Preliminary Comparison of Portland Limestone Cement with a Type I/II Portland Cement in Tennessee

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Abstract

Approximately four percent of the world's Carbon Dioxide (CO_2) emissions are generated from producing Portland cement. The average replacement of 10% limestone in Portland Limestone Cement (PLC) can result in about a 10% reduction in CO_2 production, as well as in energy used. In some cases of PLC use, there can be a 12% improvement in environmental performance compared to ordinary Portland cement (OPC).

Tennessee Department of Transportation (TDOT) bridge deck (Class D) and general use (Class A) concrete mixtures, each containing 25% Class F fly ash, were selected for the initial comparison of PLC to an ASTM C150 Type I/II OPC. All mixtures met appropriate TDOT plastic property requirements.

Six batches of each mixture were tested. Resistance to chloride penetration (AASHTO T358-17), by surface resistivity was measured at 7, 14, 28, and 56 days. Compressive strength (ASTM C 39M-18) was also measured at 7, 14, 28, and 56 days. Static modulus of elasticity (ASTM C 469M-14) was measured at 28 and 56 days. Absorption after boiling (ASTM C 642-13) was measured at 56 days.

All mixtures easily met the appropriate TDOT 28-day Class D (4000-psi) or Class A (3000-psi) compressive strength requirements. The surface resistivity results of both PLC mixtures were statistically superior to both OPC mixtures at all testing intervals. All PLC compressive strength and static modulus of elasticity results were superior to or not significantly different from OPC results. There were no significant differences between PLC absorption after boiling results and those of OPC mixtures.

Introduction and Literature Review

PLC has been used in the United States for several years, however, it is becoming more prevalent as of late (1). The first step in producing PLC is adding crushed, dried limestone to the grinding mill, along with portland cement clinker and gypsum. According to ASTM C150, OPC is limited to a maximum limestone content of 5% by mass. PLC, however, is defined as having a 5-15% limestone content by mass according to ASTM C595 (1, 2). This is an area of interest to lessen the environmental footprint that is becoming a concern for OPC production (1, 2).

Since the limestone is a softer material, it is generally more finely ground than the clinker that is produced. Limestone also requires less energy to grind due to its softness. PLC has a broader gradation, with a uniform distribution of the limestone particles, which results in better overall particle packing. The enhanced particle packing and uniform size distribution improves the PLC finish-ability and paste density (1, 3).

The strength effects on PLC concrete is affected by the amount of limestone substitution in the cement. It has been proven that the upper allowable limit of limestone substitution (15%), may potentially increase early-age strength, resulting from the improved particle packing. The efficiency of supplementary cementitious materials (SCMs), such as fly ash and slag, can be increased with the use of PLC. The use of PLC with SCMs reduces the retardation effects of SCMs, which in turn improves strength at all ages. The fineness of the limestone contributes to the workability of the concrete but does not affect the water demand. Limestone generally contributes to the hydration reactions rather than being an inert filler (4). Therefore, PLCs can feasibly be used in the same situations as OPC (1).

About four percent of the world's Carbon Dioxide emissions are generated from producing portland cement (5). The average replacement of 10% limestone in PLC can result in around a 10% reduction in the CO_2 production, as well as energy. The limestone that is used must contain a minimum of 70% Calcium Carbonate ($CaCO_3$) (3). CO_2 emissions from cement plants are caused by two main sources. These sources include calcination of the limestone and the consumption of fossil fuels to heat the raw materials to the required temperature to form clinker. With the substitution of 5% to 15% limestone by mass in PLC, this reduces the use of clinker. This in turn consumes less energy and reduces the CO_2 emissions and greenhouse gases. Overall, it has been proven that with the use of PLC, there can be a 12% improvement in environmental performance compared to OPC (6).

