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CONCRETE PAVEMENT TEST SECTIONS WITH OPTIMIZED AGGREGATE MIXTURES AND PORTLAND-LIMESTONE CEMENT IN MINNESOTA

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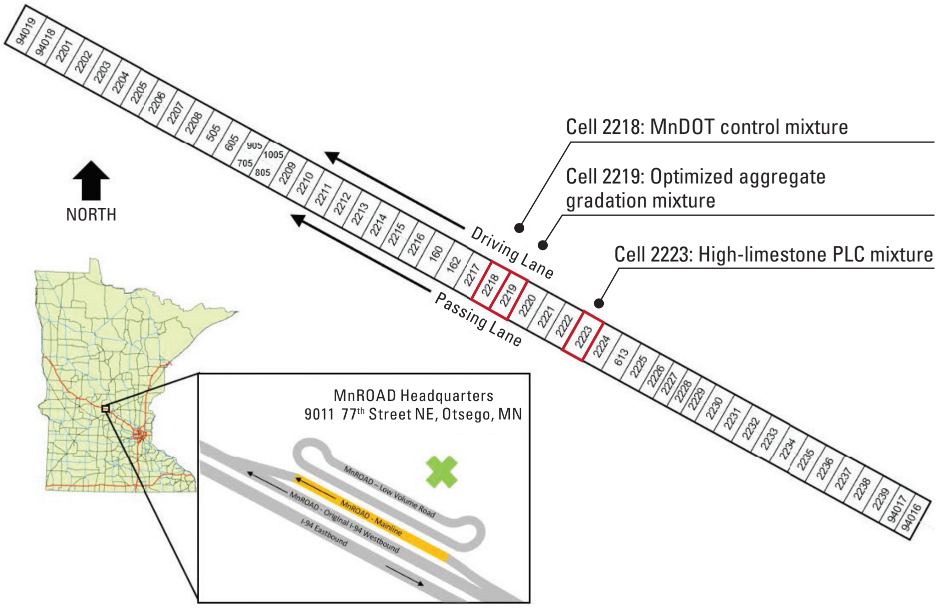
Introduction

In 2022, the Minnesota Department of Transportation (MnDOT), in collaboration with the National Road Research Alliance (NRRA), conducted a concrete pavement experiment at the MnROAD test track facility to investigate sustainability-related research topics. Sixteen sections were constructed with reduced embodied carbon concrete paving mixtures to evaluate, test, and observe the mixtures' constructability, effectiveness, and behavior (Bautista et al. 2023).

Two test cells from this experiment are highlighted in this case study. One (Cell 2219) contained a concrete mixture with a reduced total cementitious materials content achieved using an optimized aggregate gradation, and the other (Cell 2223) contained a high-limestone (20%) portland-limestone cement (PLC). Additionally, a third cell (Cell 2218) was constructed from a typical MnDOT concrete paving mixture as an experimental control. The locations of the test cells relative to the MnROAD facility are shown in Figure 1.

The following carbon reduction strategies were used in the two test cells:

1. In Cell 2219, a reduced total cementitious content of 501 lb/yd³ achieved through further optimization of the aggregate gradation
2. In Cell 2223, a high-limestone (20% limestone) PLC



Adapted from Bautista et al. 2023

Figure 1. Cell locations

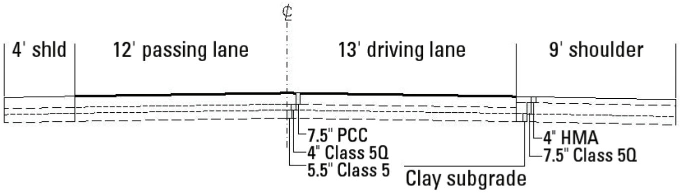
Pavement Design, Materials, and Construction

Structural Design

All three cells were constructed with similar cross sections consisting of 7.5 in. of concrete placed on 4 in. of Class 5Q aggregate base over 5.5 in. of Class 5 subbase (per MnDOT requirements) (Bautista et al. 2023). All sections had a 13 ft wide driving lane, a 12 ft wide passing lane, and 4 ft and 9 ft wide shoulders, as shown in Figure 2. In general, the concrete slabs were 15 ft long, and the transverse joints contained 1.25 in. diameter epoxy-coated steel dowel bars spaced 12 in. on center.

