U.S. Department of Transportation Federal Highway Administration

Turner-Fairbank

Portland Limestone Cement Variability and Use in High-Early-Strength (HES) Concrete Mixtures

American Concrete Institute (ACI) Spring 2024 Meeting New Orleans, LA

Michelle Cooper Concrete Materials Research Engineer, Federal Highway Administration (FHWA), Office of Infrastructure Research and Development, Infrastructure Materials Team

March 26, 2024



Who Am I?

- B.S. in Civil Engineering from Virginia Tech
- Worked at NIST
- ► M.S. in Civil Engineering from UIUC
- Worked as a forensic structural engineer
- Concrete Materials Research Engineer for FHWA TFHRC
- Concrete Sustainability Ph.D. student at Michigan Tech





Turner-Fairbank Highway Research Center

Source: FHWA.



© Michigan Tech, https://www.mtu.edu/umc/resources/download/



Robert Marinello Robert.Marinello.CTR@dot.gov

> Technician Genex Systems

Scott Muzenski Scott.Muzenski.CTR@dot.gov

Concrete Research Engineer Concrete Contract Laboratory Manager Genex Systems

Dr. Maria Juenger mjuenger@mail.utexas.edu Professor The University of Texas at Austin

Michelle Cooper

Michelle.Cooper@dot.gov Concrete Materials Research Engineer Federal Highway Administration

Acronyms and Abbreviations

Acc	accelerator
ADOT	Arizona Department of Transportation
AE	air entrained
AFt	aluminate ferrite trisubstituted
AI	alumina
AI_2O_3	alumina oxide
FHWA	Federal Highway Administration
GG	ground glass
HES	high-early-strength
HRWR	high-range water reducer
MK	metakaolin
NAE	non-air entrained
OPC	ordinary portland cement
PennDOT	Pennsylvania Department of Transportation
PLC	portland limestone cement
SCM	supplementary cementitious material
TxDOT	Texas Department of Transportation
w/c	water-to-cement ratio
Wt	weight

_ _ _ _ _

Why Is FHWA Performing **PLC Research?**

PLC TechNote is available!⁽¹⁾ It discusses implementation challenges and best practices.



Portland Limestone Cement FHWA Publication No.: FHWA-HRT-23-104 FHWA Contact: Michelle Cooper (ORCID: 0000.0001-8112-693X), HRDI-10. 202-493-3691, michelle.cooper@dot.gov CID: 0000-0001-9205-1486). HICP-40. 2-366-0120, robert spragg@dot.gov e cement (PLC) is g to ASTM International (ASTM) C59500 or American Associati Highway and Transportation Officials (AASHTO) M 240,00 PLC thins 5- to 15-percent blended or interground limestone and is als nent in ASTM C595 and AASHTO M 240.03 PLC i ice equivalent to that of ordinary portland c

are typically producing PLC with

contractors have reported challenges with it a due to limited field expe Note is designed to help State h e acquainted with technical and backy a regarding PLC and to promote its successful application natides information regarding the history, specification

AASHTO M 85(**) for 1:1 replac potential (GWP) 8.3 percent on average, thanks to

listory of PLC in the United States

Financy of FLO in the others denter ASTM C150 began allowing the use of up to 5-percent interground limestone in OPC types 1-V in 2004 on Before then, in North Amer national in GPU (JPU I-V in 2006)," sectore taes, in Porth American pecifications, limestone had not been permitted as an addition to cense ASHTO M 85 was harmonized with ASTM C150 in 2007, when the interest ellowable limeters with ASTM C150 in 2007. percent allowable limestone content for OPC was balloted and accept PLC was introduced in the United States in 2005 through ASTM C115 mance cement.⁽⁷⁾ While cements with high ground limer been successfully used in Europe for 15-20 yr, North Ar differs in that it was designed to have mechanical prodiffers in that it was designed to have nucleating properties similar to those of OCC at 2.4 and the cancer producers often add applementary connentiations materials (SCAM) to PEC conformation at 0.23 ASTM C593 and AASTTO AD4 standard specifications add systemic creates the standard of the specification and the specifications address to be used in historized product creates, and the specifications address the produc-tion of the specification and the specifications address and the produc-ant La PEC to Whate PLC has been allowed in many Materia size 2012.

Source: FHWA.(1)



https://highways.dot.gov/research /publications/infrastructure/FHWA -HRT-23-104.pdf (1)

Use tools such as calorimetry to investigate the early-age reaction behavior of the PLC or the PLC in combination with the anticipated admixtures and SCMs.

Differing sulfate content requirements for PLC concretes especially with SCMs, compared to **OPC** concretes.

Evaluate production variation (e.g.,

strength or air content) prior to transitioning from OPC to PLC to provide an understanding of within-plant product variations.

FHWA PLC Research

PLC Variability

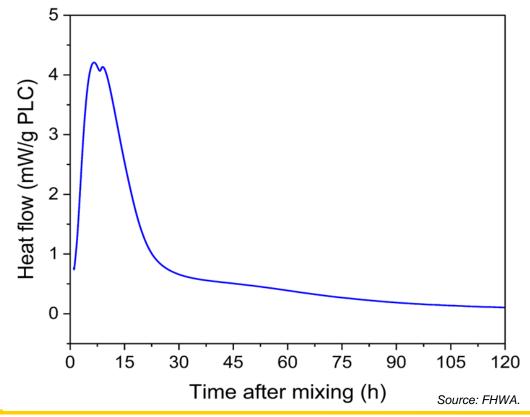
Provide the industry with information regarding how different PLC characteristics can affect performance.

PLC for HES Concretes

Evaluate how PLCs can be used in HES concretes.

