 7.84 | 19.46 | 3.67 | 4.39 | 57.04 | 3.84 | 2.99 | 3.88 | 0.26 | 0.230 | 0.048 |
| C1-L1-25 | 9.63 | 19.11 | 2.45 | 4.23 | 54.45 | 4.18 | 3.00 | 6.84 | 0.18 | 0.25 | 0.058 |
| C1-L1-30 | 11.48 | 19.24 | 2.73 | 4.76 | 54.66 | 5.05 | 2.98 | 5.94 | 0.17 | 0.22 | 0.058 |
| C1-L2 -5 | 1.52 | 19.62 | 3.92 | 5.01 | 61.49 | 4.33 | 3.31 | 0.68 | 0.20 | 0.19 | 0.075 |
| C1-L2 -10 | 4.93 | 18.44 | 3.90 | 4.26 | 60.66 | 4.04 | 2.93 | 0.91 | 0.19 | 0.160 | 0.071 |
| C1-L2 -15 | 6.52 | 17.74 | 3.75 | 4.01 | 59.72 | 4.30 | 2.95 | 0.98 | 0.16 | 0.260 | 0.069 |
| C1-L2 -20 | 9.24 | 17.19 | 3.59 | 3.97 | 57.84 | 4.99 | 2.98 | 1.53 | 0.16 | 0.150 | 0.057 |
| C1-L2 -25 | 11.88 | 16.59 | 2.48 | 3.97 | 55.35 | 6.10 | 2.97 | 1.9 | 0.08 | 0.09 | 0.059 |
| C1-L2 -30 | 13.84 | 15.03 | 2.36 | 4.06 | 55.63 | 5.20 | 2.97 | 2.05 | 0.16 | 0.16 | 0.056 |

L1 – Low Grade ( Dolomitic limestone )

L2 – Cement Grade ( Dolomitic limestone )

# Physical Properties of of C1-CTL, C1L1 & C1L2

| PLC Blend | NC (%) | Blaine Fineness ($m^2/kg$) | Specific Gravity | Compressive Strength (MPa) | | | | | Soundness Le Chatelier's (mm) | Soundness Autoclave % | Drying Shrinkage (%) | Initial Setting Time (min) | Final Setting Time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 Day | 3 Day | 7 Day | 28 Day | 90 Day | | | | | |
| C1 - CTL | 26.50 | 380 | 3.20 | 28.00 | 43.00 | 55.00 | 70.00 | 74.50 | 1.00 | NA | 0.07 | 60 | 110 |
| C1-L1 - 5 | 27.00 | 383 | 3.16 | 23.00 | 42.00 | 53.00 | 65.00 | 71.00 | 1.00 | 0.2 | 0.07 | 65 | 120 |
| C1-L1 - 10 | 26.00 | 374 | 3.15 | 22.00 | 39.00 | 51.00 | 63.00 | 67.50 | 1.00 | 0.2 | 0.07 | 65 | 120 |
| C1-L1 - 15 | 24.50 | 383 | 3.09 | 19.00 | 33.00 | 44.00 | 55.00 | 64.50 | 1.00 | 0.1 | 0.06 | 90 | 150 |
| C1-L1 - 20 | 24.50 | 362 | 3.06 | 16.00 | 29.00 | 38.00 | 53.00 | 60.00 | 1.00 | 0.09 | 0.05 | 85 | 145 |
| C1-L1 - 25 | 24.60 | 353 | 3.02 | 14.50 | 27.50 | 37.00 | 50.00 | 56.50 | 1.50 | 0.05 | 0.03 | 105 | 155 |
| C1-L1 - 30 | 25.40 | 353 | 3.00 | 11.00 | 26.50 | 35.00 | 47.00 | 52.00 | 1.00 | 0.06 | 0.02 | 110 | 160 |
| C1-L2 - 5 | 26.50 | 387 | 3.20 | 19.00 | 40.50 | 52.50 | 62.00 | 66.00 | 1.00 | NA | 0.06 | 65 | 115 |
| C1-L2 - 10 | 26.50 | 414 | 3.18 | 18.50 | 38.00 | 50.00 | 58.00 | 64.00 | 1.00 | 0.07 | 0.06 | 60 | 115 |
| C1-L2 - 15 | 27.50 | 396 | 3.15 | 15.00 | 31.50 | 42.00 | 55.00 | 63.00 | 1.00 | 0.08 | 0.05 | 55 | 105 |
| C1-L2 - 20 | 26.00 | 390 | 3.10 | 14.00 | 26.50 | 40.00 | 52.00 | 58.00 | 1.00 | 0.06 | 0.06 | 75 | 135 |
| C1-L2 - 25 | 25.60 | 368 | 3.07 | 13.50 | 23.50 | 36.00 | 45.00 | 54.00 | 1.00 | 0.06 | 0.03 | 115 | 150 |
| C1-L2 - 30 | 26.00 | 350 | 3.03 | 9.50 | 19.00 | 33.50 | 43.00 | 52.00 | 1.00 | 0.05 | 0.03 | 110 | 155 |

L1 – Low Grade ( Dolomitic limestone )

L2 – Cement Grade ( Dolomitic limestone )

# Chemical Composition of C2-CTL, C2L3 & C2L4

| PLC Blend | LOI | $SiO_2$% | $Fe_2O_3$% | $Al_2O_3$% | CaO% | MgO% | $SO_3$% | IR % | $Na_2O$% | $K_2O$% | Cl% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C2-CTL | 1.73 | 19.82 | 3.46 | 5.17 | 62.60 | 2.35 | 2.94 | 0.27 | 0.32 | 1.13 | 0.015 |
| C2-L3-5 | 3.69 | 18.68 | 3.58 | 5.09 | 61.49 | 2.46 | 2.96 | 1.15 | 0.43 | 1.14 | 0.029 |
| C2-L3-10 | 5.02 | 18.69 | 3.35 | 5.24 | 60.38 | 2.46 | 2.82 | 2.11 | 0.44 | 1.04 | 0.030 |
| C2-L3-15 | 6.77 | 17.79 | 3.29 | 5.07 | 59.50 | 2.34 | 3.09 | 3.29 | 0.42 | 1.11 | 0.026 |
| C2-L3-20 | 8.50 | 18.10 | 3.18 | 4.73 | 58.27 | 2.03 | 3.03 | 4.75 | 0.46 | 1.14 | 0.031 |
| C2-L3-25 | 12.25 | 16.60 | 2.70 | 4.68 | 56.07 | 2.68 | 3.34 | 5.93 | 0.25 | 1.02 | 0.013 |
| C2-L3-30 | 12.08 | 16.50 | 2.63 | 4.79 | 56.25 | 2.94 | 2.88 | 5.70 | 0.29 | 1.13 | 0.014 |
| C2-L4-5 | 3.45 | 18.62 | 3.62 | 4.69 | 61.78 | 2.77 | 2.88 | 0.80 | 0.46 | 1.20 | 0.017 |
| C2-L4-10 | 4.91 | 18.55 | 3.33 | 4.27 | 61.41 | 2.49 | 2.96 | 1.58 | 0.43 | 1.11 | 0.010 |
| C2-L4-15 | 7.22 | 17.12 | 2.99 | 4.83 | 62.31 | 0.84 | 2.78 | 2.12 | 0.45 | 1.06 | 0.039 |
| C2-L4-20 | 9.08 | 16.82 | 2.97 | 4.71 | 59.48 | 2.97 | 2.99 | 2.57 | 0.45 | 1.10 | 0.032 |
| C2-L4-25 | 12.94 | 16.07 | 2.33 | 4.18 | 56.37 | 2.60 | 3.70 | 4.34 | 0.30 | 1.02 | 0.016 |
| C2-L4-30 | 12.92 | 15.94 | 2.57 | 4.66 | 56.77 | 2.49 | 2.87 | 4.38 | 0.24 | 1.04 | 0.013 |

