ERDC/GSL TR-14-8

Geotechnical and Structures Laboratory

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Improved Concrete Cutting and Excavation Capabilities for Crater Repair

Phase 2

Lulu Edwards, Haley P. Bell, Jay F. Rowland,
and Craig A. Rutland

May 2015









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Report 2 of a series

Prepared for Headquarters, Air Force Civil Engineer Center
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Abstract

The U.S. Army Engineer Research and Development Center was tasked by the U.S. Air Force Civil Engineer Center to further improve the saw cutting and excavation production rates and robustness of crater repairs in thick portland cement concrete (PCC) pavements for airfield damage repair (ADR) scenarios. The Vermeer concrete cutting saws (CC1531 and RW1236W) were investigated and compared to the previously tested concrete saws (Caterpillar SW45, Caterpillar SW60, and Bradco RS24). Several methods of excavation were compared in terms of production rate and ease of execution. The current ADR techniques, tactics, and procedures (TTPs) indicate cutting of pavement around a small crater should be completed in 22 min or less, and excavation (breaking and removal) of the repair area should be completed in 23 min or less for an 8.5-ft by 8.5-ft crater. Various equipment and methods were evaluated for sawing and removing concrete and base course materials in 18-in.-thick and 24-in.-thick PCC pavements. The effects of base course strength and overcut lengths on excavation production rates were of particular interest for this investigation. This report presents the technical evaluation of various models of sawing and excavation equipment and various methods for improving the efficiency of removing damaged pavement associated with crater repair.

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Preface

This study was conducted for the U.S. Air Force's Civil Engineer Modernization Program sponsored by Headquarters, Air Combat Command, Langley Air Force Base, VA. Headquarters, U.S. Air Force Civil Engineer Center (AFCEC), Tyndall Air Force Base, FL, provided funding for the research project described in this report, and Dr. Craig Rutland from that organization provided guidance during the project.

The work was performed by the Airfields and Pavements Branch (APB) of the Engineering Systems and Materials Division (ESMD) with quality control testing provided by the Materials Testing Center, both of the U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). Jeb S. Tingle (ESMD) was the ERDC Airfield Damage Repair program manager. At the time of publication, Dr. Gary L. Anderton was Chief, APB; Dr. Larry N. Lynch was Chief, ESMD; and Dr. David A. Horner was the Technical Director for Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Dr. David W. Pittman.

LTC John T. Tucker III was the Acting Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
gallons per minute	3.78541178	liters per minute
inches	0.0254	meters
mils	0.0254	millimeters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

1 Introduction

1.1 Background

In March 2002, the Joint Airfield Damage Repair Working Group identified the lack of certification of existing airfield damage repair (ADR) methods for C-17 aircraft as the number one issue requiring immediate attention. The U.S. Air Force (USAF) Air Mobility Command funded the U.S. Army Engineer Research and Development Center (ERDC) to evaluate existing ADR expedient repair technologies under C-17 aircraft loads.

The general objective of the USAF ADR Modernization Program is to update the Air Force's ADR capability through development of new ADR solutions that are scalable to the threat or damage.

The ADR program has been assessing technologies, materials, and methods needed to support repairs of up to 120 small craters (8.5 by 8.5 ft) on runway and taxiway surfaces within 3 hr (objective) or 6.5 hr (threshold) after an attack. The ADR process can be divided into seven general steps: (1) assessing the crater, (2) removing initial debris, (3) marking the limits of upheaval, (4) saw cutting, (5) excavating, (6) backfilling, and (7) capping. After the initial crater assessment, each process is executed by separate teams, each of which should ideally take a similar amount of time to achieve optimal efficiency and a continuous work flow. If one process requires a longer length of time, then the teams performing the subsequent tasks will be required to wait, thus slowing the entire ADR process.

Results combined from previous demonstrations and evaluations were used to create the techniques, tactics, and procedures (TTPs) manual describing the processes and requirements of crater repair. The TTPs indicate that using two saws to cut the pavement around a small crater should require 22 min or less, and excavating (breaking and removing) the damaged pavement in the repair area should require 23 min or less. However, based on the previous demonstrations, the breaking time averaged 16 min or less, and the removal time averaged 11 min or less (Priddy et al. 2013b).

Minimal testing and evaluation of crater repair methods have been conducted in thick pavement surfaces. It was determined that the cutting and excavation rates in thick (18 in. or thicker) portland cement concrete (PCC) did not meet the required production rates for optimal efficiency and continuous work flow during the 2009 Operational Utility Assessment (OUA) in Avon Park, FL (Priddy et al. 2013b). This demonstration also revealed that cutting in thick PCC was more difficult when dowels were present.

In general, the OUA demonstration validated that the new materials, equipment, and procedures were capable of meeting the required ADR threshold timeline of repairs (6.5 hr) and sustaining both fighter and cargo aircraft traffic. Based on the results of the OUA, the USAF decided to begin refinement to achieve the objective timeline of 3 hr and procurement of the new ADR equipment.

In 2012, ERDC conducted additional testing in Vicksburg, MS, to determine the most efficient method of cutting and excavating 18- and 24-in.-thick PCC (Bell et al. 2014). The PCC consisted of a limestone aggregate mixture. A summary of the findings are as listed:

- The Caterpillar Sw45 and SW60 wheel saws are capable of cutting a maximum of 18 and 24 in. deep, respectively. However, they cut at their maximum depth only when used in the most efficient manner – with minimal concrete debris buildup under the saw, with the saw level, and with the guard kept at its lowest position continuously. Generally, the SW45 and SW60 wheel saws effectively cut to maximum depths of 17 and 23 in., respectively.
- The performances of the Caterpillar SW45 and SW60 wheel saws on the 18-in.-thick PCC were similar, and their average production rates met the 1 ft/min goal for saw cutting. On average, the SW45 wheel saw cut approximately 4 percent faster than the SW60 wheel saw in the 18-in.-thick PCC.
- The Husqvarna FS 6600D walk-behind saw was capable of cutting through the 1.25- and 2-in.-diam, grade 60 steel dowel rods in the 18- and 24-in.-thick PCC, respectively. The average production rate was faster than the 1 ft/min goal for saw cutting. The presence of dowel rods in the PCC had minimal effect on the walk-behind saw's capability to cut thick PCC.