Hydration Kinetics

Typical Hydration Kinetics Curve From Isothermal Calorimetry



Hydration kinetics relate to:

- Performance.
- Reactivity:
 - \triangleright Rate of reaction.
 - Magnitude of reaction.



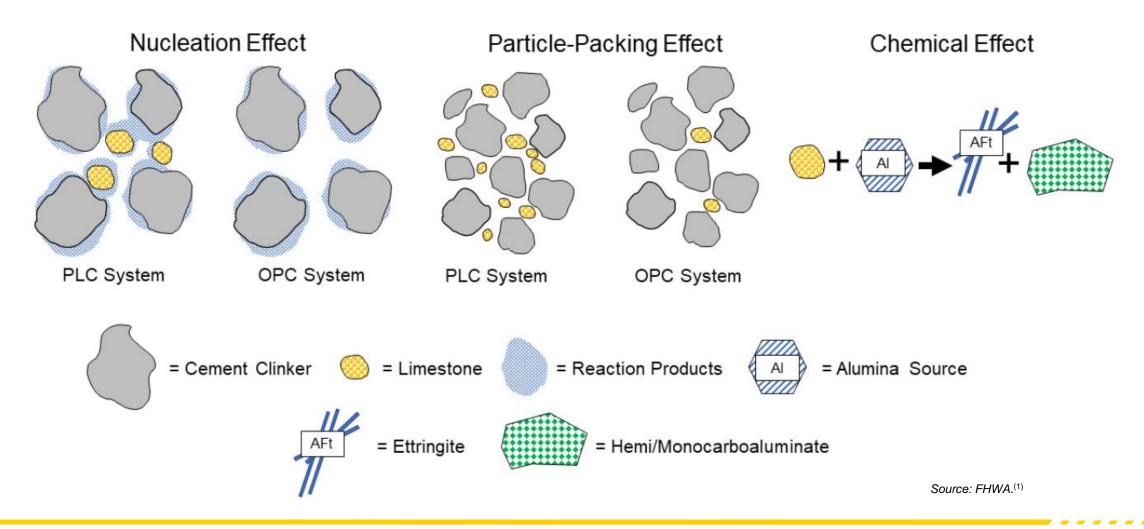
© Uschools/iStock.

PLC Variability

U.S. Department of Transportation Federal Highway Administration

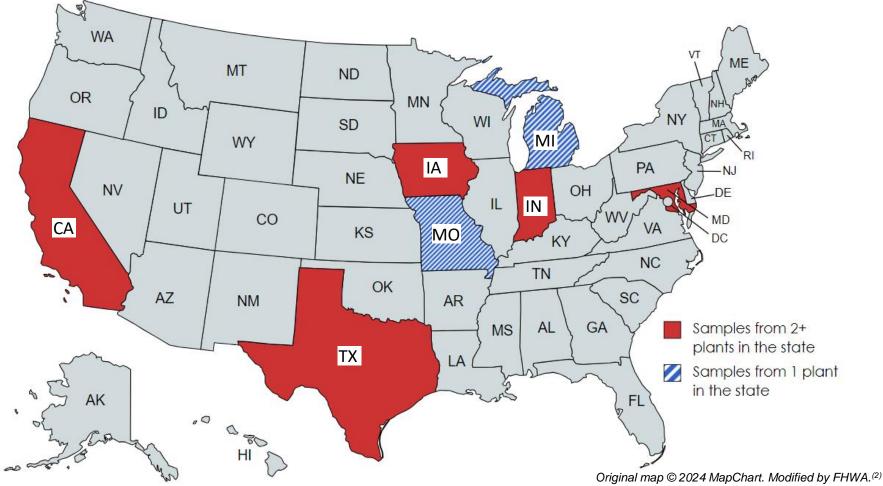
Turner-Fairbank

Limestone Effects in Cement



U.S. Department of Transportation Federal Highway Administration

Map of PLCs Tested From Around the United States

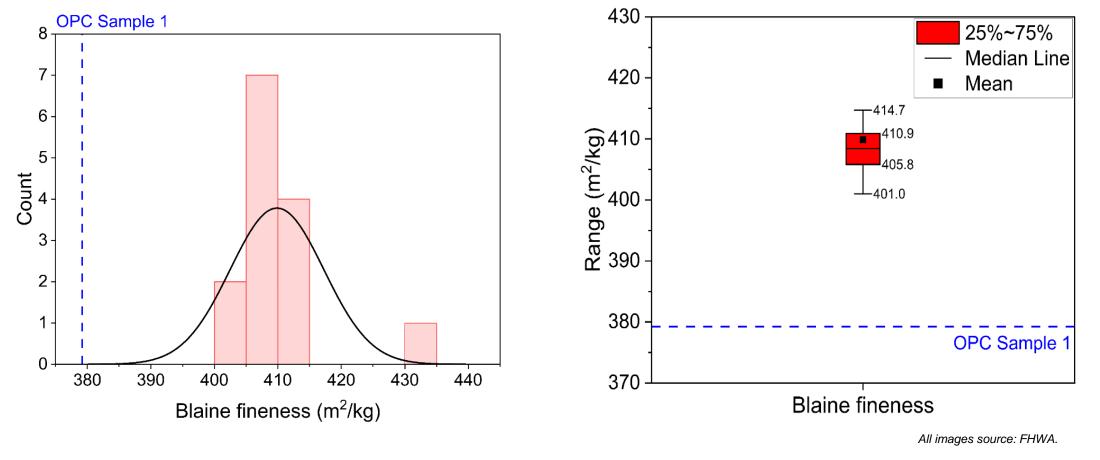


10

U.S. Department of Transportation Federal Highway Administration



Distribution of Measurements



U.S. Department of Transportation Federal Highway Administration

Minimum and Maximum of Fineness Measured for PLCs Versus OPC

- - 11

Density

Distribution of Measurements

OPC Sample 1 3.16 8 25%~75% Median Line 3.14 7. Mean 3.12 6 **OPC Sample 1** Range (g/cm³) 3.10 5 Count 4 3.08 -3.08 3. 3.06 3.06 3.05 2 3.04 <u>____3.03</u> 1-3.02 3.00 3.02 3.04 3.06 3.08 3.10 3.12 3.14 2.98 3.00 Density Density (g/cm³) All images source: FHWA

