CONCRETE PAVEMENT WITH PORTLAND-LIMESTONE CEMENT, COAL ASH, OPTIMIZED AGGREGATE GRADATIONS, AND RECYCLED CONCRETE AGGREGATE IN COLORADO

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Introduction

Colorado State Highway 470 (C-470) is a heavily traveled highway located south of the city of Denver near Littleton, Colorado. Due to estimates of increasing traffic and roadway demand, a 12.5 mi segment of this road was reconstructed and expanded in 2018 at a cost of $276 million. Two westbound tolled express lanes were added between I-25 and Colorado Boulevard, one westbound tolled express lane was added from Colorado Boulevard to Wadsworth Avenue, and one eastbound tolled express lane was added between I-25 and Wadsworth Avenue. Two concrete mixtures were used, a three-aggregate optimized mixture and a four-aggregate optimized mixture, both featuring recycled concrete aggregates. The location of the project is shown in Figure 1.

The following carbon reduction strategies were used in the concrete mixtures:

1. An ASTM C1157 Type GU performance hydraulic cement was used in lieu of ASTM C150 Type I/II portland cement or ASTM C595 Type IL blended cement.
2. An optimized aggregate gradation was used in the concrete mixtures, which allowed for a reduced paste content without negatively impacting workability.
3. Coal ash (20% by weight of total cementitious materials) was used as a supplementary cementitious material (SCM).
4. Recycled concrete aggregate (ASTM C33) was used for part of the coarse aggregate in the mixture. (Note that while using recycled concrete aggregates is a good strategy for environmental stewardship, it inconsistently reduces the embodied carbon in the concrete mixture.

CDOT n.d.-a

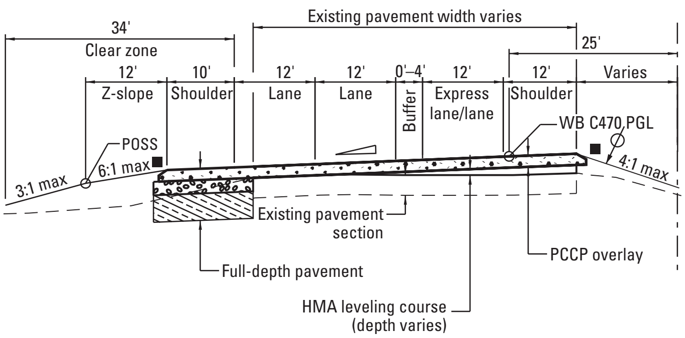
Figure 1. Project location

The true reduction in embodied carbon must be evaluated through a life-cycle assessment (LCA) in accordance with ISO standards on a case-by-case basis.)

Pavement Design, Materials, and Construction

Structural Design

Figure 2 provides a detail and the geometric configuration of a typical westbound pavement section between Colorado Boulevard and Wadsworth Avenue. This project included widening with a new concrete pavement section (9.5 in. of portland cement concrete [PCC] over 12 in. of cement-treated subgrade over a 24 in. moisture-treated subgrade) and an unbonded concrete overlay of the existing pavement (9.5 in. of PCC over a hot-mix asphalt (HMA) level course of varying thickness).



Recreated from CDOT, used with permission

Figure 2. Example cross section of the westbound half of C-470 between Colorado Boulevard and Wadsworth Avenue (looking east)

Paving Materials

Two concrete mixtures were used throughout this project, a three-aggregate optimized mixture and a four-aggregate optimized mixture, both featuring recycled concrete aggregates. While most construction utilized the four-aggregate mixture, the three-aggregate mixture was utilized when there was limited availability of the intermediate aggregate. The optimized aggregate gradation allowed for a lower paste volume of 24.7% while maintaining mixture workability. Additionally, an ASTM C618 Class F coal ash was used as an SCM to enhance durability and reduce embodied carbon. The laboratory mixtures were designed for a 28-day compressive strength of 4,500 psi (650 psi flexural strength). The proportions of the two optimized mixtures are shown in Table 1 along with a typical Colorado Department of Transportation (CDOT) Class P paving mixture for comparison.

The aggregate gradations are plotted on a Tarantula Curve (FHWA 2015) in Figure 3. The three-aggregate blend fits completely within the density recommendations of the Tarantula Curve and is considered well-graded. The four-aggregate blend exceeds the limits on the No. 8 and No. 16 sieves, implying a slight excess of intermediate material per Tarantula Curve density recommendations. The typical CDOT aggregate mixture more significantly exceeds the limits on the ¾ in. and No. 16 sieves, implying an excessive amount of coarse aggregate outside of the recommended limits of the Tarantula Curve.