L3 – Marginal Grade ( High calcium limestone )

L4 – Cement Grade ( High calcium limestone )

# Physical Properties of C2-CTL, C2L3 & C2L4

| PLC Blend | NC (%) | Blaine Fineness (m2/kg) | Specific Gravity | Compressive Strength (MPa) | | | | | Soundness Le Chatelier's (mm) | Soundness Autoclave % | Drying Shrinkage (%) | Initial Setting Time (min) | Final Setting Time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 Day | 3 Day | 7 Day | 28 Day | 90 Day | | | | | |
| C2 - CTL | 27.00 | 402 | 3.17 | 30.00 | 42.00 | 49.00 | 55.00 | 61.00 | 1.00 | 0.04 | 0.06 | 100 | 150 |
| C2-L3 - 5 | 26.00 | 402 | 3.06 | 26.50 | 37.50 | 45.00 | 52.50 | 59.00 | 1.00 | 0.05 | 0.07 | 120 | 160 |
| C2-L3 - 10 | 26.00 | 407 | 3.08 | 24.50 | 36.50 | 44.00 | 50.50 | 55.00 | 1.00 | 0.02 | 0.05 | 85 | 130 |
| C2-L3 - 15 | 25.00 | 385 | 3.08 | 22.50 | 35.50 | 40.50 | 48.50 | 54.00 | 1.00 | 0.06 | 0.03 | 115 | 155 |
| C2-L3 - 20 | 25.00 | 383 | 3.04 | 18.00 | 34.00 | 38.00 | 43.00 | 53.50 | 1.00 | 0.07 | 0.04 | 120 | 160 |
| C2-L3 - 25 | 25.00 | 381 | 2.95 | 16.00 | 29.50 | 35.00 | 38.00 | 45.00 | 1.00 | 0.02 | 0.03 | 110 | 160 |
| C2-L3 - 30 | 25.20 | 383 | 2.91 | 13.50 | 27.50 | 34.00 | 37.50 | 44.00 | 2.00 | 0.04 | 0.02 | 120 | 170 |
| C2-L4 - 5 | 27.50 | 402 | 3.13 | 29.00 | 40.50 | 45.00 | 52.00 | 57.50 | 1.00 | 0.02 | 0.03 | 100 | 145 |
| C2-L4 - 10 | 26.00 | 412 | 3.07 | 28.00 | 40.00 | 45.00 | 51.00 | 57.00 | 1.00 | 0.02 | 0.02 | 100 | 140 |
| C2-L4 - 15 | 26.50 | 407 | 3.05 | 22.50 | 36.00 | 41.50 | 46.00 | 53.00 | 1.00 | 0.06 | 0.04 | 100 | 135 |
| C2-L4 - 20 | 25.50 | 395 | 3.02 | 18.00 | 32.00 | 38.50 | 45.50 | 51.00 | 1.00 | 0.04 | 0.05 | 90 | 120 |
| C2-L4 - 25 | 25.60 | 380 | 2.89 | 16.50 | 31.00 | 37.00 | 41.00 | 49.00 | 1.00 | 0.02 | 0.03 | 120 | 180 |
| C2-L4 - 30 | 25.40 | 436 | 2.90 | 14.00 | 28.00 | 35.00 | 40.00 | 48.00 | 2.00 | 0.03 | 0.02 | 80 | 150 |

L3 – Marginal Grade ( High calcium limestone )

L4 – Cement Grade ( High calcium limestone )

# Chemical Composition of C3-CTL, C3L5 & C3L6

| PLC Blend | LOI | $SiO_2$% | $Fe_2O_3$% | $Al_2O_3$% | CaO% | MgO% | $SO_3$% | IR % | $Na_2O$% | $K_2O$% | Cl% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C3-CTL | 2.93 | 21.2 | 2.94 | 5.09 | 61.75 | 2.27 | 1.82 | 2.96 | 0.66 | 0.85 | 0.014 |
| C3-L5-5 | 3.75 | 21.50 | 2.89 | 5.60 | 60.27 | 2.29 | 1.72 | 3.07 | 0.66 | 0.97 | 0.017 |
| C3-L5-10 | 5.65 | 20.03 | 2.22 | 5.91 | 59.73 | 2.80 | 1.68 | 4.03 | 0.69 | 0.94 | 0.020 |
| C3-L5-15 | 6.17 | 19.06 | 2.62 | 5.38 | 60.02 | 1.89 | 2.94 | 3.90 | 0.64 | 0.89 | 0.013 |
| C3-L5-20 | 8.85 | 20.02 | 2.77 | 5.07 | 57.23 | 2.63 | 1.59 | 6.17 | 0.61 | 0.82 | 0.014 |
| C3-L5-25 | 11.77 | 17.82 | 2.45 | 5.11 | 55.84 | 2.33 | 3.02 | 6.28 | 0.46 | 0.87 | 0.014 |
| C3-L5-30 | 10.23 | 18.57 | 2.77 | 5.25 | 56.92 | 1.40 | 3.00 | 5.97 | 0.53 | 0.91 | 0.013 |
| C3-L6-5 | 4.71 | 19.54 | 3.04 | 5.48 | 60.20 | 3.29 | 1.80 | 2.11 | 0.55 | 0.89 | 0.021 |
| C3-L6-10 | 6.23 | 19.90 | 2.53 | 5.42 | 58.67 | 3.42 | 1.90 | 2.10 | 0.58 | 0.80 | 0.020 |
| C3-L6-15 | 8.63 | 17.03 | 2.54 | 4.81 | 57.82 | 4.68 | 2.87 | 0.60 | 0.58 | 0.71 | 0.014 |
| C3-L6-20 | 10.05 | 18.10 | 2.45 | 4.69 | 55.68 | 5.20 | 2.11 | 3.67 | 0.63 | 0.82 | 0.021 |
| C3-L6-25 | 15.60 | 13.50 | 2.03 | 4.42 | 54.22 | 5.78 | 2.98 | 1.07 | 0.39 | 0.69 | 0.039 |
| C3-L6-30 | 13.74 | 14.55 | 2.42 | 4.27 | 54.56 | 6.02 | 3.04 | 0.68 | 0.41 | 0.74 | 0.029 |