- The average production rate of the Caterpillar SW60 wheel saw on the 24-in.-thick PCC was slightly less than the goal of 1 ft/min. The SW60 wheel saw was the only option tested for saw cutting 24-in.-thick PCC to full depth.
- The Volvo EW180D excavator with the Volvo HB1400 moil point hammer was the most efficient technology for breaking up the 18- and 24-in.-thick PCC and required far less time than the goal of 16 min per repair slab. The Volvo EW180D excavator with the Volvo HB1400 chisel point hammer was also capable of requiring less than the goal time of breaking up the 18- and 24-in.-thick PCC.
- The Caterpillar 416D and 430D backhoes, using both the moil and chisel point hammers, failed to break up the 18-in.-thick PCC. The impact energy of the largest hammer compatible with the Caterpillar 416D and 430D backhoes was not enough to penetrate the thick PCC; the hammers simply chipped away at the surface.
- Relief cuts using the Caterpillar SW45 and SW60 wheel saws and the Husqvarna FS6600D walk-behind saw were not beneficial to the excavation process. It was more efficient to break up and remove the thick PCC with a hammer mounted on an excavator than it was to replace or supplement the breaking process with relief cuts. The study determined that if an excavator with a hammer attachment is not available, then the relief cuts could serve as an alternative for breaking the PCC. The relief cut pattern (“x” or “t”) did not make a difference, but two relief cuts were required to break the slab into quadrants. The subbase had to be removed using a backhoe or similar equipment.
- The Volvo EW180D excavator with the 36-in.-wide bucket and 7.75-in.-long teeth was the most efficient technology for removing the thick PCC and underlying debris for small crater repair. The average production rate required less time than the removal goal of 11 min per repair.
- Occasionally, when the Caterpillar SW45 and SW60 wheel saws did not cut full depth, the breaking process caused the parent slab to crack from the repair corner to the parent slab corner.
- The rock splitter (Darda, size 9) was capable of cracking the 18-in.-thick PCC to its full depth; however, the drilling process was slow. The rock splitter did not consistently break the 24-in.-thick PCC to its full depth.
- Although slow, the 695F4 ICS utility chain saw was capable of cutting through PCC and dowel bars. The study showed that the utility chain saw could be used as a supplement for thinner pavements (12 in. or less) if no other equipment is available but should be used with caution for safety reasons.

- With the use of a Caterpillar TL1055 forklift, a Caterpillar 966G front-end loader, and the Volvo EW180D excavator, the concrete expansion anchors successfully removed 8.5-ft by 4.25-ft by 18-in.-thick PCC sections; however, the process of installing the anchors was labor intensive and slow.

1.2 Objective and scope

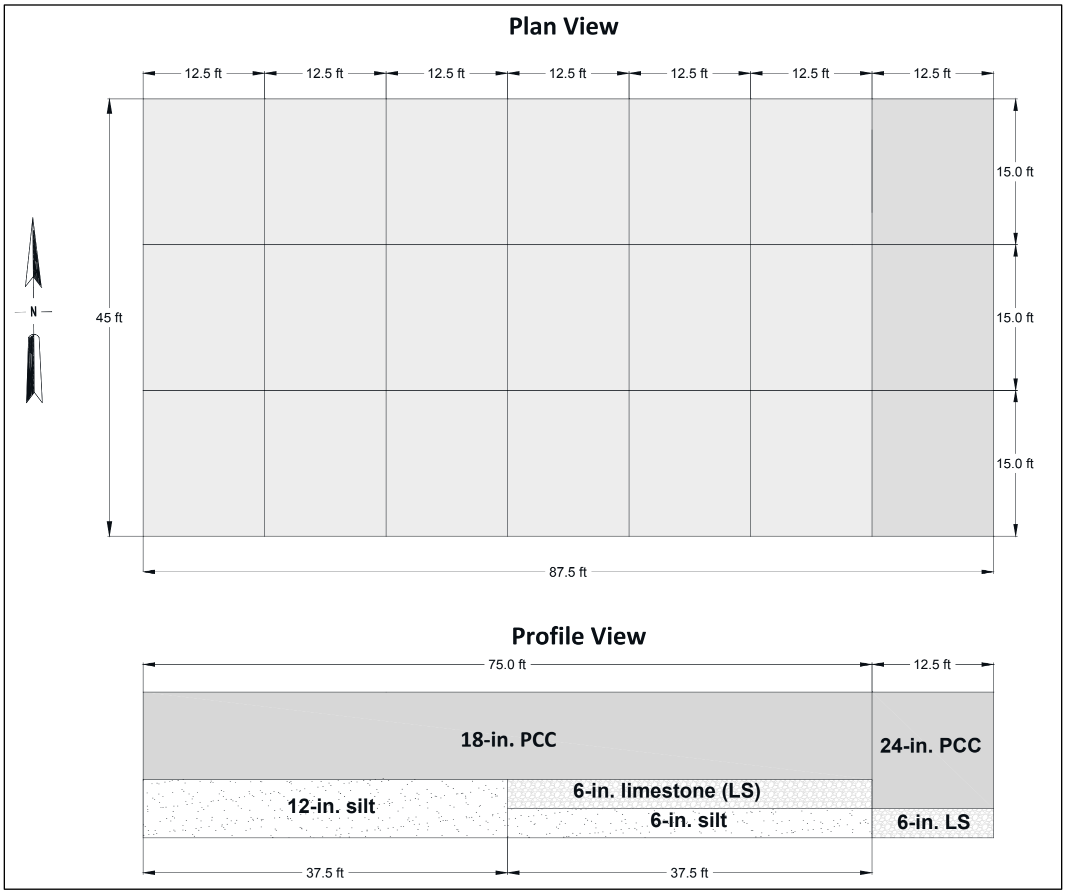
The objective of this project was to further investigate improved equipment and/or TTPs to saw cut and excavate small craters with average dimensions of 8.5 by 8.5 ft in 18- and 24-in.-thick PCC while using minimal manpower. A full-scale test section was constructed of 18-in.-thick PCC and 24-in.-thick PCC. No dowels were included. Various combinations of equipment were tested and evaluated to determine the most efficient use of equipment and manpower for sawing and excavating bomb-damaged pavements. The study was interested specifically in adhesive anchoring systems and the comparison of varying-sized wheel saws. This report provides information for the following:

1. Specification of required capabilities for excavation of craters for repairs,
2. Description of the test site,
3. Description of the evaluated equipment, and
4. Testing matrix and field evaluation results.

2 Test Section Description and Characterization

A full-scale test section was constructed of 18- and 24-in.-thick PCC to provide a testing area for purposes of evaluating sawing and excavation equipment and developing updated TTPs of crater repair. The test section was located on a pavement test area at ERDC. The plan and profile views of the test section are shown in Figure 1. Two types of base materials, a weak and a strong material, were used under the 18-in.-thick PCC to determine their effect on the sawing and breaking processes of crater repair. The 24-in.-thick PCC area was constructed to evaluate the cutting capabilities of the larger wheel saws.

Figure 1. Plan and profile views of test section.



2.1 Test site preparation

The existing subgrade was graded prior to construction with a 0.7 percent grade in the profile (east to west) and 0.3 percent grade south to north to allow for drainage (Figure 2). A drainage ditch was also constructed off the side of the center of the section (depicted in the far left of Figure 2). Silt was placed and compacted to a 12-in. depth over the western half (37.5 ft by 45 ft) of the test section as the base. For the eastern half (37.5 ft by 45 ft) of the test section, 6 in. of silt was used for the subbase, and 6 in. of crushed limestone was used as the base course. For the 24-in.-thick PCC section, 6 in. of limestone was used as the base course. Each layer was compacted to a target of 95 percent modified Proctor density or to the point that the in-place density did not increase with additional compactive effort. A Caterpillar CS433E vibratory smooth-drum roller and a Wacker WP 1550W plate compactor were used for compaction.

Figure 2. Test site construction preparation.

2.2 Material characterization

The materials for each foundation layer were characterized in the laboratory. The grain size distribution curves are included in the appendix in Figures A1 and A2. The Unified Soil Classification System defined in ASTM D2487-11 (2011a) was used to classify the silt as brown silt (ML) and the limestone as a silty, clayey gravel (GC-GM) with sand.

The liquid limit, plastic limit, and plasticity index were determined by using ASTM D4318-10 (2010c). The limestone and silt were nonplastic.

The modified Proctor compaction tests were completed in accordance with ASTM D1557-12 (2012) for each layer of the test section, and the results are summarized in Table 1. These values were used during construction of the base and subbase of the test section. The dynamic cone penetrometer (ASTM 2003) was used as a quality assurance method.

Table 1. Modified Proctor compaction test result summary.

Material	Maximum dry density (pcf)	Optimum moisture (%)
Silt (ML)	112.0	15.0
Limestone (GC-GM)	141.7	5.4

2.3 PCC construction

The PCC pavement was constructed in March 2013 of an airfield-quality concrete. Eighteen slabs were 18 in. thick, and three slabs were 24 in. thick; each slab had dimensions of 12.5 ft by 15 ft. The slab dimensions were established in accordance with Department of Defense specifications described in UFC 3-260-02 for PCC airfield pavements (HQ, Army, Navy, and Air Force 2001).

The PCC construction work was completed by Dark Horse Construction, LLC from DeSoto, MO. The PCC mixture was produced by using a local chert gravel mix design with 4,000-psi unconfined compressive strength (UCS) mixture (Figure A3). During placement, test specimens were prepared in accordance with ASTM C39 (2010a) for compressive cylinders and ASTM C78 (2010b) for flexural beams. Laboratory data for this mixture are included in Table 2.

Table 2. Laboratory PCC test data from field samples.

Parameter	Cure Time	Value
Modulus (ksi)	28-Day	5,900
	90-Day	6,200
UCS (psi)	28-Day	6,500
	90-Day	6,700
Flex strength (psi)	28-Day	610
	90-Day	810

The PCC was placed by a pump truck (Figure 3), consolidated with 2-in. spud vibrators, and screeded with a self-powered, vibratory truss screed. A maximum slump of 7 ± 1 in. was specified. The PCC section was completed with a light broom finish, coated with a curing compound, and then saw cut to provide transverse and longitudinal joints. The joints were saw cut approximately 24 hr after the concrete placement. The 18-in.-thick section was saw cut to a depth of 5 in., and the 24-in.-thick section was saw cut to a depth of 6.5 in. Saw cut depths met the PCC specifications described in UFC 3-260-02. A white-pigmented curing compound meeting the ASTM C309-11 (2011b) specifications was used.