Table 1. Mixture proportions for a typical CDOT Class P mixture and the optimized mixtures used for C-470

Mixture Constituent	Four-Aggregate Optimized Mixture, per yd³	Three-Aggregate Optimized Mixture, per yd³	Typical CDOT Concrete Paving Mix, per yd³
ASTM C150 Type I/II Portland Cement	—	—	542 lb
ASTM C595 Type IL Cement	440 lb	440 lb	-
ASTM C618 Class F Coal Ash	110 lb	110 lb	136 lb
ASTM C33 Coarse Aggregate #4 (Recycled Concrete Aggregate)	397 lb	434 lb	—
ASTM C33 Coarse Aggregate #57	1,130 lb	1,426 lb	1,595 lb
ASTM C33 Intermediate Aggregate #9	550 lb	-	290 lb
ASTM C33 Fine Aggregate	977 lb	1,240 lb	1,015 lb
Water	221 lb	226 lb	210 lb
Air	6%	6%	6%
Water-to-Cementitious Materials (w/cm) Ratio	0.40	0.41	0.39
ASTM C260 Air-Entraining Admixture (Euclid Chemical AEA-92 at 0.5 oz/cwt)	4.4 oz	3.2 oz	2.5 oz
ASTM C494 Type A Water Reducer (Euclid NW at 7.9 oz/cwt)	35 oz	43.3 oz	52 oz

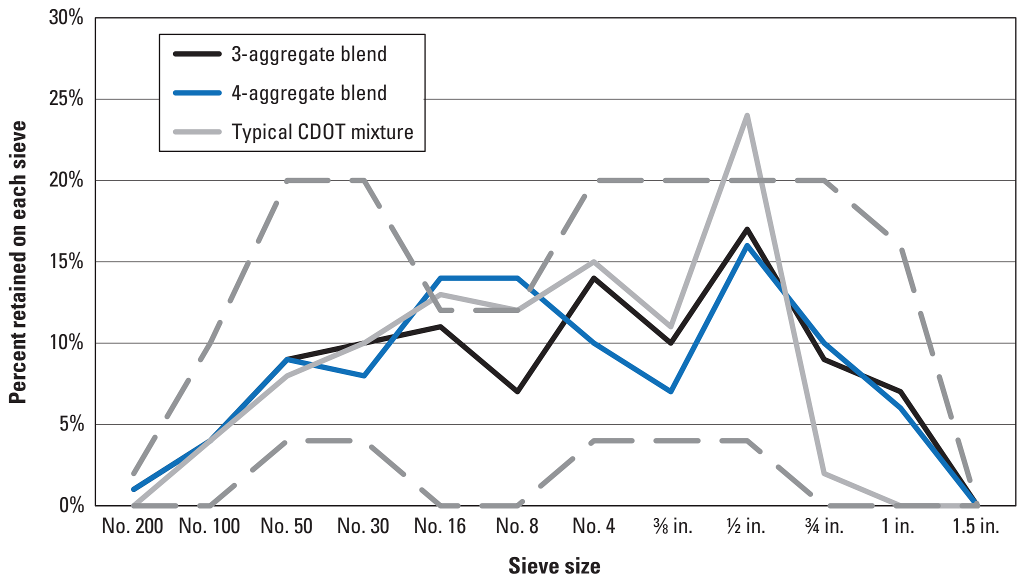


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Figure 3. Aggregate gradations plotted on Tarantula Curve

Construction

Paving began in 2017 and was completed in 2020. The project involved placing approximately 1.2 million square yards of concrete pavement using 100,000 tons of recycled concrete aggregate. Three batch plants were set up along the 12.5 mi length of the project, allowing for minimized haul times. Epoxy-coated deformed tie bars and 1.5 in. diameter epoxy-coated dowel bars were inserted during mainline paving with a slipform paver. A burlap drag was considered sufficient to apply surface texture because CDOT discontinued its tining specification in 2013. During paving, it was reported that the optimized concrete mixtures were extremely workable, finished easily, and held a consistent edge. Photos of the concrete placement, finishing, and texturing operations are shown in Figure 4, and a finished edge is shown in Figure 5.

FHWA 2018

Figure 5. Finished edge with inserted tie bars

FHWA 2018

Figure 4. Concrete placement, finishing, and texturing of C-470

Test results obtained during construction by the Federal Highway Administration's (FHWA's) Mobile Concrete Technology Center (MCTC) for the four-aggregate blend are listed in Table 2. These results indicate that the optimized mixture exceeded the target 28-day strength of 4,500 psi and had acceptable surface resistivity and rapid chloride penetration testing results.

Table 2. Test results obtained by the FHWA MCTC during construction

Test	Compressive Strength (psi)			Split Tensile Strength (psi)			Surface Resistivity (kΩ•cm)			Rapid Chloride Penetration Testing (coulombs)
Testing Age (days)	3	7	28	3	7	28	7	28	56	64
Testing Result	3,230	3,579	4,869	293	287	350	6.9	15.9	28.2	1,191 (low)

Carbon Reduction Analysis

Using historical and estimated construction data, an analysis of the global warming potential (GWP) of the three case study mixtures was conducted based on the methodology outlined in the *Guide for Reducing the Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete*, First Edition (AASHTO 2025). A concrete's GWP, in kg CO_2-eq/m^3 of concrete, can be estimated utilizing information from the concrete mix design supplemented with information from environmental product declarations (EPDs).