Paving Materials

The control mixture (Cell 2218), representing a typical MnDOT concrete paving mixture, had a total cementitious materials content of 570 lb/yd³ that consisted of 70% by weight AASHTO M 240 (ASTM C595) Type IL(8) PLC and 30% by weight AASHTO M 295 (ASTM C618) Class F coal ash.



Recreated from Bautista et al. 2023

Figure 2. Typical test cell cross section and geometry

The mixture for Cell 2219 used the same constituent materials as the control mixture but with an aggregate gradation that was further optimized from the control to specifically increase aggregate volume, which consequently allowed a significant reduction in the cementitious materials content to 501 lb/yd³.

The mixture for Cell 2223 contained an off-specification high-limestone Type IL(20) PLC and 30% by weight AASHTO M 295 (ASTM C618) Class F coal ash. The aggregate proportions were roughly the same as those of the control mixture.

The mixture proportions for all three test cells are listed in Table 1. In addition to the materials listed in Table 1, all test cells included the following admixtures: Sika Air 260 (air entrainer), Sika Viscocrete 1000 (high-range water reducer), Sikatard 440 (set retarder), and Sika Stabilizer 4R (stabilizer).

The percentages retained on each sieve for the two aggregate gradations are plotted on the Tarantula Curve in Figure 3.

Table 1. Mixture proportions for MnROAD test cells (Cells 2219 and 2223) and the control section (Cell 2218)

Mixture Constituent	Cell 2218 (Control Mix)	Cell 2219 (Optimized Mix)	Cell 2223 (High-Limestone Mix)
AASHTO M 240 (ASTM C595) Type IL(8) Blended Cement[1]	400 lb/yd³	351 lb/yd³	—
ASTM C1157 Portland-Limestone Cement (20%) IL(20)[1]	—	—	400 lb/yd³
AASHTO M 295 (ASTM C618) Class F Coal Ash	170 lb/yd³	150 lb/yd³	170 lb/yd³
AASHTO M 80 (ASTM C33) Coarse Aggregate ¾"+	457 lb/yd³	669 lb/yd³	458 lb/yd³
AASHTO M 80 (ASTM C33) Coarse Aggregate #67	1,167 lb/yd³	963 lb/yd³	1,169 lb/yd³
AASHTO M 80 (ASTM C33) Intermediate Aggregate	244 lb/yd³	255 lb/yd³	244 lb/yd³
AASHTO M 6 (ASTM C33) ASTM C33 Fine Aggregate	1,171 lb/yd³	1,318 lb/yd³	1,173 lb/yd³
Water	228 lb/yd³	200 lb/yd³	228 lb/yd³
Air Content	7%	7%	7%
Water-to-Cementitious Materials (w/cm) Ratio	0.40	0.40	0.40
Paste Content	25%	22%	25%

[1] Cell 2223 utilized a cement with a higher percentage of limestone, Continental Davenport IL(20), while Cells 2218 and 2219 used a cement with a lower percentage of limestone, Holcim, St. Genevieve Type IL(8).