L5 – Very Low Grade Limestone ( High calcium limestone )

L6 – Low Grade Limestone (Calcic Dolomite)

# Physical Properties of C3-CTL,C3L5 & C3L6

| PLC Blend | NC (%) | Blaine Fineness ($m^2$/kg) | Specific Gravity | Compressive Strength (MPa) | | | | | Soundness Le Chatelier's (mm) | Soundness Autoclave % | Drying Shrinkage (%) | Initial Setting Time (min) | Final Setting Time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 Day | 3 Day | 7 Day | 28 Day | 90 Day | | | | | |
| C3 - CTL | 28.20 | 387 | 3.13 | 26.50 | 37.50 | 42.50 | 49.50 | 56.00 | 2.00 | 0.04 | 0.02 | 125 | 180 |
| C3-L5 - 5 | 29.00 | 394 | 3.11 | 23.00 | 31.50 | 33.50 | 45.00 | 51.00 | 1.00 | 0.04 | 0.02 | 120 | 170 |
| C3-L5 - 10 | 27.40 | 401 | 3.11 | 22.50 | 30.00 | 34.50 | 40.50 | 48.50 | 1.00 | 0.04 | 0.03 | 120 | 175 |
| C3-L5 - 15 | 26.20 | 398 | 3.06 | 20.50 | 29.00 | 33.00 | 39.00 | 46.50 | 1.00 | 0.05 | 0.03 | 115 | 170 |
| C3-L5 - 20 | 26.40 | 411 | 3.07 | 19.00 | 28.00 | 32.00 | 37.00 | 43.50 | 1.50 | 0.06 | 0.04 | 120 | 170 |
| C3-L5 - 25 | 25.00 | 363 | 2.98 | 16.50 | 25.00 | 28.00 | 35.00 | 39.50 | 2.00 | 0.02 | 0.03 | 80 | 160 |
| C3-L5 - 30 | 26.40 | 370 | 3.04 | 16.00 | 22.00 | 24.50 | 32.00 | 36.00 | 1.00 | 0.03 | 0.04 | 75 | 160 |
| C3-L6 - 5 | 27.80 | 383 | 3.12 | 27.00 | 35.00 | 38.50 | 46.00 | 51.00 | 1.00 | 0.06 | 0.03 | 135 | 185 |
| C3-L6 - 10 | 27.00 | 388 | 3.10 | 26.00 | 34.00 | 37.50 | 45.00 | 50.00 | 2.00 | 0.05 | 0.04 | 125 | 190 |
| C3-L6 - 15 | 28.00 | 397 | 3.07 | 25.00 | 35.00 | 37.00 | 43.00 | 47.50 | 1.00 | 0.05 | 0.03 | 130 | 175 |
| C3-L6 - 20 | 27.60 | 383 | 3.08 | 20.00 | 33.50 | 35.00 | 41.50 | 45.00 | 1.50 | 0.06 | 0.03 | 135 | 185 |
| C3-L6 - 25 | 26.40 | 374 | 2.92 | 17.00 | 27.50 | 32.50 | 39.50 | 53.00 | 2.00 | 0.04 | 0.03 | 75 | 155 |
| C3-L6 - 30 | 27.00 | 381 | 3.00 | 15.00 | 26.00 | 31.00 | 36.00 | 51.50 | 2.00 | 0.05 | 0.03 | 100 | 190 |

L5 – Very Low Grade Limestone ( High calcium limestone )

L6 – Low Grade Limestone (Calcic Dolomite)

# Chemical Composition of C4-CTL & C4L7

| PLC Blend | LOI | $SiO_2$% | $Fe_2O_3$% | $Al_2O_3$% | CaO% | MgO% | $SO_3$% | IR % | $Na_2O$% | $K_2O$% | Cl% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C4-CTL | 1.57 | 20.45 | 3.71 | 5.08 | 63.49 | 1.66 | 2.77 | 0.45 | 0.04 | 0.54 | 0.033 |
| C4-L7-5 | 3.73 | 18.76 | 3.50 | 4.95 | 63.13 | 1.60 | 2.81 | 1.59 | 0.17 | 0.55 | 0.034 |
| C4-L7-10 | 4.87 | 18.99 | 3.27 | 4.58 | 62.81 | 1.29 | 2.87 | 2.61 | 0.08 | 0.41 | 0.035 |
| C4-L7-15 | 6.59 | 19.13 | 3.04 | 4.50 | 61.39 | 1.20 | 2.84 | 3.80 | 0.09 | 0.46 | 0.033 |
| C4-L7-20 | 8.24 | 19.34 | 2.99 | 4.22 | 59.80 | 1.29 | 2.78 | 4.97 | 0.13 | 0.44 | 0.031 |
| C4-L7-25 | 9.94 | 19.15 | 2.69 | 4.25 | 58.63 | 1.27 | 2.85 | 6.21 | 0.07 | 0.45 | 0.032 |
| C4-L7-30 | 11.59 | 19.22 | 2.44 | 4.07 | 57.17 | 1.33 | 2.84 | 7.38 | 0.13 | 0.43 | 0.029 |

**L7 – Marginal Grade ( High calcium limestone )**

# Physical Properties of C4-CTL & C4L7

| PLC Blend | NC (%) | Blaine Fineness ($m^2/kg$) | Specific Gravity | Compressive Strength (MPa) | | | | | Soundness Le Chatelier's (mm) | Soundness Autoclave % | Drying Shrinkage (%) | Initial Setting Time (min) | Final Setting Time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 Day | 3 Day | 7 Day | 28 Day | 90 Day | | | | | |
| C4 - CTL | 26.40 | 397 | 3.13 | 42.00 | 47.00 | 63.00 | 67.00 | 73.00 | 1.00 | 0.04 | 0.03 | 95 | 135 |
| C4-L7 - 5 | 26.00 | 416 | 3.10 | 39.00 | 44.00 | 60.00 | 63.00 | 68.00 | 1.00 | 0.05 | 0.02 | 90 | 135 |
| C4-L7 - 10 | 27.00 | 402 | 3.08 | 37.00 | 37.00 | 50.50 | 55.00 | 61.50 | 1.50 | 0.04 | 0.02 | 105 | 150 |
| C4-L7 - 15 | 26.60 | 390 | 3.06 | 25.00 | 33.50 | 43.50 | 49.00 | 60.00 | 2.00 | 0.06 | 0.03 | 95 | 140 |
| C4-L7 - 20 | 27.40 | 375 | 3.08 | 13.50 | 30.00 | 39.00 | 46.00 | 57.50 | 1.50 | 0.05 | 0.02 | 100 | 155 |
| C4-L7 - 25 | 27.80 | 371 | 3.05 | 12.00 | 23.00 | 33.00 | 42.00 | 56.00 | 2.00 | 0.06 | 0.03 | 110 | 160 |
| C4-L7 - 30 | 27.60 | 365 | 3.01 | 9.50 | 20.00 | 28.00 | 37.00 | 45.50 | 2.00 | 0.05 | 0.02 | 105 | 165 |