Figure 3. PCC placement using pump truck.

3 Evaluated Technologies

A variety of equipment and tools was assessed for potential in improving the speed of the cutting and excavation processes for small crater repair in 18- and 24-in.-thick PCC. The Vermeer rock saws, Bradco rock saw, and epoxy-anchoring methods were new technologies included in this test. All other technologies had been used in previous ADR testing and demonstrations (Bell et al. 2014; Priddy et al. 2013a, 2013b).

3.1 Equipment

3.1.1 Caterpillar 279C and 299C compact track loaders

Caterpillar 279C compact track loaders (CTL), or skid steers, are high-flow, rubber-tracked machines with quick disconnect fittings that are used extensively in the current ADR TTPs. The quick disconnect allows attachments to be switched out rapidly without the use of tools. The Caterpillar 299C CTLs (Figure 4) are similar to the 279C CTLs except the 299C model has slightly more power and a higher operating capacity. The multi-purpose machines are employed for many of the ADR processes, including rapidly cutting around the upheaval area adjacent to craters in bomb-damaged pavement with wheel saw attachments, breaking pavement with the hammer attachment, removing debris with bucket attachments, screeding asphalt caps with the asphalt screed attachment, or cleaning up with the broom attachment. Specifications for the machines are listed in Table 3.

Figure 4. Caterpillar 299C CTL, operating the SW45 wheel saw attachment.

Table 3. Caterpillar 279C CTL and 299C CTL specifications.

Parameter Specifications	Caterpillar 279C CTL	Caterpillar 299C CTL
Net power	82 hp	90 hp
Operating weight	9,495 lb	10,730 lb
Rated operating capacity	3,200 lb at 50% tipping load	4,150 at 50% tipping load
Travel speed	5.0 mph	8.5 mph
Tipping load	6,483 lb	8,338 lb
Breakout force, tilt cylinder	7,308 lb	7,308 lb
Maximum loader hydraulic pressure*	4,061 psi	4,061 psi
Maximum loader hydraulic flow*	33 gal/min	33 gal/min

* For high-flow XPS models

3.1.2 Caterpillar SW45 and SW360B wheel saw attachments

The Caterpillar CTLs are equipped to operate the Caterpillar SW45 (Figure 4) and/or SW360B wheel saw attachments. These wheel saw attachments produce a 3.5-in.-wide cut. The SW45 has an 18-in.-maximum cutting depth, and the SW360B has a 24-in.-maximum cutting depth. The wheel saws are equipped with a hydraulic side-shift (22 to 26 in. in either direction from the center of the machine) to assist in wheel positioning. Specifications for both machines are shown in Table 4.

Table 4. Caterpillar SW45 and SW360B wheel saw specifications.

Parameter Specifications	Caterpillar SW45	Caterpillar SW360B
Overall width	71 in.	73 in.
Overall height	57 in.	70 in.
Length	78 in.	93 in.
Weight	2,295 lb	3,240 lb
Wheel width (without teeth)	3 in.	3 in.
Hydraulic flow requirement	24-42 gal/min	33 gal/min
Optimal hydraulic pressure range	2,611 to 4,351 psi	4,000 psi
Wheel torque at maximum pressure	4,944 ft-lb	5,538 ft-lb
Wheel speed at maximum flow	115 rpm	74 rpm
Number of teeth	64 per wheel	70 per wheel
Maximum depth of cut	18 in.	24 in.
Side-shift travel	26 in.	22 in.

3.1.3 Wheel saw targets and rulers

The use of wheel saw targets and rulers on the Caterpillar SW45 and SW360B wheel saw attachments eliminates the need for extra spotters and decreases the potential for excessive overcuts during the saw cutting for crater repairs. The positioning of the saw targets was developed with the Caterpillar SW45 and SW360B wheel saws in 18-in.-thick PCC and is discussed later in this report. The user's desired overcut length is required to determine where to place the saw and the saw target.

The saw target system (Figure 5) consists of four parts: (1) an alignment guide for the top of the wheel saw, (2) an end target stand, (3) rulers adhered to the wheel saw, and (4) magnetic arrows above the rulers. The alignment guide is a "rookie" pole attached with a small metal plate and two bolts in the small opening at the top front of the wheel saw. The rookie pole is a flexible, strong fluorescent orange plastic pole normally used on larger vehicles for greater visibility for safety. The rookie pole has a 0.75-in. diam and a 24-in. length. The metal plate specifications and placement are shown in Figure 6. The end target stand consists of a T-shaped base that is 18 in. wide and 18 in. long and is made of 2-in. by 2-in. square steel tubing (0.1875-in. wall thickness) (Figure 7). A threaded 0.5-in.-aluminum pipe that is 48 in. tall is screwed into the base. The aluminum pipe is machined at the top to a 0.75-in. inner diam and a 2-in. depth to hold the rookie pole (Figure 8).

Figure 5. Wheel saw target setup.