Minimum and Maximum of Density

12

Measured for PLCs Versus OPC

Turner-Fairbank U.S. Department of Transportation Highway Research Center Federal Highway Administration

2

Calcium Carbonate Content

Distribution of Measurements

OPC Sample 1 8 18 25%~75% 7 Median Line 16 Mean 6 14 5 Count 10.33 9.74 3 7.87 2 6 1 4 **OPC** Sample 1 0 12 14 18 2 10 16 20 6 8 0 Δ 2 Calcium Carbonate Calcium Carbonate (%) All images source: FHWA

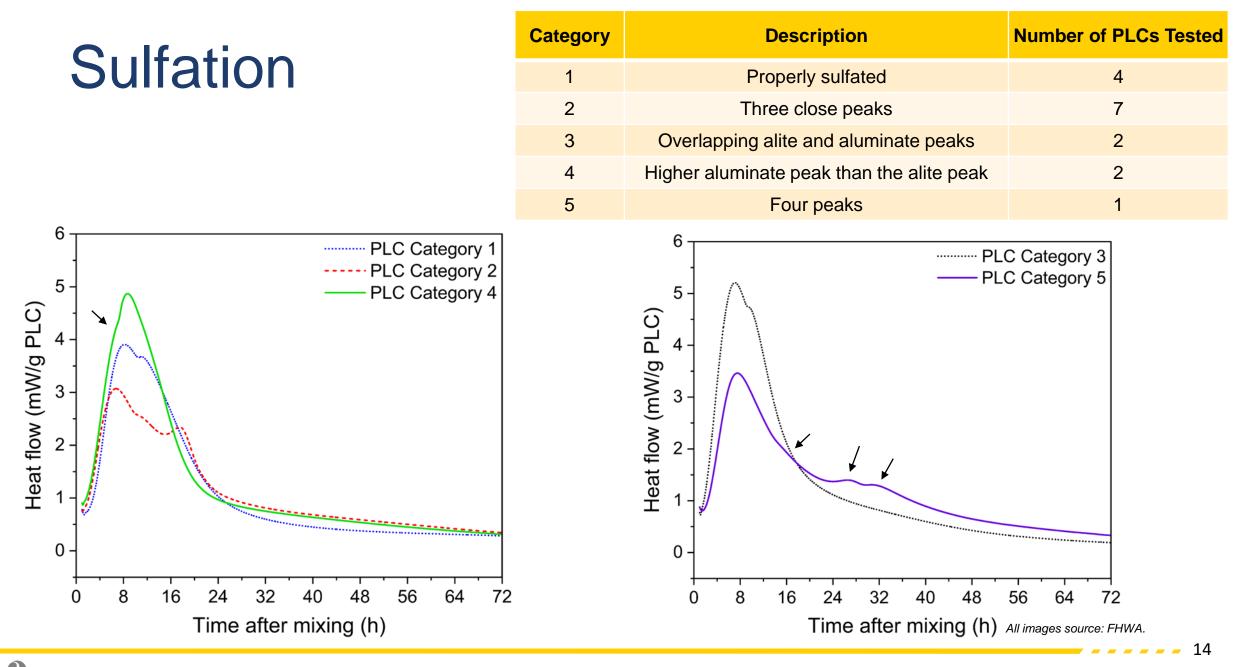
Minimum and Maximum of

Calcium Carbonate Content

Measured for PLCs Versus OPC

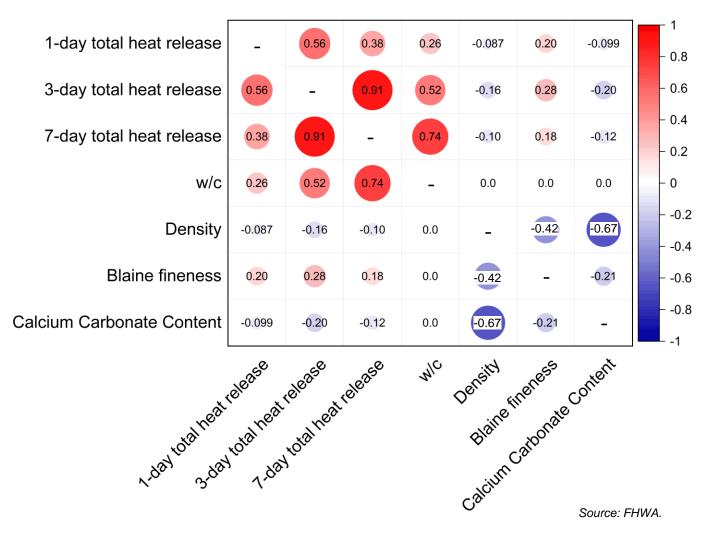
13

U.S. Department of Transportation Federal Highway Administration



U.S. Department of Transportation Federal Highway Administration

Correlations



How Can PLC Characteristics Affect Performance? (1/3)

PLC characteristic:

- Fineness.
- Density.
- Sulfate level.
- Calcium carbonate content.