Materials and Procedure

Table 1, column 1 shows the TDOT-approved materials for concrete that were used in this study. This comes with the exception of the use of PLC that was investigated. The proportions of the four mixtures used in this study (see Table 1) were determined through trial batching. After trialing, all four mixtures met the indicated TDOT 604.03 (7) concrete plastic and hardened property requirements. Tables 2 and 3 show TDOT 604.03 (7) requirements for minimum cementing materials, w/cm ratio, fine aggregate percentage by total aggregate volume, and allowable SCM replacement percentages for TDOT Class D and A concrete, respectively. Six 0.85-cubic-foot batches of each mixture were made and tested as per Table 4 criteria.

Table 1: Mixtures Used to Evaluate PLC

Materials	Control Class D	PLC Class D	Control Class A	PLC Class A
Type I/II PC, lbs/CY (kg/m^3)	465 (276)	0	423 (251)	0
PLC, lbs/CY (kg/m^3)	0	465 (276)	0	423 (251)
Popular TN Class F Fly Ash, lbs/CY (kg/m^3)	155 (92)	155 (92)	141 (84)	141 (84)
No. 57 Stone, SSD lbs/CY (kg/m^3)	1849 (1097)	1845 (1095)	1747 (1037)	1746 (1046)
River Sand, SSD lbs/CY (kg/m^3)	1112 (660)	1109 (658)	1270 (754)	1266 (751)
Water, lbs/CY (kg/m^3)	229.5 (136)	229.5 (136)	242.5 (144)	242.5 (144)
Design Percent Air	7	7	6	6
Air Entrainer, oz/cwt (mL/m^3)	2.77 (107)	3.81 (148)	2.48 (96)	2.85 (110)
Mid-Range Water Reducer, oz/cwt (mL/m^3)	3.11 (120)	3.12 (121)	7.62 (295)	10.47 (405)
High-Range Water Reducer, oz/cwt (mL/m^3)	4.5 (174)	4.15 (161)	0	0

Table 2: Comparison of PLC Mixtures with TDOT Class D PCC Requirements

Property	TDOT 604.03 Class D PCC Requirements	Control Class D	PLC Class D
Cement content, lbs/CY (kg/m^3)	620 (368) minimum	620 (368)	620 (368)
Water-cement ratio	0.40 maximum	0.37	0.37
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	38	38
Percent Class F Fly Ash Substitution (by weight) for PC	25 maximum	25	25

Table 3: Comparison of PLC Mixtures with TDOT Class A PCC Requirements

Property	TDOT 604.03 Class A PCC Requirements	Control Class A	PLC Class A
Cement content, lbs/CY (kg/m^3)	564 (335) minimum	564 (335)	564 (335)
Water-cement ratio	0.45 maximum	0.43	0.436
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	42.5	42.5
Percent Class F Fly Ash Substitution (by weight) for PC	25 maximum	25	25

Table 4: Testing Protocol for PLC Evaluation Mixtures

Test Method	Frequency	Specimens
Compressive Strength, AASHTO T22 (8)	3 @ 7, 14, 28 and 56 days	4 x 8-inch (100 x 200-mm) cylinders
Static Modulus of Elasticity ASTM C 469 (9)	1 of 3 @ 28 and 56 days	4 x 8-inch (100 x 200-mm) cylinders
Surface Resistivity, AASHTO T358 (10)	3 @ 7, 14, 28 and 56 days	56-day compressive strength 4 x 8 (100 x 200-mm) cylinders
Hardened Concrete Absorption, ASTM C642 (11)	3 @ 56 days	3 x 6 (75 x 150-mm) cylinders

Results and Data Quality

Tables 5 and 6 show compressive strength results, result ranges, and allowable result ranges for the TDOT Class D and A mixtures, respectively. Tables 7 and 8 show static modulus of elasticity results, result ranges, and allowable result ranges for the TDOT Class D and A mixtures, respectively. Tables 9 and 10 show surface resistivity results, result ranges, and allowable result ranges for the TDOT Class D and A mixtures, respectively. Table 11 shows absorption after boiling results, result ranges, and coefficients of variation.