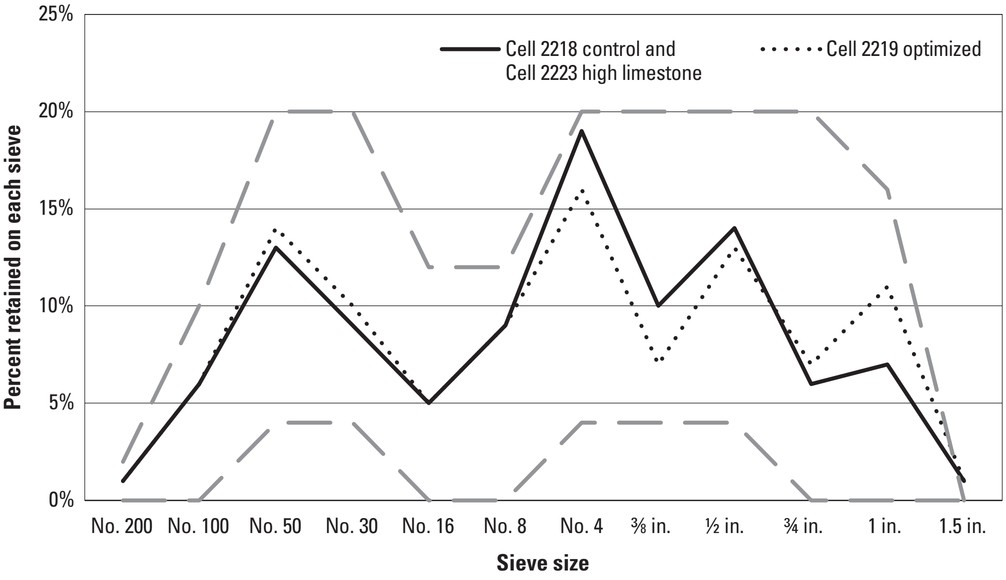


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Figure 3. Comparison of aggregate gradations

Construction

The construction of the test cells followed the procedure outlined in section 2301 of the MnDOT *Standard Specifications for Construction*, and the special provisions in the project specification included a turf drag finish for texture. Concrete was produced at a central batch ready mix plant and placed using a slipform paver, with joint sawing occurring approximately 4 to 6 hours after placement.

The optimized mixture (Cell 2219) was placed on August 5, 2022, and required 180 yd³ for paving 268 ft of length. Weather conditions were reported as 76°F and sunny with a maximum wind speed of 21 mph. During construction, there were delays of more than 15 minutes between concrete deliveries primarily due to sampling. This mixture also required additional mixing time. Cell 2219, along with most of the other test cells, required diamond grinding after construction due to inadequate texture from the initial drag. This was attributed to the short length of the test cells in this experiment and the challenges associated with finishing low-paste mixtures. Figure 4 shows the concrete mixture in front of the paver and the pavement surface during construction.

NCE, used with permission

Figure 4. Cell 2219 during construction, with the mixture in front of the paver (top) and the surface texture after placement (bottom)

The high-limestone cement mixture (Cell 2223) was constructed on August 3, 2022, and required 172 yd³ of concrete for paving 257 ft of length. Weather conditions were reported as 74°F and sunny with a maximum wind speed of 21 mph. During construction, there were delays of more than 30 minutes between concrete deliveries due to transport and sampling delays unrelated to the mixture. These delays resulted in the need for water to be added to the trucks before the concrete was placed, and consequently this mixture had more bleed water compared to other mixtures. However, such delays are expected when demonstrating novel materials on a small scale. Additionally, the lengths of all of the test cells in this experiment were short, which limited the amount of time in which necessary water adjustments could be made between mixes. This adjustment process is often necessary in conventional concrete projects and is part of the reasoning behind the requirement of test strips in some specifications. As with Cell 2219, diamond grinding was required to correct the surface texture. Figure 5 shows the concrete mixture in front of the paver and the pavement surface during construction.

The control mixture (Cell 2218) was constructed on August 8, 2022, and required 202 yd³ of concrete for constructing 302 ft of length. Weather conditions were reported as 76°F and sunny with a maximum wind speed of 9 mph. This mixture was reported to have a significant amount of bleed water, to the extent that 1.5 hours was required to allow for bleed water evaporation. Similar to Cell 2223, the excessive bleed water can be attributed to the limited time available for adjustment between mixes in combination with the high humidity on the day of paving. The mix was adjusted to correct this issue, and the pavement was finished without incident. The astroturf drag was sufficient to effectively texture the pavement surface. The mixture in front of the paver and the surface of this section following construction are shown in Figure 6, where the excessive bleed water is evident.

Several key concrete performance parameters, including compressive and flexural strength, resistivity, and rapid chloride penetration, were measured from specimens cast during construction. The test results are listed in Table 2.