Potential influence on performance:

- Air content.
- Slump.
- Setting time.
- Strength development.
- Water demand.
- Shrinkage.

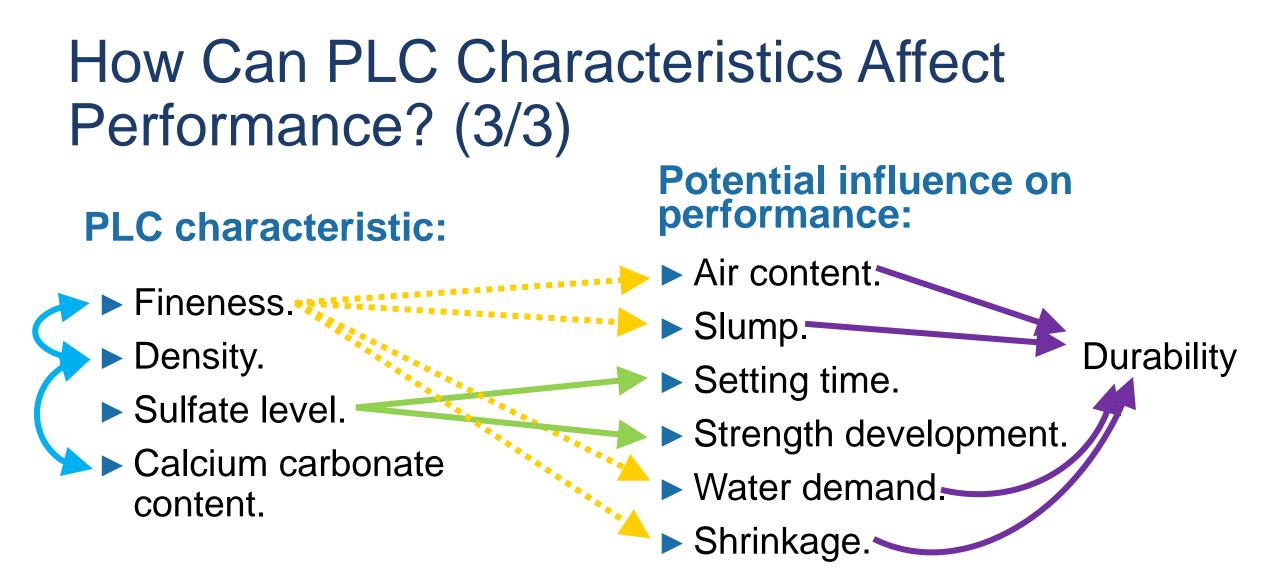
How Can PLC Characteristics Affect Performance? (2/3)

PLC characteristic:

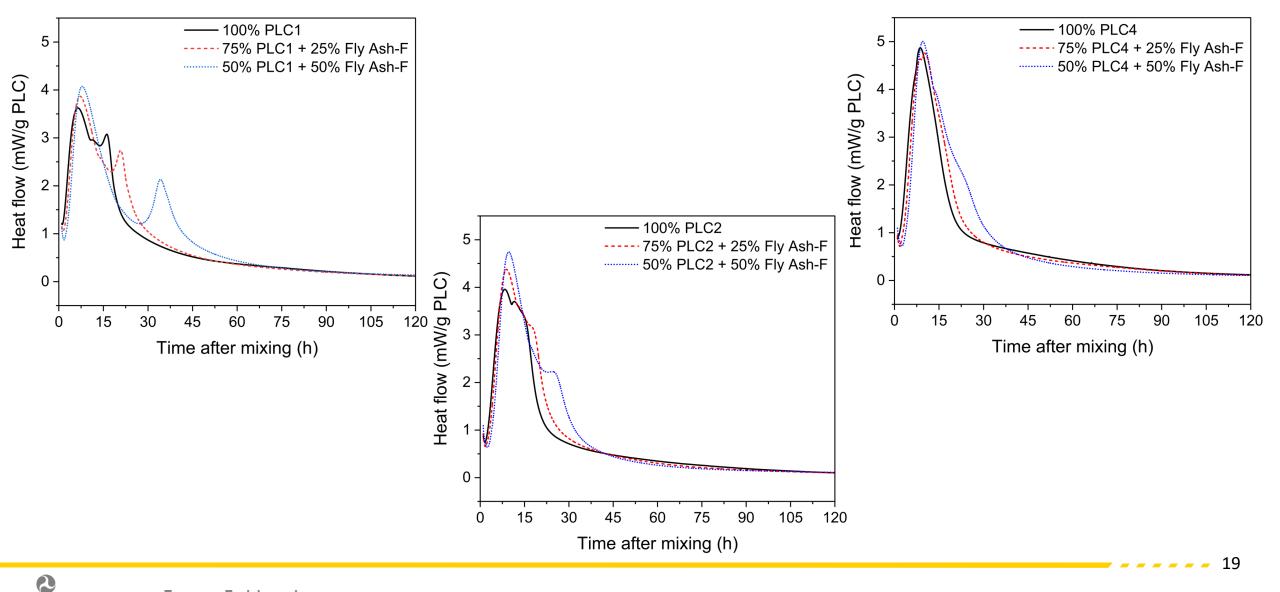
Fineness.
Density.
Sulfate level.
Calcium carbonate content.

Potential influence on performance:

- ► Air content.
- ► Slump.
- Setting time.
- Strength development.
- ► Water demand.
- Shrinkage.