**L7 – Marginal Grade ( High calcium limestone )**

# Chemical Composition of C5-CTL & C5L8

| PLC Blend | LOI | $SiO_2$% | $Fe_2O_3$% | $Al_2O_3$% | CaO% | MgO% | $SO_3$% | IR % | $Na_2O$% | $K_2O$% | Cl% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C5-CTL | 1.57 | 20.48 | 4.33 | 5.81 | 63.22 | 0.92 | 2.89 | 0.30 | 0.11 | 0.31 | 0.028 |
| C5-L8-5 | 3.25 | 19.73 | 4.29 | 5.80 | 62.39 | 0.85 | 2.95 | 0.73 | 0.10 | 0.30 | 0.020 |
| C5-L8-10 | 5.00 | 19.34 | 3.97 | 5.38 | 61.34 | 1.22 | 2.87 | 1.42 | 0.11 | 0.27 | 0.021 |
| C5-L8-15 | 6.77 | 18.70 | 3.94 | 5.30 | 60.28 | 1.22 | 2.91 | 2.77 | 0.13 | 0.27 | 0.022 |
| C5-L8-20 | 8.75 | 18.55 | 3.89 | 4.91 | 59.48 | 0.80 | 2.91 | 3.02 | 0.11 | 0.25 | 0.023 |
| C5-L8-25 | 10.42 | 17.76 | 3.75 | 4.87 | 58.53 | 1.11 | 2.87 | 4.06 | 0.15 | 0.24 | 0.019 |
| C5-L8-30 | 12.19 | 17.03 | 3.70 | 5.14 | 57.70 | 0.86 | 2.82 | 4.39 | 0.08 | 0.22 | 0.020 |

**L8 – Cement Grade( High calcium limestone )**

# Physical Properties of C5-CTL & C5L8

| PLC Blend | NC (%) | Blaine Fineness ($m^2/kg$) | Specific Gravity | Compressive Strength (MPa) | | | | | Soundness Le Chatelier's (mm) | Soundness Autoclave % | Drying Shrinkage (%) | Initial Setting Time (min) | Final Setting Time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 Day | 3 Day | 7 Day | 28 Day | 90 Day | | | | | |
| C5 - CTL | 25.00 | 367 | 3.07 | 29.00 | 42.00 | 57.00 | 62.00 | 70.00 | 1.00 | 0.06 | 0.03 | 105 | 145 |
| C5-L8 - 5 | 25.20 | 366 | 3.08 | 22.50 | 38.00 | 51.50 | 58.00 | 64.50 | 1.50 | 0.05 | 0.02 | 100 | 150 |
| C5-L8 - 10 | 25.40 | 349 | 3.06 | 20.00 | 36.50 | 49.00 | 55.00 | 62.50 | 2.00 | 0.06 | 0.02 | 95 | 145 |
| C5-L8 - 15 | 25.50 | 368 | 3.01 | 16.00 | 33.00 | 43.50 | 50.00 | 56.50 | 1.50 | 0.07 | 0.03 | 110 | 155 |
| C5-L8 - 20 | 23.40 | 356 | 2.97 | 9.50 | 27.50 | 38.50 | 46.50 | 52.00 | 1.00 | 0.06 | 0.02 | 110 | 145 |
| C5-L8 - 25 | 24.00 | 360 | 2.95 | 7.00 | 24.00 | 32.50 | 44.00 | 49.00 | 2.00 | 0.06 | 0.03 | 105 | 150 |
| C5-L8 - 30 | 24.20 | 352 | 2.92 | 6.00 | 18.00 | 25.50 | 36.00 | 42.00 | 1.50 | 0.05 | 0.02 | 120 | 155 |

**L8 – Cement Grade ( High calcium limestone )**

# Observations on Chemical Composition of PLC

- $SO_3$ content was found to be in targeted range of 2.98-3.02%
- Loss on ignition (LOI) increases with increase in limestone percentage
- Insoluble Residue increased with increase in limestone content
- Other chemical parameters ( $Al_2O_3$, MgO, $Fe_2O_3$, $SiO_2$, alkali and chlorides) depend upon their relative composition in clinker and limestone

# Observations on Physical Properties of PLC

- **Blaine Fineness**

  Fineness for all PLC blends was kept between 380±20 $m^{2/}kg$. Actual values lie in the range of 380±30 $m^{2/}kg$.

- **Normal Consistency**

  Increases with fineness, since fineness was kept similar, NC was found to be in range of 27±2 %

- **Specific Gravity**

  Slightly decreased as the limestone content is increased. Average 3.14 for control to average 2.98 for 30% replacement

- **Soundness, Drying Shrinkage, IST and FST**

  No significant effect of limestone addition of these properties was observed. The values of these tests on PLC blend are similar to that of control and well within the limits for all grades of OPC as per IS 269:2015

# Observations on Compressive Strength of PLC

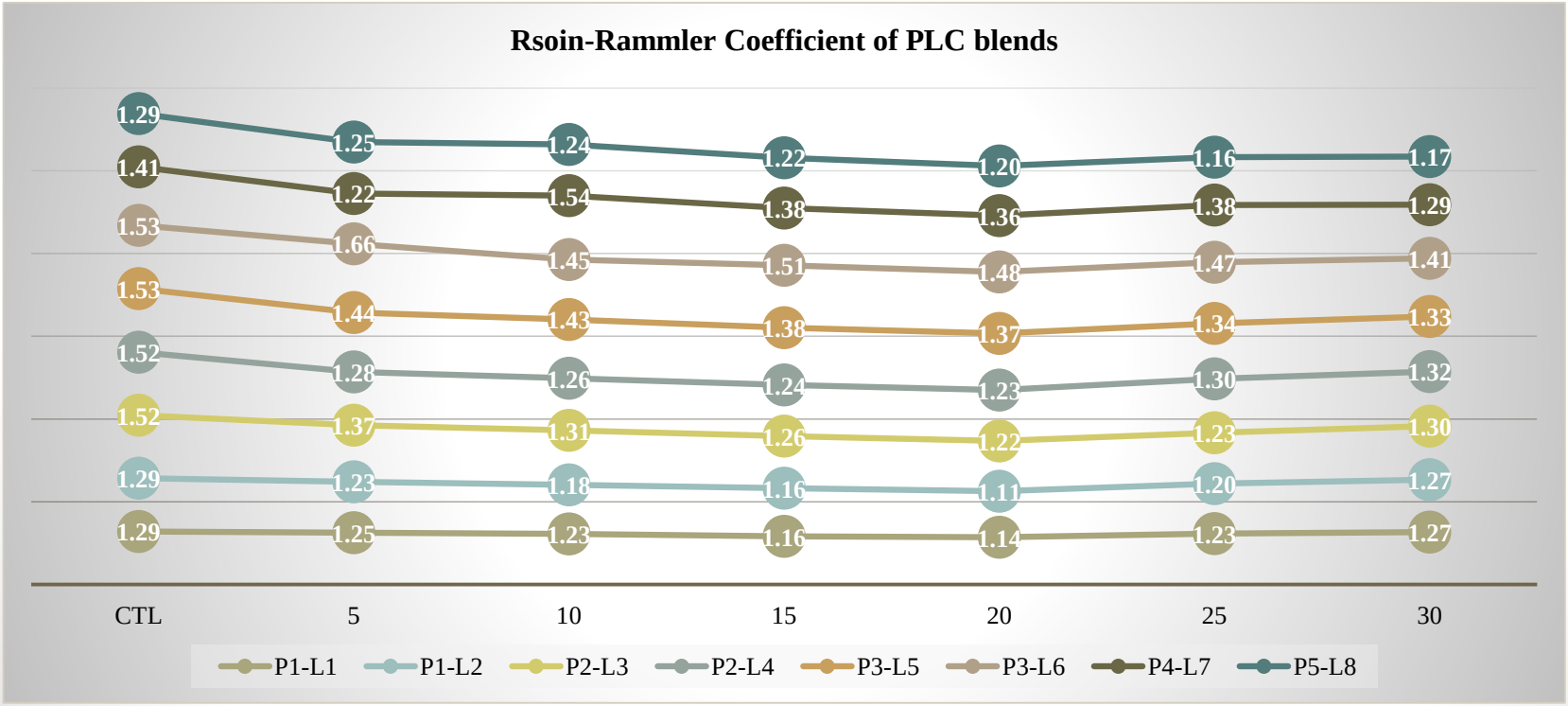
- Strength of mortar reduced due to limestone at all the replacement levels.
- Average percentage reduction in mortar strength with respect to percentage of limestone at different ages is given below