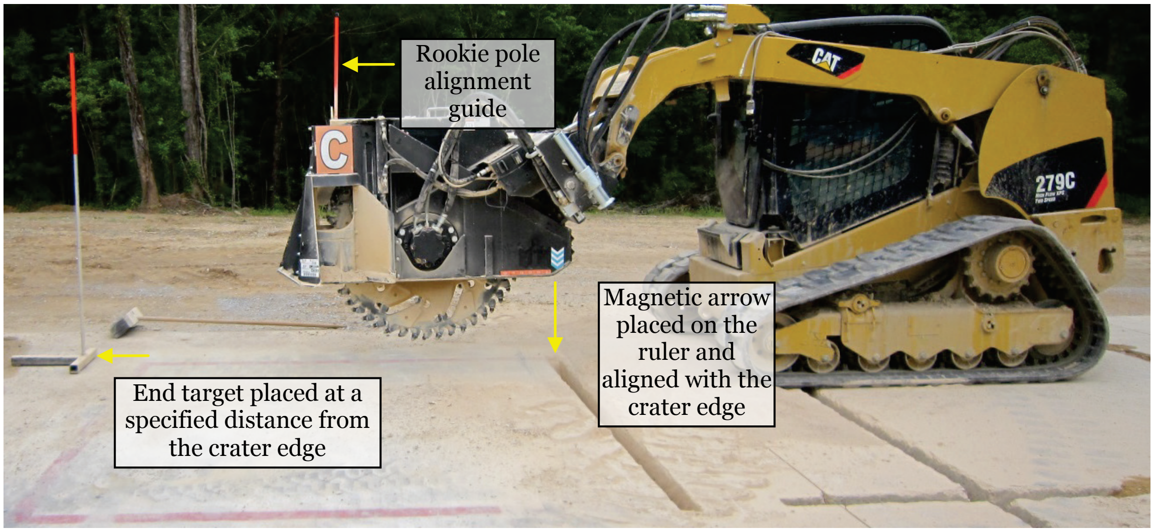


Figure 6. Specifications for metal plate attachment piece for alignment guide attached to top of wheel saw.

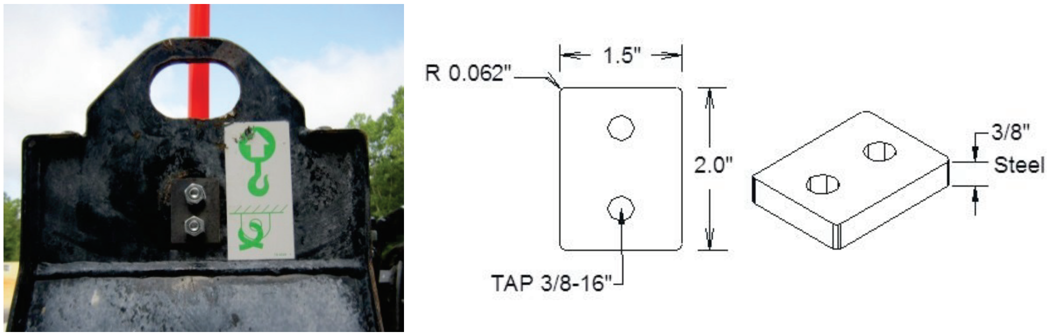


Figure 7. Specifications for the end target stand.