The acceptable range of the hardened property results was determined by obtaining the standard deviation or coefficient of variation from the appropriate test method and multiplying by an ASTM C670 factor for the number of test results (12). The multi-laboratory precision was used for the 4×8-inch cylinder results. This was used since AASHTO T 358 states that the preparation of cylinders by different operators would increase the variation above multi-laboratory precision criteria (13). All hardened property test results met the acceptable precision criteria except the TDOT Class D and A PLC compressive strength at 7 days and the TDOT Class A control at 7, 14, and 28 days (indicated in red in Tables 5 and 6). Unfortunately, there is no precision criteria available for hardened concrete absorptions after boiling. However, the coefficient of variation (COV) was determined for each mixture, and the results were lower than 10%, which was deemed acceptable. The hardened property results obtained seemed to be of sufficient quality on which to base reasonable conclusions.

Table 5: TDOT Class D Compressive Strength Results and Data Quality, psi (Mpa)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
7-days									
Control Class D	5500 (37.9)	5280 (36.4)	5780 (39.9)	5530 (38.1)	5730 (39.5)	5890 (40.6)	5618 (38.7)	610 (4.2)	719 (5.0)
PLC Class D	5790 (39.9)	6090 (42.0)	6010 (41.4)	5420 (37.3)	5330 (36.8)	6320 (43.6)	5827 (40.2)	**990 (6.8)**	746 (5.1)
14-days									
Control Class D	6190 (42.7)	6190 (42.7)	6500 (44.8)	6090 (42.0)	6210 (42.8)	6470 (44.6)	6275 (43.3)	410 (2.8)	803 (5.5)
PLC Class D	6780 (46.8)	6840 (47.2)	6740 (46.5)	6280 (43.3)	6250 (43.1)	6440 (43.4)	6555 (45.2)	590 (4.1)	839 (5.8)
28-days									
Control Class D	6780 (46.8)	6750 (46.5)	7110 (49.0)	6750 (46.5)	7230 (49.9)	7240 (49.9)	6977 (48.1)	490 (3.4)	893 (6.2)
PLC Class D	7560 (52.1)	7600 (52.4)	7700 (53.1)	7030 (48.5)	6930 (47.8)	7500 (51.7)	7387 (50.9)	770 (5.3)	946 (6.5)
56-days									
Control Class D	7800 (53.8)	7610 (52.5)	7890 (54.4)	7630 (52.6)	7650 (52.7)	8200 (56.5)	7797 (53.8)	590 (4.1)	998 (6.9)
PLC Class D	8420 (58.1)	8780 (60.5)	8700 (60.0)	7970 (55.0)	8130 (56.1)	8500 (58.6)	8417 (58.0)	810 (5.6)	1077 (7.4)

Table 6: TDOT Class A Compressive Strength Results and Data Quality, psi (MPa)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
7-days									
Control Class A	3990 (27.5)	4250 (29.3)	4180 (28.8)	4260 (29.4)	4110 (28.3)	4720 (32.5)	4252 (29.3)	**730** **(5.0)**	544 (3.8)
PLC Class A	4750 (32.8)	5430 (37.4)	5060 (34.9)	5340 (36.8)	4710 (32.5)	4860 (33.5)	5025 (34.7)	**720** **(5.0)**	643 (4.4)
14-days									
Control Class A	4650 (32.1)	4780 (33.0)	4490 (31.0)	4700 (32.4)	4460 (30.8)	5250 (36.2)	4722 (32.6)	**790** **(5.5)**	604 (4.2)
PLC Class A	5840 (40.2)	5920 (40.8)	5900 (40.7)	5960 (41.1)	5590 (38.5)	5890 (40.6)	5850 (40.3)	370 (2.5)	749 (5.2)
28-days									
Control Class A	5080 (35.0)	5080 (35.0)	5080 (35.0)	5120 (35.3)	5190 (35.8)	6030 (41.6)	5263 (36.3)	**950** **(6.6)**	674 (4.7)
PLC Class A	6770 (46.7)	6870 (47.4)	6670 (46.0)	6830 (47.1)	6420 (44.3)	6590 (45.4)	6692 (46.1)	450 (3.1)	857 (5.9)
56-days									
Control Class A	5880 (40.5)	5980 (41.2)	5910 (40.8)	5990 (41.3)	5970 (41.2)	6520 (45.0)	6042 (41.7)	640 (4.4)	773 (5.3)
PLC Class A	7320 (50.5)	7820 (53.9)	7850 (54.1)	7570 (52.2)	7080 (48.8)	7440 (51.3)	7513 (51.8)	770 (5.3)	962 (6.6)