| Age | 5% | 10% | 15% | 20% | 25% | 30% |
|---|---|---|---|---|---|---|
| 1Day | 13.23 | 17.53 | 30.27 | 45.10 | 51.57 | 59.35 |
| 3Day | 7.62 | 12.81 | 19.91 | 27.56 | 36.41 | 43.58 |
| 7 Day | 8.69 | 12.40 | 20.78 | 26.87 | 33.57 | 39.36 |
| 28 Day | 7.14 | 12.38 | 18.95 | 23.36 | 29.56 | 34.98 |
| 90 Day | 6.81 | 10.79 | 15.08 | 19.50 | 25.00 | 30.54 |

- No trend with respect to grade of limestone was observed, However Reduction is strength was alarming for L5 VERY LOW GRADE limestone
- Limestone L6 **Low Grade Limestone (Calcic Dolomite)** containing 70% of dolomite mineral performed similar to other grade limestone
- Percentage reduction values at all ages are similar form cement, marginal and low grade limestone.
- Early age (1-day) average strength reduction is higher and subsequently reduces with age

# Observations on Particle Size Distribution

- Since limestone is softer material as compared to clinker (evident from grindability values) and inter-griding method was used, **wider PSD curve was obtained in comparison to control.** This is also evident from uniformity coefficient ‘n’ obtained using Rosin-Rammler distribution. Decrease in ‘n’ w.r.t percentage of limestone indicate wider range of particles present in PLC



# FRESH HARDENED AND DURABILITY PERFORMANCE EVALUATION OF CONCRETE MADE WITH PLC

# PLC Concrete – Mixes

- Total 18 concrete mixes, 9 each with w/c of 0.4 and 0.6 were prepared and samples were cast as per experimental plan
- **One control mix each at w/c 0.4 and 0.6 was prepared using clinker C1**
- Mix design and details of mixes are given below

| w/c Ratio | Cement content kg/m$^3$ | Water content kg/m$^3$ | CA:FA | 20 mm:10 mm |
|---|---|---|---|---|
| 0.4 | 400 | 160 | 66:34 | 60:40 |
| 0.6 | 280 | 168 | 63:37 | 60:40 |

| Cement Plant | Clinker | Limestone | Concrete Mixes | |
|---|---|---|---|---|
| **Plant 1** | **C1** | **No Limestone (Control Mix)** | **C1-CTL 0.4** | **C1-CTL 0.6** |
| **Plant 1** | **C1** | **L1** | **C1-L1 0.4** | **C1-L1 0.6** |
| | | **L2** | **C1-L2 0.4** | **C1-L2 0.6** |
| **Plant 2** | **C2** | **L3** | **C2-L3 0.4** | **C2-L3 0.6** |
| | | **L4** | **C2-L4 0.4** | **C2-L4 0.6** |
| **Plant 3** | **C3** | **L5** | **C3-L5 0.4** | **C3-L5 0.6** |
| | | **L6** | **C3-L6 0.4** | **C3-L6 0.6** |
| **Plant 4** | **C4** | **L7** | **C4-L7 0.4** | **C4-L7 0.6** |
| **Plant 5** | **C5** | **L8** | **C5-L8 0.4** | **C5-L8 0.6** |

# Fresh Properties of PLC Concrete

- Workability

Slump of fresh concrete was maintained between 75-100 mm by using PCE based admixture. Dosage of admixture varied from 0.4-0.6% for 0.4 w/c concrete and 0.2-0.4 for 0.6 w/c concrete.

Air Content

The air content for all the concrete mixes varied between 2 and 4%. Air content of PLC concrete was comparable to that of control concrete.

IST and FST

IST and FST for all concrete mixes irrespective of w/c ratio are similar for PLC concrete and control concrete. IST vary from 370 min to 590 minutes and FST varied from 515 min to 730 min.

# Hardened Properties of PLC Concrete w/c 0.4

| Mix | Compressive Strength (MPa) | | | MOE (GPa) | | Poisson Ratio | | DS (%) |
|---|---|---|---|---|---|---|---|---|
| | 7 Day | 28 Day | 56 Day | 28 Day | 56 Day | 28 Day | 56 Day | 28 Day |
| C1-CTL 0.4 | 42.70 | 56.55 | 58.04 | 41.55 | 44.36 | 0.130 | 0.147 | 0.018 |
| C1-L1 0.4 | 42.88 | 51.39 | 49.50 | 40.37 | 39.07 | 0.118 | 0.133 | 0.017 |
| C1-L2 0.4 | 38.51 | 52.07 | 53.38 | 36.37 | 41.30 | 0.130 | 0.107 | 0.019 |
| C2-L3 0.4 | 35.13 | 39.78 | 45.21 | 35.29 | 34.97 | 0.128 | 0.130 | 0.016 |
| C2-L4 0.4 | 35.34 | 40.52 | 40.91 | 34.75 | 31.57 | 0.137 | 0.119 | 0.019 |
| C3-L5 0.4 | 33.15 | 38.93 | 39.53 | 36.13 | 38.59 | 0.115 | 0.111 | 0.017 |
| C3-L6 0.4 | 29.38 | 33.18 | 33.29 | 33.84 | 35.64 | 0.118 | 0.122 | 0.018 |
| C4-L7 0.4 | 45.41 | 52.17 | 52.30 | 41.16 | 42.76 | 0.127 | 0.127 | 0.016 |
| C5-L8 0.4 | 36.79 | 41.30 | 45.98 | 32.25 | 33.91 | 0.125 | 0.138 | 0.017 |

| Grade of Limestone | | | |
|---|---|---|---|
| L1 | Low Grade | L5 | Very Low Grade |
| L2 | Cement Grade | L6 | Calcic Dolomite |
| L3 | Marginal Grade | L7 | Marginal Grade |
| L4 | Cement Grade | L8 | Cement Grade |