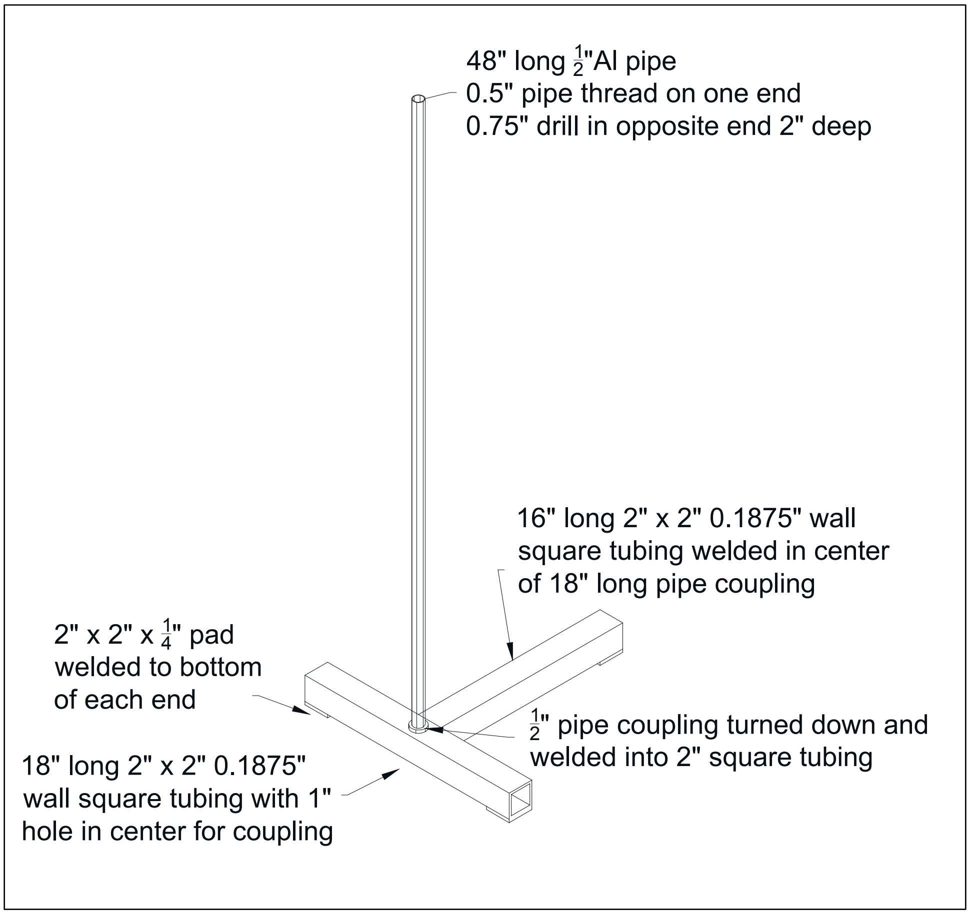
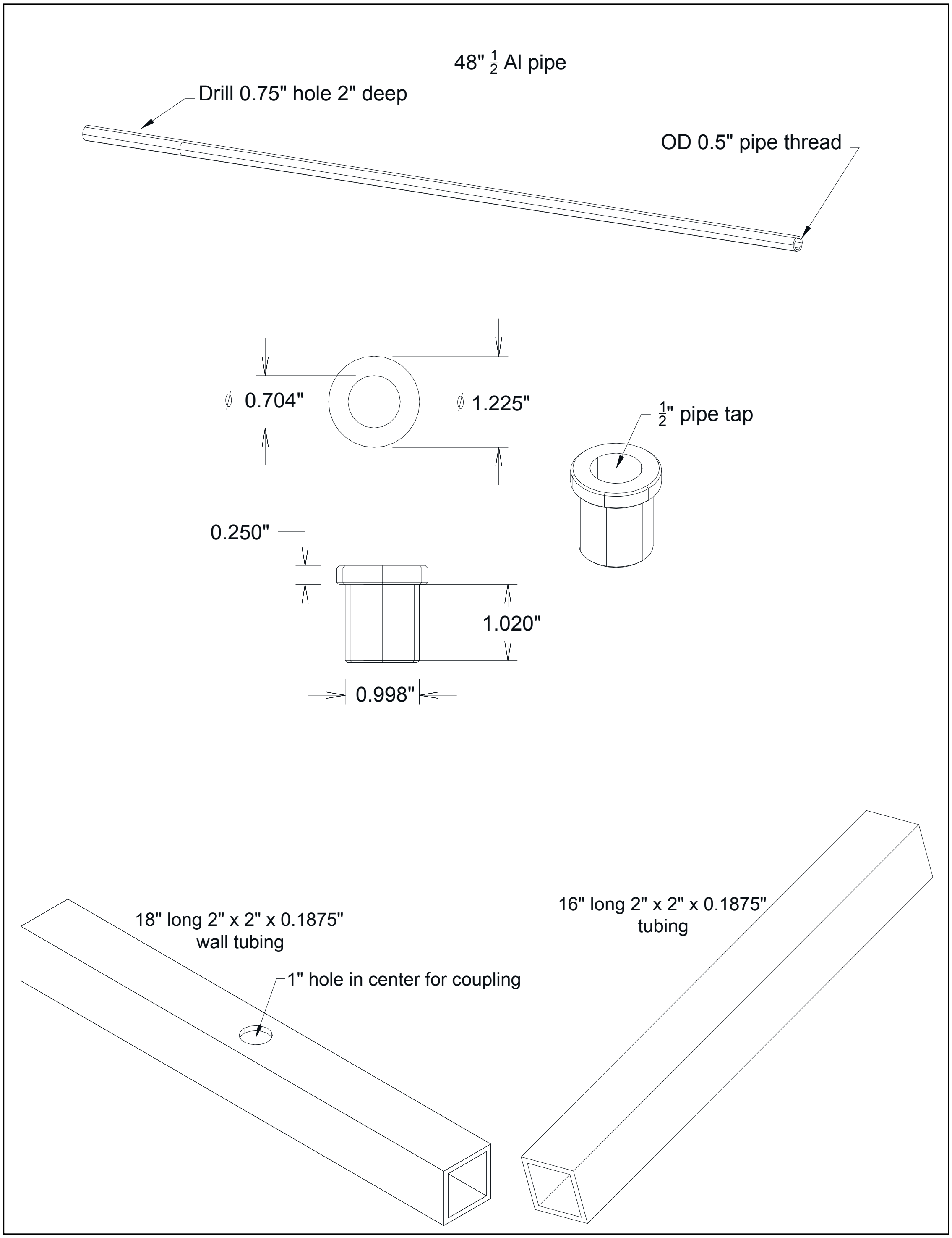


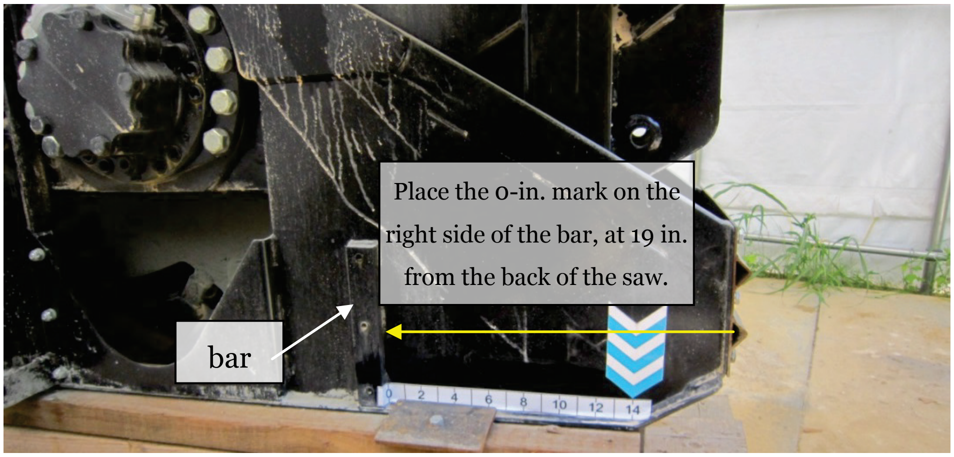
Figure 8. Specifications for the end target stand parts.



Rulers were printed on self-adhesive vinyl and placed on the sides of the wheel saws to assist with wheel saw positioning. A ruler was placed on the wheel saw such that the 0-in. mark lined up with the right side of the fixed bar on the left side of the saw. The right side of the fixed bar was 19 in.

from the back of the saw, as seen in Figure 9. Ruler placement on the right side of the saw was 19 in. from the back of the saw; a ruler with the numbers in reverse order was required.