Varying effects when combined with SCMs



U.S. Department of Transportation Federal Highway Administration

Summary

- Higher fineness typically results in higher water demand.
- Densities ranged from 3.03 to 3.10 g/cm³.
- Calcium carbonate contents:
 - ▷ Ranged from 5 to 17 percent.
 - Correlated with lower densities.
- Varying sulfation levels lead to varying hydration kinetics and performance.
- Greater variability in hydration kinetics expected when used with SCMs.

PLC-Related Publications

Background and best practices TechNote

is available!⁽¹⁾



2

U.S. Department of Transportation

Federal Highway Administratio

Turner-Fairbank

Research, Development,

and Technology Turner-Fairbank Highway Research Center

6300 Georgetown Pike McLean, VA 22101-229

ittps://highways.dot.gov/researcl

Portland Limestone Cement FHWA Publication No.: FHWA-HRT-23-104 FHWA Contact: Michelle Cooper (ORCID: 0000-0001-8112-693X), HRDI-10,

202-493-3691, michelle cooper@dot.gov Robert Spragg (ORCID: 0000-0001-9205-1486), HICP-40 202-366-0120, robert.spragg@dot.gov

INTRODUCTION

Portland limestone cement (PLC) is a binary blended cement manufactured according to ASTM International (ASTM) C595⁽⁰⁾ or American Association accorage to rob 1 or americanobal (AS 1 A) C 3979 or American Association of State Highway and Transportation Officials (AASHTO) M 240 to PLC contains 5 to 15 percent blended or interground limestone and is alternatively community to 15-percent thermore or margarounds interactions and an interaction identified with the term "IL," which indicates portland cement-limestone Identication what use terms ______ want at faunt-ance portunities tenterin-materionee blended cement in ASTM C595 and AASHTO M 240.0.3 PLC is engineered to becauce venera in A-3 in U-39 and A-Astrillo At 240.....FLU is engineered to provide 28.4 performance equivalent to that of ordinary portland cement (OPC) (ASTM C150th or AASHTO M 85⁽⁴⁾) for 1.1 replacement while reducing (ASIM UDD** or AASH1U M 85*) for 11 reprocesses while result global-warming potential (GWP) 8.3 percent on average, thanks to its Borden manuage processors (Core J and percessor to a treating) transition of an lower clinker content.⁽⁶⁾ Centent suppliers are typically producing PLC with 10- to 12-percent limestone powder because such a blend results in a more

Though PLC has now become widely available throughout the United States, several agencies and contractors have reported challenges with its Surrey, several agenates and connectors have appendent characteristics with no implementation due to limited field experience using the material in the United inspectmentation one to manual scale conversion training the same state on the States (*) This TechNote is designed to help State highway agencies (SHAs) and contractors become more acquainted with technical and background and contractors become more acquained with rectances and onceground information regarding PLC and to promote its successful application nationwide. mortmaton regarding rice and to pressive an accession appreciations. The document provides information regarding the history, specifications, The occurate provides information regarding the matory, spectrications, sustainability, manufacture, engineering principles, and performance of PLC. sustainaouny, manufacture, engineering principies, may principation of a sec-In addition, the document presents successful case studies and best practices for

History of PLC in the United States

ASTM C150 began allowing the use of up to 5-percent interground limestone in OPC types I-V in 2004 to Before then, in North American American provide the second se AASTI10 M 0.9 was harmonized with AS1M 0.100 m 2007, when use 5 percent allowable limestone content for OPC was balloted and accepted 40 PLC was introduced in the United States in 2005 through ASTM C1157 as a PLC was introduced in the content states in 2000 introduction extents performance cement (7) While cements with high ground limestone contents performance cement, with white cements with high ground innerstone contents have been successfully used in Europe for 15–20 yr, North American PLC differs in that it was designed to have mechanical properties similar to ements in mar it was mesigned to have mechanical properties summar at those of OPC at 28 d, and the concrete producers often add supplementary cementitious materials (SCMs) to PLC in Beginning in 2012, ASTM C595 cementitious materians (SCANS) to FLC. " Degimining in 2012, AD 1100 COST and AASHTO M 240 standard specifications for blended hydraulic cements started allowing up to 15-percent blended or interground limestone to be sauce anowing up to 12-percent otended or interground innestone to be used in binary blended cements, and the specifications defined the product as IL or PLC⁽¹³⁾ While PLC has been allowed in many States since 2012,



https://highways.dot.gov/research /publications/infrastructure/FHWA -HRT-23-104⁽¹⁾

Upcoming Publications

TechNote: PLC Variability*



Journal paper: "Determining the sulfation level of PLC using isothermal calorimetry"†

Determining the sulfation level of portland-limestone cement (PLC) using

Payam Hosseini¹, Michelle Helsel², Scott Muzenski¹ Genex Systems, LLC, Turner-Fairbanks Highway Research Center (TFHRC), 6300 smes systems, 1.4.5., 1.188897-2.98780888 ruggivosy něostavku venus (1.87.1876-2.9.1806) orgetosu Pike, McLean VA 22101; poyum houseini etr@dot.gov, scoti muzenski etr@dot.gov ² Federal Highway Administration (FHWA), TFHRC, 6300 Georgetown Pike, McLean VA