**28 Day Strength of Cement used**

C1 – 70 MPa
C2 – 55 MPa
C3 – 49.5 MPa
C4 – 67 MPa
C5 – 62 MPa

# Hardened Properties of PLC Concrete w/c 0.6

| Mix | Compressive Strength (MPa) | | | MOE (GPa) | | Poisson Ratio | | DS (%) |
|---|---|---|---|---|---|---|---|---|
| | 7 Day | 28 Day | 56 Day | 28 Day | 56 Day | 28 Day | 56 Day | 28 Day |
| C1-CTL 0.6 | 29.45 | 39.59 | 40.33 | 35.63 | 37.77 | 0.111 | 0.119 | 0.017 |
| C1-L1 0.6 | 21.70 | 27.99 | 30.86 | 30.50 | 29.47 | 0.111 | 0.122 | 0.018 |
| C1-L2 0.6 | 22.58 | 28.67 | 34.55 | 26.88 | 29.17 | 0.107 | 0.115 | 0.018 |
| C2-L3 0.6 | 18.51 | 20.30 | 25.17 | 31.01 | 29.05 | 0.130 | 0.110 | 0.017 |
| C2-L4 0.6 | 22.14 | 24.01 | 27.78 | 30.78 | 27.99 | 0.111 | 0.120 | 0.018 |
| C3-L5 0.6 | 18.03 | 22.26 | 21.96 | 21.29 | 21.23 | 0.111 | 0.107 | 0.017 |
| C3-L6 0.6 | 16.15 | 16.63 | 17.70 | 20.53 | 21.17 | 0.116 | 0.117 | 0.019 |
| C4-L7 0.6 | 21.64 | 26.78 | 28.72 | 26.32 | 26.39 | 0.132 | 0.129 | 0.018 |
| C5-L8 0.6 | 17.09 | 20.45 | 22.89 | 24.09 | 30.09 | 0.120 | 0.137 | 0.019 |

| Grade of Limestone | | | |
|---|---|---|---|
| L1 | Low Grade | L5 | Very Low Grade |
| L2 | Cement Grade | L6 | Calcic Dolomite |
| L3 | Marginal Grade | L7 | Marginal Grade |
| L4 | Cement Grade | L8 | Cement Grade |

**28 Day Strength of Cement used**

C1 – 70 MPa
C2 – 55 MPa
C3 – 49.5 MPa
C4 – 67 MPa
C5 – 62 MPa

# Observations on Compressive Strength

- Limestone addition led to decrease in compressive strength of 9.81%, 9.12% and 14.71% for w/c 0.4 at 7, 28 and 56 days respectively and 26.32%, 29.30%, 23.48% for w/c of 0.6 at 7, 28 and 56 days respectively.
- Similar compressive strength was obtained from different grades limestone, no specific effect of limestone grade could be observed.

| Clinker | MIX | Limestone Grade | 28 D CS (MPa) |
|---|---|---|---|
| C1 | C1L1-0.4 | Low Grade | 51.39 |
| | C1L2-0.4 | Cement Grade | 52.07 |
| C2 | C2L3-0.4 | Marginal Grade | 39.78 |
| | C2L4-0.4 | Cement Grade | 40.52 |
| C3 | C3L5-0.4 | Very Low Grade | 38.93 |
| | C3L6-0.4 | Low Grade, Calcic Dolomite | 35.18 |

| Clinker | MIX | Limestone Grade | 28 D CS (MPa) |
|---|---|---|---|
| C1 | C1L1-0.6 | Low Grade | 27.99 |
| | C1L2-0.6 | Cement Grade | 28.67 |
| C2 | C2L3-0.6 | Marginal Grade | 20.30 |
| | C2L4-0.6 | Cement Grade | 24.01 |
| C3 | C3L5-0.6 | Very Low Grade | 22.26 |
| | C3L6-0.6 | Low Grade, Calcic Dolomite | 21.40 |

# Observations on MOE, PR & Drying Shrinkage

- MOE results for PLC concrete are found to be in range of 30-45 GPa for 0.4 w/c concrete & 20-35 GPa for 0.6 w/c concrete. MOE results for PLC concrete are on lower side w.r.t control concrete as the compressive strength of PLC is also lower w.r.t. control. **The constitutive relationship between CS and MOE is same for PLC and control concrete.**
- The Poisson Ratio for all the Control as well as PLC Concrete Mixes are found to be between 0.10 and 0.15, which are in the typical range of 0.10 – 0.20 for concrete
- Drying shrinkage vary between 0.0150% - 0.0200% for all the concrete mixes (0.4 as well as 0.6 w/c). Results of PLC concrete are similar to that of control concrete.

# Durability Properties of PLC Concrete w/c 0.4

| Mix | RCPT (Coulomb) | | Water Penetration (mm) | Initial Sorptivity (x 10-3) ($mm/s^{0.5}$) | Carbonation Depth (mm) | | | Abrasion Depth (mm) | |
|---|---|---|---|---|---|---|---|---|---|
| | 28 Day | 56 Day | 28 Day | 28 Day | 70 Day | 140 Day | 210 Day | 28 Day | 56 Day |
| C1-CTL 0.4 | 1575 | 1404 | 12.33 | 0.60 | 0.00 | 0.00 | 0.00 | 0.32 | 0.28 |
| C1-L1 0.4 | 2494 | 1756 | 32.67 | 1.20 | 0.00 | 5.00 | 12.50 | 0.43 | 0.41 |
| C1-L2 0.4 | 2380 | 2103 | 18.67 | 1.20 | 0.00 | 6.00 | 12.00 | 0.39 | 0.45 |
| C2-L3 0.4 | 3217 | 2616 | 33.63 | 1.60 | 9.75 | 11.00 | 12.25 | 0.31 | 0.31 |
| C2-L4 0.4 | 2221 | 2001 | 18.67 | 1.50 | 6.25 | 9.50 | 10.50 | 0.46 | 0.45 |
| C3-L5 0.4 | 2302 | 1215 | 24.80 | 2.00 | 3.00 | 4.25 | 6.50 | 0.28 | 0.29 |
| C3-L6 0.4 | 1832 | 1248 | 14.00 | 1.80 | 5.75 | 8.50 | 13.25 | 0.22 | 0.24 |
| C4-L7 0.4 | 2269 | 2182 | 18.87 | 2.90 | 2.75 | 4.00 | 6.75 | 0.25 | 0.24 |
| C5-L8 0.4 | 2181 | 2139 | 14.67 | 3.10 | 8.50 | 11.25 | 15.50 | 0.32 | 0.26 |

| Grade of Limestone | | | |
|---|---|---|---|
| L1 | Low Grade | L5 | Very Low Grade |
| L2 | Cement Grade | L6 | Calcic Dolomite |
| L3 | Marginal Grade | L7 | Marginal Grade |
| L4 | Cement Grade | L8 | Cement Grade |