Figure 9. Ruler on wheel saw.



The magnetic arrow was placed at the desired location and used by the spotter to determine where to position the saw prior to cutting. The arrow on the wheel saw was aligned with the edge of the crater repair when the wheel saw was parallel to the ground. The spotter often used the rookie stick from the end target to assist in lining up the saw (Figure 10). The end saw target was placed at the desired distance from the edge of the crater repair. The locations of the arrow and the end target depended on the desired overcut lengths, as discussed later in this report. The CTL operator used the rookie pole alignment guide on the wheel saw to line up with the end target placed by the wheel saw spotter. Once the wheel saw attachment bumped the end target, the cut was complete.

3.1.4 Vermeer CC155 concrete cutter with CC1531 wheel

The Vermeer CC155 machine was equipped with the CC1531 concrete cutter wheel (Figure 11). The wheeled machine has a cab for the operator and has the ability to perform wet or dry cuts. Two water tanks are mounted on the machine with a total capacity of approximately 200 gal. The water is optional and can be used to suppress dust and to keep the cutting teeth from getting too hot. The CC1531 concrete cutter wheel is mounted near the center of the machine as opposed to being an attached arm. The CC1531 concrete cutter wheel makes a 5.5-in.-wide cut.

Table 5 presents the specifications of the CC155 concrete cutter with the CC1531 wheel.

Figure 10. Using the rookie stick to line up to the edge of the crater.

Figure 11. Vermeer CC155 concrete cutter with CC1531 wheel.

Table 5. Vermeer CC155 with CC1531 specifications.

Parameter Specifications	Vermeer CC155/CC1531 combination
Gross power	155 hp
Overall width	96 in.
Overall height	120 in.
Length	165 in.
Weight (water tanks empty)	22,800 lb
Weight (water tanks full)	24,600 lb
Wheel diameter	84 in.
Wheel width (without teeth)	2 in.
Turning radius	18 ft
Max transport speed	10 mph or 900 ft/min
Number of teeth	90 per wheel
Maximum depth of cut	31 in.
Cutter tip speed (high gear)	1,844 ft/min
Cutter tip speed (low gear)	922 ft/min

3.1.5 Vermeer RTX1250 tractor

The Vermeer RTX1250 tractor (Figure 12) can switch between rubber tires and a rubber quad-track system. The rubber tracks were used for this evaluation. Although this evaluation included the tractor with no cab, there is an optional cab for the machine to protect the operator from concrete dust. The RTX1250 comes with many optional attachments: a reel carrier, a plow, a wheel saw, a trencher, a backhoe, and a backfill blade. Table 6 lists some key specifications of the tractor.

3.1.6 Vermeer RW1236W rockwheel attachment

The RW1236W rockwheel attachment (Figure 12) is used on the Vermeer RTX1250 tractor for trenching or sawing through concrete. The center-mounted wheel is pulled behind the operator. The RW1236W makes a 5-in.-wide cut. Specifications for the RW1236W are shown in Table 7.

Figure 12. RTX1250 tractor with RW1236W rockwheel attachment.

Table 6. Vermeer RTX1250 tractor specifications.

Parameter Specifications	Vermeer RTX1250
Gross power	120 hp
Height	109 in.
Width	93 in.
Length	161 in.
Weight	13,620 lb
Max torque	350 ft-lb
Max transport speed	9 mph
Turning radius	20 ft

Table 7. Vermeer RW1236W rockwheel specifications.

Parameter Specifications	Vermeer RW1236W
Length	89 in.
Weight (without teeth and segments)	4,260 lb
Wheel diameter	88 in.
Number of teeth	90 per wheel
Maximum depth of cut	36 in.
Hydraulic motor RPM, full throttle, full flow	85 rpm

3.1.7 CASE TV380 compact track loader

The CASE TV380 CTL (Figure 13) is similar to the Caterpillar 279C CTL. The tracked machine has a rigid track frame, which results in fewer moving parts than suspension track systems. Many optional attachments such as augers, rakes, backhoes, brooms, buckets, cold planers, couplers, dozer blades, hammers, forks, and wheel saws can be used with the CASE TV380 CTL. Table 8 presents the basic specifications for the machine.

Figure 13. CASE TV380 with Bradco RS24 rock saw attachment.

Table 8. CASE TV380 CTL basic specifications.

Parameter Specifications	Case TV380
Net power	84 hp
Operating weight	10,200 lb
Rated operating capacity	3,800 lb at 50% tipping load
Travel speed	5.1 mph
Tipping load	7,600 lb
Breakout force (tilt cylinder)	7,510 lb
Hydraulic pressure	3,050 psi
Standard pump flow	24 gal/min

3.1.8 Bradco RS24 rock saw attachment

The Bradco RS24 rock saw (Figure 13) is similar to the Caterpillar SW360B wheel saw; however, the Bradco RS24 is equipped with 10 fewer cutting tools and produces 4-in.-wide cuts. The Bradco RS24 may be operated with different equipment but was controlled using the CASE TV380 CTL and the Caterpillar 279C CTL. Specifications for the Bradco RS24 rock saw attachment are presented in Table 9.

Table 9. Bradco RS24 rock saw specifications.

Parameter Specifications	Bradco RS24
Overall width	67 in.
Overall height	81 in.
Length	86 in.
Operating weight	2,420 lb
Hydraulic flow requirement	30-44 gal/min
Operating pressure	2,500 to 3,000 psi
Wheel diameter	60 in.
Number of teeth	56 per wheel
Maximum depth of cut	24 in.
Side shift travel to right	24 in.
Cutting width	4 in.