The two optimized mixtures and the typical CDOT paving mixture were evaluated using this methodology, and the results are shown in Table 3. Use of an optimized aggregate gradation along with an ASTM C595 Type IL cement resulted in an estimated 24% reduction in GWP relative to the typical CDOT paving mixture. It should be noted that the production efficiency of the recycled concrete aggregate was estimated to be similar to that of typical coarse aggregate because more refined estimating information for the recycled concrete aggregate was unavailable.

Pavement Performance and Maintenance History

CDOT monitors pavement performance based on three quantified metrics, including (1) faulting between slabs (in inches), (2) percent slabs cracked, and (3) surface roughness (reported in terms of International Roughness Index [IRI] in inches per mile). Additionally, CDOT provides a composite overall rating based on the combination of these three metrics. Table 4 provides the most recent performance data collected in 2022, which approximately represents three-year performance data for the pavements.

According to these data, most (84%) of the segments surveyed are in "good" condition. Specifically, roughness is the factor that most limits current performance, given that all slabs are rated in "good" condition in terms of faulting and 98% of slabs are rated in "good" condition in terms of cracking.

Table 3. Concrete mixture GWP approximations based on mix designs

Mixture Constituent	Production Efficiency (kg CO_2-eq/m^3)[1]	Optimized Mixture – Three-Aggregate Blend		Optimized Mixture – Four-Aggregate Blend		Typical CDOT Mixture	
		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)
ASTM C150 Cement	919	—	—	—	—	0.322	295.9
ASTM C595 Type IL	844	0.261	220.3	0.261	220.3	—	—
ASTM C618 Class F Coal Ash	50	0.065	3.3	0.065	3.3	0.081	4.1
ASTM C33 Coarse Aggregate	6.18	0.846	5.2	0.997	6.2	1.12	6.9
ASTM C33 Recycled Concrete Aggregate	6.18	0.258	1.6	0.236	1.5	—	—
ASTM C33 Fine Aggregate	5.15	0.736	4.1	0.579	3.2	0.602	3.3
Water	0.22	0.134	0.03	0.131	0.03	0.125	0.03
Air-Entraining Admixture	439	0.00012	0.05	0.00016	0.07	0.000093	0.04
Water-Reducing Admixture	1,340	0.0016	2.1	0.0013	1.7	0.0019	2.6
Sum		**236.7**		**236.3**		**312.9**	

[1] *Values from AASHTO 2025*

Table 4. Performance data collected in 2022 (approximately three-year performance data)

Measured Parameter	Average Rating	Threshold for "Good" Rating	Percent of Measured Segments in "Good" Condition	Percent of Measured Segments in "Fair" Condition
Faulting between Slabs (in.)	0.0103 in.	< 0.10 in.	100%	0%
Percent Slabs Cracked	0.4% slabs cracked	<5% slabs cracked	98% 92% of slabs with no cracking	2%
International Roughness Index (in./mi)	86 in./mi	<100 in./mi	86%	14%
Overall Condition Rating	—	—	84%	16%

Source: CDOT n.d.-b

Lessons Learned

The southern segment of C-470 (C-470A) south of Denver, Colorado, is an excellent example of a reduced-carbon concrete paving project. This project incorporated portland-limestone cement, coal ash as an SCM to replace cement, optimized aggregate grading to allow for decreased paste content while maintaining workability, and recycled concrete aggregates. The lessons learned from this reduced-carbon concrete pavement section include the following:

- **Sufficient workability and finishing were attainable with the reduced-carbon mixtures.** The reduced-carbon concrete mixtures exhibited sufficient workability, allowed for adequate surface finishing and texturing, and were reported to finish easily and hold a consistent edge.
- **Reduced-carbon mixture strategies effectively reduced the estimated greenhouse gas emissions.** The reduced-carbon concrete mixtures were estimated to have approximate GWPs of 236 and 237 kg CO_2-eq/m^3. These are roughly 24% less than the estimated GWP of a typical CDOT paving mixture, which was 313 kg CO_2-eq/m^3.
- **The reduced-carbon concrete mixtures met the required performance targets.** The mixtures exceeded project strength requirements, and testing indicated low concrete permeability in field-cast specimens.
- **The reduced-carbon mixtures are performing well.** The three-year performance results indicate little to no faulting and a low amount of slab cracking. The ride quality is as expected, with 86% of the segments rated as "good" (having IRI values of 100 in./mi or less). It should be noted that the pavement management data used for the performance analysis do not exclude the several bridge approaches along the project, which may have an impact on IRI.

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