# Durability Properties of PLC Concrete w/c 0.6

| Mix | RCPT (Coulomb) | | Water Penetration (mm) | Initial Sorptivity (x 10-3) ($mm/s^{0.5}$) | Carbonation Depth (mm) | | | Abrasion Depth (mm) | |
|---|---|---|---|---|---|---|---|---|---|
| | 28 Day | 56 Day | 28 Day | 28 Day | 70 Day | 140 Day | 210 Day | 28 Day | 56 Day |
| C1-CTL 0.6 | 2906 | 2057 | 16.60 | 1.30 | 6.25 | 10.75 | 14.00 | 0.43 | 0.46 |
| C1-L1 0.6 | 3763 | 2945 | 78.33 | 3.40 | 13.25 | 14.75 | 17.50 | 0.70 | 0.64 |
| C1-L2 0.6 | 3724 | 3238 | 37.67 | 2.70 | 14.50 | 21.00 | 28.00 | 0.74 | 0.53 |
| C2-L3 0.6 | 3982 | 3382 | 65.33 | 4.90 | 11.00 | 11.45 | 44.00 | 0.49 | 0.33 |
| C2-L4 0.6 | 2565 | 2350 | 38.37 | 2.00 | 10.75 | 13.75 | 17.00 | 0.51 | 0.48 |
| C3-L5 0.6 | 3271 | 2972 | 80.67 | 5.20 | 12.00 | 22.75 | 30.00 | 0.42 | 0.32 |
| C3-L6 0.6 | 3726 | 2754 | 43.33 | 6.10 | 20.75 | 27.50 | 40.25 | 0.62 | 0.78 |
| C4-L7 0.6 | 3111 | 2640 | 56.50 | 6.40 | 22.00 | 24.25 | 29.75 | 0.36 | 0.37 |
| C5-L8 0.6 | 2754 | 2277 | 40.00 | 6.20 | 14.25 | 28.00 | 33.25 | 0.56 | 0.41 |

| Grade of Limestone | | | |
|---|---|---|---|
| L1 | Low Grade | L5 | Very Low Grade |
| L2 | Cement Grade | L6 | Calcic Dolomite |
| L3 | Marginal Grade | L7 | Marginal Grade |
| L4 | Cement Grade | L8 | Cement Grade |

# Observations on RCPT, Sorptivity & Water Penetration

- Limestone incorporation led to increase in RCPT, Sorptivity and Water Penetration values
- Carbonation depth is on higher side for PLC concrete
- Abrasion resistance of PLC concrete is found to be similar / higher to that of control concrete
- No trend w.r.t quality of limestone was observed

| Concrete Type | RCPT (28D) charge passed (coulomb) | | Initial Sorptivity (x 10-3) ($mm/s^{0.5}$) | | Water Penetration under pressure 28 day (mm) | |
|---|---|---|---|---|---|---|
| | 0.4 w/c | 0.6 w/c | 0.4 w/c | 0.6 w/c | 0.4 w/c | 0.6 w/c |
| Control Concrete | 1575 | 2906 | 0.60 | 1.30 | 12.33 | 16.60 |
| PLC Concrete (avg.) | 2362 | 3362 | 1.91 | 4.61 | 22.00 | 55.00 |

| Concrete Type | Avg. Carbonation mm 0.4 w/c | | | Avg. Carbonation mm 0.6 w/c | | |
|---|---|---|---|---|---|---|
| | 70 D | 140 D | 210 D | 70 D | 140 D | 210 D |
| Control Concrete | 0 | 0 | 0 | 6 | 10 | 14 |
| PLC Concrete | 5 | 8 | 12 | 14 | 20 | 30 |

# Sulphate Resistance of PLC

| Age | C1-CTL | | C1-L1 | | C1-L2 | | C2-L3 | | C2-L4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C |
| 1 Week | 0.004 | 0.003 | 0.003 | 0.005 | 0.004 | 0.003 | 0.006 | 0.003 | 0.008 | 0.004 |
| 2 Week | 0.009 | 0.005 | 0.007 | 0.009 | 0.008 | 0.006 | 0.010 | 0.005 | 0.011 | 0.006 |
| 3 Week | 0.013 | 0.008 | 0.009 | 0.013 | 0.012 | 0.009 | 0.014 | 0.006 | 0.016 | 0.008 |
| 4 Week | 0.018 | 0.010 | 0.011 | 0.016 | 0.016 | 0.011 | 0.018 | 0.008 | 0.023 | 0.012 |
| 8 Week | 0.023 | 0.014 | 0.013 | 0.017 | 0.018 | 0.014 | 0.023 | 0.011 | 0.028 | 0.013 |
| 13 Week | 0.028 | 0.017 | 0.019 | 0.023 | 0.022 | 0.016 | 0.030 | 0.013 | 0.031 | 0.015 |
| 15 Week | 0.029 | 0.018 | 0.030 | 0.031 | 0.024 | 0.018 | 0.032 | 0.016 | 0.034 | 0.018 |
| 4 Month | 0.030 | 0.018 | 0.038 | 0.039 | 0.027 | 0.021 | 0.033 | 0.017 | 0.035 | 0.019 |
| 6 Month | 0.035 | 0.021 | 0.042 | 0.044 | 0.036 | 0.031 | 0.035 | 0.018 | 0.037 | 0.020 |
| 9 Month | 0.039 | 0.023 | 0.045 | 0.048 | 0.040 | 0.036 | 0.039 | 0.021 | 0.041 | 0.022 |
| 12 Month | 0.045 | 0.026 | 0.050 | 0.056 | 0.044 | 0.040 | 0.043 | 0.025 | 0.046 | 0.028 |

| Age | C3-L5 | | C3-L6 | | C4-L7 | | C5-L8 | |
|---|---|---|---|---|---|---|---|---|
| | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C | Sulphate Expansion (%) 23°C | Thaumasite Expansion (%) 6°C |
| 1 Week | 0.007 | 0.004 | 0.006 | 0.002 | 0.006 | 0.004 | 0.007 | 0.005 |
| 2 Week | 0.014 | 0.007 | 0.011 | 0.004 | 0.012 | 0.006 | 0.010 | 0.009 |
| 3 Week | 0.020 | 0.009 | 0.014 | 0.005 | 0.017 | 0.011 | 0.015 | 0.013 |
| 4 Week | 0.023 | 0.012 | 0.018 | 0.005 | 0.020 | 0.015 | 0.021 | 0.018 |
| 8 Week | 0.023 | 0.017 | 0.024 | 0.009 | 0.025 | 0.019 | 0.028 | 0.021 |
| 13 Week | 0.030 | 0.026 | 0.032 | 0.015 | 0.029 | 0.024 | 0.032 | 0.027 |
| 15 Week | 0.038 | 0.031 | 0.039 | 0.021 | 0.034 | 0.027 | 0.036 | 0.030 |
| 4 Month | 0.048 | 0.033 | 0.043 | 0.024 | 0.038 | 0.031 | 0.042 | 0.034 |
| 6 Month | 0.052 | 0.036 | 0.048 | 0.029 | 0.043 | 0.036 | 0.043 | 0.039 |