Portind-lineatone ensual (PLC) represents a modern type of portland cennent gaining significant fractions within the United States' cennent industry due to its reduced environmental simpler compared to onlineary mortifield cenner (OPC, Although reducid) recent in the U.S. environmental instact, concernent (OPC, Although Archiver, and Archiver, and Archiver, and the early stages of hydrafion. This study moderways to a supply isofhermal calorimetry to major the hydrafic isoffaction of hydrafic and the study of the original calorimetry to any the hydrafic isoffaction of the study of the ment (PLC) represents a modern type of portland cer Just enzy sugges or nyunation. This study enservors to employ isotnermal encomment to analyze the hydration kinetics of commercially-available PLCs in the United States, specifically focusing ate nyummon americs or commercisaty-available PLCs in the United States, specifically focusie in the early stages of up to 7 days. Sixteen PLC samples sourced from diverse centern plants acr on the early stages of cap to 7 days. Stateen PLC samples sourced from fiverse connext plants across the constry underwrate examination. Additionally, the research explored the impact of applementary connextition materials (SCM) on the hybridine behavior of PLC. The finding the state of the state. supplementary communitions materials (SCMs) on the hydrotical convertor or Pr.A.: His intensing highlight a proceeding incurs many commercially-available Pr.C. activity independent evidence raising concerns about their computability with SCMs which may potentially lead to a subfar-raising concerns about their computability with SCMs which may potentially lead to a subfar-ter of the subfar g concerns arous mear companions with SLASS which may portunally lead to lance in concrete materials. This paper underscores the critical need for sulfate adjur PLCs, particularly when considering their utilization alongside SCMs. Keywords: Portland-limestone cement (PLC): Cement hydration kinetics: Isothermal calorimetry

1. Introduction

newtone stands out as a globally abundant and cost-efficieve material extensively utilized in the storenova ennov ou no a postority secondar mo correcterity e material extensively utilized in the production of ennersh and concrete [1]. In contribution to the mechanical strength and durability of concrete arises from both physical and chemical effects.

All images source: FHWA

21

*Hosseini, P., M. Helsel, and S. Muzenski. Portland Limestone Cement Variability. Washington, DC: FHWA. In progress.

[†]Hosseini, P., M. Helsel, and S. Muzenski. Forthcoming. "Determining the sulfation level of portlandlimestone cement (PLC) using isothermal calorimetry." In progress.



© Uschools/iStock.

Use of PLCs in HES Mixtures



Turner-Fairbank Highway Research Center



Highlight the potential differences when switching OPC with PLC in HES mixtures.

Set accelerators and corrosion inhibitors

ASTM C494:⁽⁴⁾ type C calcium nitrite and calcium nitrate based Polycarboxylate HRWR to ensure workability

ASTM C494:⁽⁴⁾ types A and F High-reactivity SCM: high purity metakaolin (MK)

Low-reactivity SCM: Ground glass (GG)

Mixture Designs Tested*

	Ceme	Set Accelerating			
Mix ID	PLC	OPC	GG	MK	Admixture (Y/N)
PLC	100	0	0	0	Ν
OPC	0	100	0	0	Ν
70PLC_30GG	70	0	30	0	Ν
95PLC_5MK	95	0	0	5	Ν
70PLC_25GG_5MK	70	0	25	5	Ν
PLC_Acc	100	0	0	0	Y
OPC_Acc	0	100	0	0	Y
70PLC_30GG_Acc	70	0	30	0	Y
95PLC_5MK_Acc	95	0	0	5	Y
70PLC_25GG_5MK_Acc	70	0	25	5	Y

*Montanari, L., M.A. Helsel, P. Hosseini, and M. Juenger. "Evaluation of early age strength and porosity of binary and ternary mixtures incorporating portland limestone cement and a set accelerator." In progress.

24

_ _ _ _ _ _ _ _

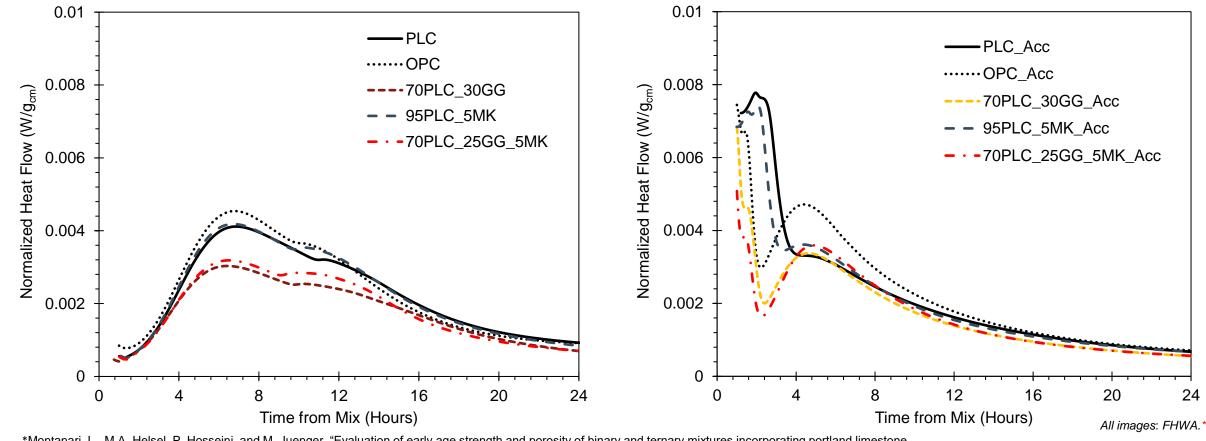
Y = yes; N = no.