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Figure 5. Cell 2223 during construction, with a dry mixture in front of the paver (left) and the surface texture after placement (right)

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Figure 6. Cell 2218 during construction, with the mixture in front of the paver (left) and the surface after placement showing excessive bleed water (right)

Table 2. Concrete test results

Parameter	Testing Age, Days	Cell 2218 (Control Mix)	Cell 2219 (Optimized Mix)	Cell 2223 (High-Limestone Mix)
Compressive strength (lb/in.²)	3	1,980	2,173	1,750
	7	2,665	2,565	2,367
	28	3,915	4,178	5,050
Flexural strength (lb/in.²)	3	450	545	390
	7	483	555	490
	28	590	608	633
Resistivity (kΩ•cm)	3	8	9	8
	7	11	11	9
	28	22	23	22
Rapid chloride penetration (Coulombs)	56	1,139	943	1,008

All three mixtures met the contract design requirement of a flexural strength of 500 lb/in.^{2} at 28 days. The mixture optimized for a reduced cementitious materials content (Cell 2219) and the high-limestone cement mixture (Cell 2223) showed higher 28-day strengths than the control mixture (Cell 2218), and all mixtures exhibited consistent surface resistivity and chloride penetration results, indicating low permeability.

Carbon Reduction Analysis

Using historical and estimated construction data, the global warming potential (GWP) for each mixture was analyzed based on the methodology outlined in Appendix B of the *Guide for Reducing the Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete* (Van Dam et al. 2024).

A concrete's GWP, in kg CO_2-eq/m^3 of concrete, can be estimated utilizing information from the concrete mixture design supplemented with information presented in documentation on the embodied carbon for each constituent material or information provided in product-specific environmental product declarations (EPDs). To estimate GWP, the mixture proportions (in metric tons/m^3 of typical concrete) are multiplied by the production efficiency (in kg CO_2-eq/metric ton), and the sum of these products represents the GWP (in kg CO_2-eq/m^3).

For each of the three mixtures, this methodology was utilized to estimate the GWP of the concrete mixture only. The resulting calculations for all three concrete mixtures are shown in Table 3; note that the production efficiency data for both types of blended cements were available from the manufacturer's EPDs.

Interestingly, the high-limestone cement concrete had a slightly higher GWP than the control mixture. This is due to the use of plant-specific EPDs that showed that the high-limestone PLC had a higher embodied carbon than the ASTM C595 Type IL(8) cement produced by a different manufacturer. The optimized mixture exhibited the lowest GWP due to the significant positive impact of lowering the total cementitious content of the mixture.

Pavement Performance

MnDOT uses a pavement rating system that incorporates several metrics of pavement performance, including observed pavement distresses, faulting between slabs, and pavement roughness, among others. The one-year pavement performance measurements for each of the three cells are listed in Table 4.

Table 3. Concrete mixture GWP approximations based on mix designs

Mixture Constituent	**Production Efficiency (kg CO_2-eq/m^3)**	**Cell 2218 (Control Mix)**		**Cell 2219 (Optimized Mix)**		**Cell 2223 (High-Limestone Mix)**	
		Quantity (metric tons/m^3)	**Estimated GWP (kg CO_2-eq/m^3)**	**Quantity (metric tons/m^3)**	**Estimated GWP (kg CO_2-eq/m^3)**	**Quantity (metric tons/m^3)**	**Estimated GWP (kg CO_2-eq/m^3)**
AASHTO M 240 (ASTM C595) Type IL(8) Blended Cement	724[1]	0.2373	171.8	0.2076	150.3	—	—
Blended PLC with 20% Limestone	774[1]	—	—	—	—	0.2373	183.7
AASHTO M 295 (ASTM C618) Class F Coal Ash	50	0.1009	5.042	0.0890	4.4450	0.1009	5.043
AASHTO M 43 (ASTM C33) Coarse Aggregate	5.51	1.108	6.849	1.1195	6.919	1.1100	6.860
AASHTO M 43 (ASTM C33) Fine Aggregate	6.18	0.6947	3.828	0.7819	4.3085	0.6959	3.834
Water	0.22	0.13526	0.02976	0.11865	0.02610	0.13530	0.02976
Sum		**187.5**		**166.0**		**199.5**	

[1] *Data from manufacturer EPDs*

Table 4. One-year pavement performance measurements

Measured Parameter	**Cell 2218 (Control Mix)**	**Cell 2219 (Optimized Mix)**	**Cell 2223 (High-Limestone Mix)**
Faulting between Slabs, in.	0.08	0.04	0.10
International Roughness Index (IRI), in./mile	63.2	66.7	67.3

The measured faulting and roughness values are consistent and indicate good performance across the reduced-carbon mixtures. Cell 2218 had low-severity joint spalling, Cell 2219 had low-severity joint spalling as well as moderate- and high-severity scaling, and Cell 2223 had low-severity joint and corner spalling as well as a small patch.