Table 7: TDOT Class D Static Modulus of Elasticity Results and Data Quality, 10^6-psi (GPa)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
28-days									
Control Class D	3.95 (27.2)	4.05 (27.9)	4.20 (29.0)	3.95 (27.2)	4.00 (27.6)	4.05 (27.9)	4.03 (27.8)	0.25 (1.7)	0.68 (4.7)
PLC Class D	4.25 (29.3)	4.35 (30.0)	4.25 (29.3)	4.35 (30.0)	4.10 (28.2)	4.35 (30.0)	4.28 (29.5)	0.25 (1.7)	0.73 (5.0)
56-days									
Control Class D	4.25 (29.3)	4.10 (28.2)	4.15 (28.6)	4.20 (29.0)	4.30 (29.6)	4.55 (31.4)	4.26 (29.4)	0.45 (3.1)	0.72 (5.0)
PLC Class D	4.40 (30.3)	4.40 (30.3)	4.50 (31.2)	4.25 (29.3)	4.35 (30.0)	4.25 (29.3)	4.37 (30.1)	0.25 (1.7)	0.74 (5.1)

Table 8: TDOT Class A Static Modulus of Elasticity Results and Data Quality, 10^6-psi (GPa)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
28-days									
Control Class A	3.60 (24.8)	3.75 (25.9)	3.55 (24.5)	3.55 (24.5)	3.60 (24.8)	3.90 (26.9)	3.66 (25.2)	0.35 (2.4)	0.62 (4.3)
PLC Class A	4.15 (28.6)	4.40 (30.3)	4.45 (30.7)	4.45 (30.7)	3.95 (27.2)	3.90 (26.9)	4.22 (29.1)	0.55 (3.8)	0.72 (5.0)
56-days									
Control Class A	4.30 (29.6)	3.85 (26.6)	4.10 (28.2)	3.90 (26.9)	3.95 (27.2)	4.15 (28.6)	4.04 (27.9)	0.45 (3.1)	0.68 (4.7)
PLC Class A	4.30 (29.6)	4.15 (28.6)	4.30 (29.6)	4.30 (29.6)	4.00 (27.6)	4.25 (29.3)	4.21 (29.0)	0.30 (2.1)	0.72 (5.0)

Table 9: TDOT Class D Surface Resistivity Results and Data Quality (kilohm-cm)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
7-days									
Control Class D	9.7	9.2	9.3	9.6	9.8	9.5	9.5	0.6	4.8
PLC Class D	11.6	11.6	11.4	11.0	11.7	12.2	11.6	1.2	5.8
14-days									
Control Class D	10.9	10.4	10.6	11.2	11.0	10.8	10.8	0.8	5.4
PLC Class D	14.6	14.3	14.4	14.2	14.8	15.1	14.6	0.9	7.3
28-days									
Control Class D	13.8	13.3	13.7	14.5	14.3	14.1	14.0	1.2	7.0
PLC Class D	21.1	21.0	20.2	20.6	23.0	23.3	21.5	3.1	10.8
56-days									
Control Class D	20.8	20.4	20.3	21.2	20.7	21.3	20.8	1.0	10.4
PLC Class D	39.4	38.8	39.6	38.9	39.6	39.4	39.3	0.8	19.6