Normalized Heat Flow

Without Accelerators

With Accelerators

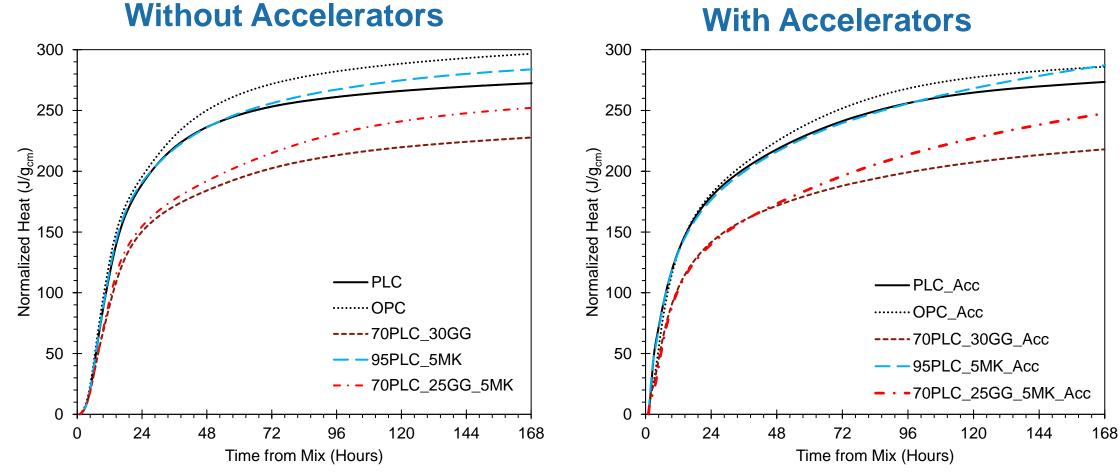
25



*Montanari, L., M.A. Helsel, P. Hosseini, and M. Juenger. "Evaluation of early age strength and porosity of binary and ternary mixtures incorporating portland limestone cement and a set accelerator." In progress.

U.S. Department of Transportation Federal Highway Administration

Cumulative Heat Released



*Montanari, L., M.A. Helsel, P. Hosseini, and M. Juenger. "Evaluation of early age strength and porosity of binary and ternary mixtures incorporating portland limestone cement and a set accelerator." In progress.

All images source: FHWA.*

U.S. Department of Transportation Federal Highway Administration

Mortar Cube Strength

Without Accelerators 120 120 Compressive Strength (Mpa) Compressive Strength (Mpa) ■ PLC ■ PLC Acc □ OPC □ OPC Acc ■70PLC 30GG ■70PLC_30GG_Acc ■95PLC 5MK ■95PLC_5MK_Acc ☑ 70PLC_25GG_5MK Z70PLC_25GG_5MK_Acc 20 20 0 0 28 7 7 28 Time from Mix (Days) Time from Mix (Days) *Montanari, L., M.A. Helsel, P. Hosseini, and M. Juenger. "Evaluation of early age strength and porosity of binary and ternary All images source: FHWA.* mixtures incorporating portland limestone cement and a set accelerator." In progress.

With Accelerators

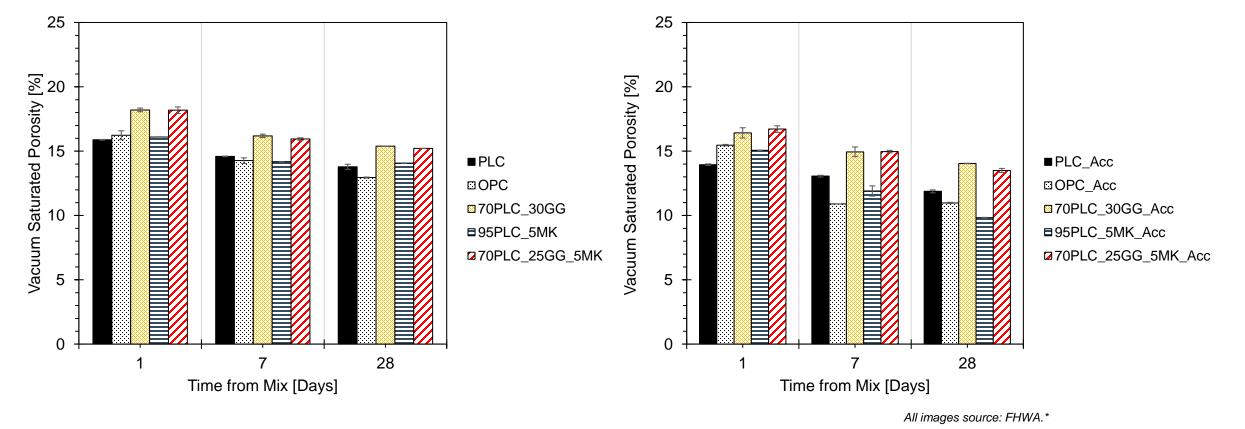
27

2 Turner-Fairbank U.S. Department of Transportation | Highway Research Cente Federal Highway Administration



Without Accelerators

With Accelerators



*Montanari, L., M.A. Helsel, P. Hosseini, and M. Juenger. "Evaluation of early age strength and porosity of binary and ternary mixtures incorporating portland limestone cement and a set accelerator." In progress.

U.S. Department of Transportation Federal Highway Administration - 28

Concrete Strength Development

Extrapolated using isothermal calorimetry, mortar cube strengths, and Bentz et al.⁵ methodology.

Air Entrained Non-Air Entrained 40 40 PLC Acc AE PLC Acc NAE 35 35 ·······OPC Acc AE 05 Strength (MPa) Compressive Strength (MPa) 0 5 5 05 0 5 05 ······OPC Acc NAE 70PLC 30GG Acc AE 70PLC 30GG Acc NAE 95PLC 5MK Acc AE 95PLC 5MK Acc NAE Compressive 12 12 10 70PLC 25GG_5MK_Acc 70PLC 25GG 5MK Ac AE c NAE — — TxDOT -TxDOT ---- ADOT 5 5 --- ADOT PennDOT 0 0 PennDOT 10 12 14 16 18 20 22 24 8 2 0 8 10 12 14 16 18 20 22 24 0 2 6 4 Time from Mix (Hours) Time from Mix (Hours) *Montanari, L., M.A. Helsel, P. Hosseini, and M. Juenger. "Evaluation of early age strength and porosity of binary and ternary mixtures incorporating portland limestone cement and a set accelerator." In progress. All images source: FHWA. 29

PLC Use in HES Mixtures Related Publications

Upcoming Publication*

*Montanari, L., M.A. Helsel, P. Hosseini, and M. Juenger. "Evaluation of early age strength and porosity of binary and ternary mixtures incorporating portland limestone cement and a set accelerator." In progress.