# Observations on Sulphate Resistance of PLC

- Sulphate expansion of PLC concrete is similar or marginally higher to that of control concrete.
- Thaumasite expansion values are higher side for PLC concrete.
- No trend w.r.t quality of limestone was observed

# Conclusions and Recommendation

## Specification of PLC and its application

- What should be the maximum and Minimum % addition of Lime stone in PLC ?
- What should be Fineness of PLC?
- Inert grinding or inter mixing after separate grinding of Limestone at higher fineness?
- Quality of Lime stone ?
- Application and uses ?

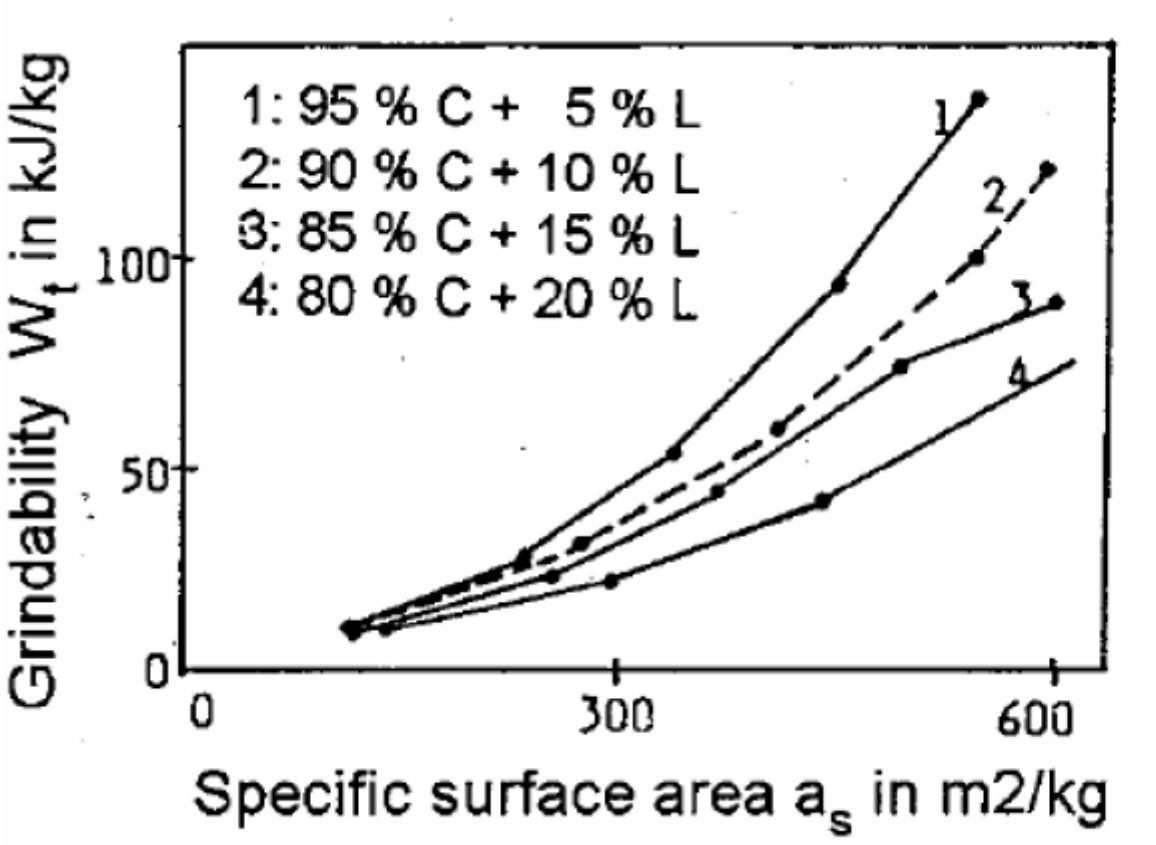
# Conclusions and Recommendation

**Action mechanism of limestone in cement**

- **Chemical effect** - $C_3A$ and $C_4AF$ react with carbonate ion from limestone to form *carboaluminates* and stabilization of ettringite . Since aluminate phase in cement clinker is limited, the chemical effect of limestone in cement-based materials is small.
- **Nucleation effect-** Due to similarity between planar configuration of Ca and O atoms in calcite and CaO layers in C-S-H, enhanced precipitation of C-S-H on the surface of limestone
- **Filler effect** -Very fine limestone helps in higher particle packing density by filling the voids between cement particles and improved particle size distribution.
- **Dilution effect** – Limestone does not have cementitious or pozzolanic properties, its replacement with cement increases the free water to react with cement particles

**Dilution effect seems to be dominating at this fineness of 380±30 $m^2/kg$. The loss of strength due to dilution must be compensated for by finer grinding.**

# Conclusions and Recommendation




: Grindability of limestone cement mixtures (Opoczky, 1992)

# Conclusions and Recommendation

## Strength of Concrete Produced with PLC

| | Plant B | | Plant G | |
|---|---|---|---|---|
| | PC | PLC | PC | PLC |
| Limestone in cement (%) | 0 | 20 | 0 | 20 |
| Fineness of cement ($m^2/kg$) | 345.0 | 482.5 | 362.0 | 489.5 |
| Strength of concrete with 270 $kg/m^3$ cement at 28 days (MPa) | 30.7 | 30.0 | 31.6 | 29.1 |
| Strength of concrete with 330 $kg/m^3$ cement at 28 days (MPa) | 39.7 | 38.0 | 37.5 | 36.5 |

(Alunno-Rossetti and Curcio, 1997)

Appropriate choice of clinker quality, limestone quality, % limestone content and cement fineness can lead to the production of a Portland limestone cement with the desired properties at least for cements with up to 15% limestone.

# Conclusions and Recommendation

The manufacturing of Portland Limestone Cement (PLC) is a rational option from the energy consumption, emission reduction, conservation of natural resources and economic point of view

**Recommendations are :**

- 15 % addition of lime stone having minimum CaO content 36% .
- Intergrinding with Minimum fineness of 450 $m^2/Kg$
- Intermixing with minimum fineness of limestone 700 $m^2/Kg$ and net fineness of PLC = 450 $m^2/Kg$
- PLC shall not be used in in concrete in service of sulfate concentration severity class -3 and above as per IS 456:2000
- PLC shall not be used in concrete in service where temperature falls below $15^0C$ throughout the day for more than one months in a year.
- PLC shall not be used for concrete when steam curing is to be employed.

# THANK YOU