Table 10: TDOT Class A Surface Resistivity Results and Data Quality (kilohm-cm)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
7-days									
Control Class A	8.6	8.3	8.5	8.5	7.7	8.2	8.3	0.9	4.2
PLC Class A	9.1	9.5	8.7	8.9	8.6	8.4	8.9	1.1	4.4
14-days									
Control Class A	9.5	9.1	9.2	9.3	8.7	9.2	9.2	0.8	4.6
PLC Class A	11.3	11.7	10.5	11.0	10.9	10.5	11.0	1.2	5.5
28-days									
Control Class A	12.1	11.7	11.6	11.9	11.5	11.9	11.8	0.6	5.9
PLC Class A	16.6	16.9	15.7	16.0	15.9	15.5	16.1	1.4	8.1
56-days									
Control Class A	19.3	19.0	18.6	18.8	18.4	20.0	19.0	1.6	9.5
PLC Class A	29.5	30.2	27.3	27.9	29.1	28.0	28.7	2.9	14.3

Table 11: 56-day Absorption after Boiling Results, Ranges and Coefficients of Variation

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	COV%
Control Class D	4.09	4.21	4.32	4.37	4.58	4.45	4.34	0.49	4.0
PLC Class D	4.50	4.69	4.42	4.41	4.58	4.33	4.49	0.36	2.9
Control Class A	4.78	4.91	4.78	4.82	4.73	4.41	4.74	0.50	3.6
PLC Class A	4.58	4.69	5.14	5.03	5.06	5.21	4.95	0.63	5.2

Analysis of Results

Statistical Comparison of Results

The tests of the hypotheses of equality of corresponding mean values of concrete properties across mixes are represented in Table 12 for the various mixtures at a given curing time and for the same mixture over various curing times respectively. A statistical t-test with the assumption of unequal variances was performed. The estimated t-value was observed to be less than the critical t-value at the corresponding degree of freedom with a five percent significance level. The compared mixes that were deemed to have statistically equal values were denoted as NSD (no significant difference) in Table 12. When the estimated t-value exceeded the critical t-value at the corresponding degree of freedom with five percent significance level, the compared mixes were deemed to have significantly different values. The green shaded cells in Table 12 indicate the PLC results are statistically significantly different and superior to the OPC results.

Table 12: Statistical Analysis Comparing PLC vs. OPC

Property	PLC Class D Concrete vs. OPC Class D Concrete	PLC Class A Concrete vs. OPC Class A Concrete
Surface resistivity @ 7 days	Superior	Superior
Surface resistivity @ 14 days	Superior	Superior
Surface resistivity @ 28 days	Superior	Superior
Surface resistivity @ 56 days	Superior	Superior
Compressive Strength @ 7 days	NSD	Superior
Compressive Strength @ 14days	NSD	Superior
Compressive Strength @ 28 days	Superior	Superior
Compressive Strength @ 56 days	Superior	Superior
Static Modulus of Elasticity @ 28 days	Superior	Superior
Static Modulus of Elasticity @ 56 days	NSD	NSD
Absorption after Boiling	NSD	NSD

Table 12 shows that in all 22 cases, or 100% of the time, PLC was superior or equal to OPC. This would seem to be strong evidence that PLC is as good if not better than OPC.

TDOT Specification Compliance

The 28-day compressive strength requirement for TDOT Class D concrete is 4000-psi. All compressive strength results shown in Table 5 exceed this specification at all ages. Similarly, all compressive strength results at all ages shown in Table 6 exceed the TDOT Class A specification for 28-day requirement of 3000-psi. There are no TDOT specifications for SR, static modulus of elasticity, or absorption for Class A or D concrete mixtures.

Material Cost

In order to compare costs between OPC and PLC, one would have to consider a number of variables. While PLC can cost less to manufacture due to the additional limestone, variables such as shipping methods and distances must be accounted for. Due to these ever-changing variables, it is difficult to accurately estimate the costs. Ultimately, there should not be a significant cost difference.

Need for Further Research

The current project only compared one source of PLC. The only source of PLC currently in the state of Tennessee is located in Memphis. It seems prudent to make further comparisons with other PLC samples, possibly from other states. However, if the other PLC sources meet the same requirements as the sample used in this project, it seems reasonable to expect similar performance.

Conclusion

Based on the testing and statistical analysis that was conducted during this project, there is evidence that strongly supports that the PLC that was evaluated is equal to or superior in performance as a cementing material compared to OPC.

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