Evaluation of Early Age Strength and Porosity of Binary and Ternary Mixtures Incorporating Portland Limestone Cement and a Set Accelerator

Authors

Luca Montanari (Corresponding Author)¹ Michelle Helsel² Payam Hosseini³ Maria Juenger⁴

¹Graduate Student Cockrell School of Engineering University of Texas at Austin Austin, TX 78712 (<u>lucopr@gmail.com</u>)

²Concrete Laboratory Federal Lab Manager Turner-Fairbank Highway Research Center Federal Highway Administration McLean, VA 22101 (<u>michelle.cooper@dot.gov</u>)

³Concrete Materials Research Engineer <u>Genex</u> Systems, LLC Turner-Fairbank Highway Research Center McLean, VA 22101 (payam.hosseini@dot.gov)

⁴Professor Cockrell School of Engineering University of Texas at Austin Austin, TX 78712 (<u>mjuenger@mail.utexas.edu</u>)

Abstract

With the goal of reaching carbon neutrality by 2050, the cement and concrete industries in the US have accelerated the implementation and adoption of technologies that promote the reduction of embodied carbon emissions in new concrete mixtures. One of the available strategies to reduce the embodied emissions of concrete is the use of cements with a lower clinker content than the typical ordinary portland cement (OPC). Portland limestone cement (PLC) is one example of lower clinker cement, thanks to the limestone content ranging between 5 and 15%. PLC is designed to provide similar 28-day compressive strength to an OPC produced from the same clinker. However, little information and data are currently available regarding PLC's ability to satisfy very early age mechanical performance (i.e., within 24 hours from initial mixing) for high-early-strength (HES) concrete applications. Due to the partial replacement of clinker with limestone in PLC, it is not immediately clear whether early age reactions can

Source: FHWA.

- 30

Summary

Can we use PLC in HES mixtures? **YES!**

- PLC can replace OPC in HES mixtures with and without SCMs and accelerating admixtures while meeting State HES requirements, depending on:
 - ▷ SCM replacement level.
 - ▷ SCM reactivity and type.
 - ▷ Exposure class.
 - ▷ Reopening strength and time requirements.
- The inclusion of accelerators improved early-age degree of reaction and compressive strength for all systems.

Questions?



Michelle Cooper

michelle.cooper@dot.gov

U.S. Department of Transportation Federal Highway Administration

Turner-Fairbank Highway Research Center

© 2021 Peeterv / iStock.

References

- Montanari, L., M. A. Helsel, R. Spragg, O. B. Isgor, and W. J. Weiss. 2023. *Portland Limestone Cement*. Publication No. FHWA-HRT-23-104. Washington, DC: FHWA. <u>https://doi.org/10.21949/1521434</u>, last accessed March 7, 2024.
- MapChart. 2024. MapChart (software). <u>https://www.mapchart.net/usa.html</u>, last accessed March 12, 2024.
- 3. ASTM. 2018. Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus. ASTM C204-18e1. West Conshohocken, PA: ASTM International.
- 4. ASTM International. 2017. *Standard Specification for Chemical Admixtures for Concrete*. ASTM C494/C494M-17. West Conshohocken, PA: ASTM International.
- Bentz, D. P., T. Barrett, I. De La Varga, and W. J. Weiss. 2012. "Relating Compressive Strength to Heat Release in Mortars." *Advances in Civil Engineering Materials* 1, no. 1: 14. <u>https://doi.org/10.1520/ACEM20120002</u>, last accessed March 7, 2024.



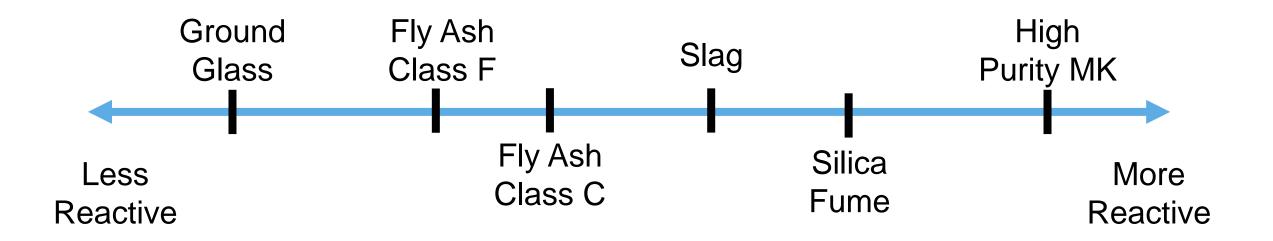
© Uschools/iStock.

Extra Slides

U.S. Department of Transportation Federal Highway Administration

Turner-Fairbank Highway Research Center

SCM Reactivity





36

_ _ _ _ _

Disclaimer

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this presentation only because they are considered essential to the objective of the presentation. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

Except for the statutes and regulations cited, the contents of this presentation do not have the force and effect of law and are not meant to bind the States or the public in any way. This presentation is intended only to provide information regarding existing requirements under the law or agency policies.