Lessons Learned

This case study highlights three test cells (2218, 2219, and 2223) constructed at the MnROAD test track facility that aimed to reduce the embodied carbon of concrete pavement relative to a standard MnDOT control mixture. While the project is relatively new, several key trends have been observed and several lessons have been learned from the construction and early performance of these test cells:

- **The mixture optimized for lower paste volume required diamond grinding.** The mixture in Cell 2219, which utilized an aggregate gradation optimized to reduce the total cementitious materials content, allowed for a 22% paste content in the mixture in contrast to the 25% paste content used in the other two mixtures. The concrete mixture was reported to be workable during construction. This cell required diamond grinding following construction to create an adequate texture for safety because the surface set prior to application of the burlap drag. It is felt that the need for diamond grinding could be avoided during routine construction once the contractor adjusts the mixture and/or construction sequence for the setting characteristics of a previously unfamiliar mixture.
- **The high-limestone PLC mixture required additional batch water.** The mixture in Cell 2223 experienced issues during construction, including low workability and dryness. This required additional water to be added during batching to allow proper finishing and texturing of the surface. It is felt that in production, the contractor would have had time to adjust the mixture by making additional use of high-range water-reducing admixtures or other means to offset this increase water demand. Trial batches were conducted in this study, which can often reduce the likelihood of placement challenges, but these can sometimes miss issues that can occur due to the mixing scale or mixing effort required for a laboratory setting versus a production setting. Additionally, transport and sampling delays were not anticipated and caused unforeseen issues.
- **The experimental mixtures had adequate fresh and hardened concrete properties.** The experimental concrete mixtures exhibited higher 28-day strengths and similar resistivity and chloride penetration values compared to the control mixture.
- **Not all embodied carbon reduction strategies yielded lower embodied carbon mixtures.** The mixture in Cell 2219 (the mixture with an optimized aggregate gradation) had the lowest approximated GWP of 166.0 kg CO_2-eq/m^3, followed by the mixture in Cell 2218 (the control mixture) at 187.5 kg CO_2-eq/m^3. The mixture in Cell 2223 (the high-limestone mixture) had the highest approximated GWP at 199.5 kg CO_2-eq/m^3. This latter observation was counterintuitive because it was assumed that the lower clinker content of the high-limestone cement would have resulted in a lower embodied carbon value for the concrete. However, based on manufacturing plant-specific EPDs, which showed that the ASTM C595 Type IL(8) blended cement had a lower GWP than the high-limestone PLC with 20% limestone, this assumption was found to be incorrect. This finding further illustrates the need to rigorously establish the embodied carbon content of concrete through manufacturing plant-specific EPDs when possible.
- **Demonstration projects play an important role for material suppliers and contractors.** Some issues with early-age concrete properties related to early set and/or increased water demand were noted during construction of the two experimental test cells. This was not unexpected because material suppliers and contractors possess a vast amount of empirical knowledge when it comes to working with traditional mixtures but have little to no experience in working with new, innovative mixtures designed specifically to reduce embodied carbon. Demonstration projects, such as the construction of these MnROAD test cells, provide the opportunity for contractors and material suppliers to gain some of the knowledge and skills required for future applications. It is understood that additional care and attention will often be required when materials change, and demonstration projects will be a stepping stone to full implementation of innovative mixtures.

References

Bautista, E., M. Wallace, J. Podolsky, T. Burnham, J. Calvert, M. Vrtis, C. Aydin, F. Sadiq, and M. Wasif. 2023. *2022 MnROAD Construction Activities*. National Road Research Alliance Final Report 2023-37. Minnesota Department of Transportation Office of Research and Innovation, St. Paul, MN.

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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of developing and implementing innovative technology and best practices for sustainable concrete pavement construction and maintenance.