3.1.9 Caterpillar M318D excavator and H120E hammer

A Caterpillar M318D wheeled excavator (Figure 14) or its equivalent is used in the ADR TTPs to break the PCC and excavate the broken PCC and underlying material. Wheeled excavators are preferred to tracked excavators for crater repair purposes because they minimize damage to the existing pavement around the repairs. The excavator is equipped with quick-disconnect fittings for the hammer and bucket work tool attachments. Table 10 presents the basic specifications of the Caterpillar M318D wheeled excavator.

The 18-in. and 24-in.-thick concrete was broken with a moil point Caterpillar H120E hammer (Figure 14). A 36-in.-wide bucket with a stationary thumb (Figure 15) was used for removing disturbed material. The teeth on the 36-in.-wide bucket were 8 in. long. Specifications for the Caterpillar H120E hammer are listed in Table 11.

Figure 14. Caterpillar M318D excavator with H120E hammer.

Table 10. Caterpillar M318D basic excavator specifications.

Parameter Specifications	Caterpillar M318D
Net power	166 hp
Maximum torque	596 ft-lb at 1,400 rpm
Breakout force	28,326 lbf
Maximum digging reach	31.5 ft
Maximum digging depth	20.9 ft
Maximum travel speed	23 mph
Operating weight	40,124 to 44,313 lb

Figure 15. Excavator 36-in.-wide bucket.

Table 11. Caterpillar H120E excavator hammer specifications.

Parameter Specifications	Caterpillar H120E
Impact energy	3,000 lb-ft
Operating weight	3,476 lb
Tool diameter	4.7 in.
Acceptable oil flows	26 to 45 gpm
Oil pressure	2,175 psi
Impact rate	350 to 620 blows per min
Excavator weight limits	27,400 to 57,200 lb

3.1.10 Caterpillar 966K front-end loader

A front-end loader is a part of the ADR kit and is readily available. A Caterpillar 966K front-end loader with a 4-yd^3 bucket (Figure 16) was employed for lifting sawed pavement sections by using anchoring systems and for general cleanup around the test site. The basic specifications for the Caterpillar 966K can be found in Table 12.

Figure 16. Caterpillar 966K front-end loader.

Table 12. Caterpillar 966K front-end loader specifications.

Parameter Specifications	Caterpillar 966K
Max net power	267 hp
Bucket capacity	3.25 to 12.0 yd^3
Operating weight	53,311 lb
Static tipping load (full turn)	32,259 lb

3.1.11 Caterpillar TH514 telehandler

An extendable boom forklift is versatile and can be used for various ADR tasks. The Caterpillar TH514 telehandler (Figure 17) was used for this evaluation. Since the telehandler is readily available, it was tested for its ability to lift sawed pavement using an epoxy-anchoring system. The specifications for the Caterpillar TH514 telehandler are provided in Table 13.

Figure 17. Caterpillar TH514 telehandler.

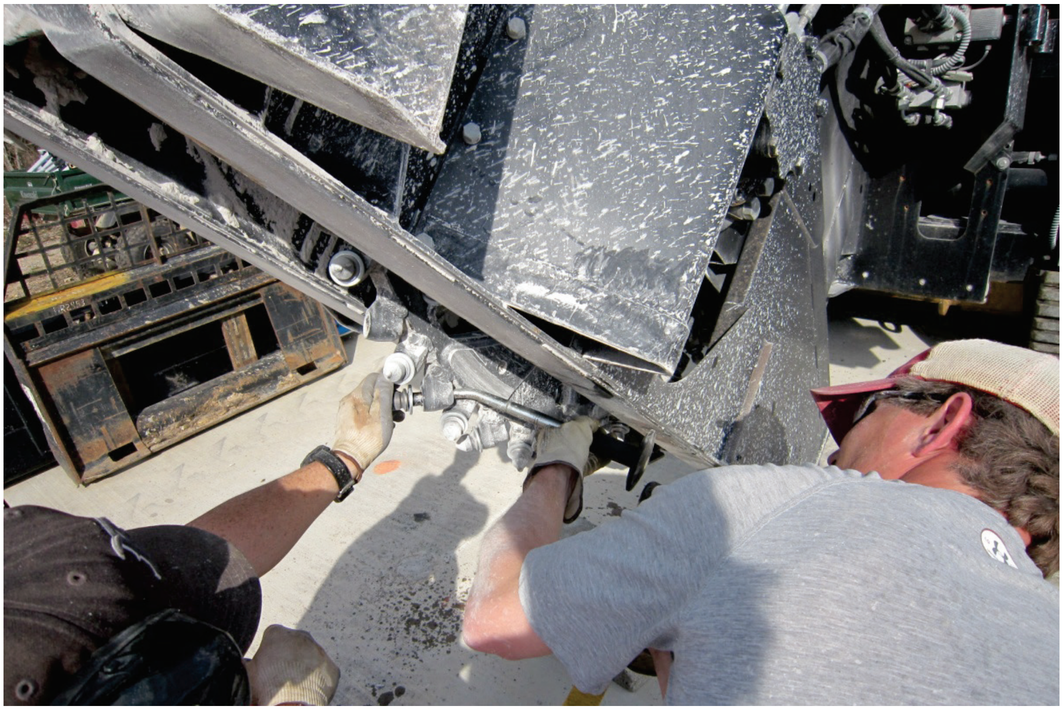
Table 13. Caterpillar TH514 telehandler basic specifications.

Parameter Specifications	Caterpillar TH514
Rated load capacity	11,000 lb
Maximum lift height, stabilizers up or down	45 ft
Gross power	101 hp
Maximum torque	1400 rpm
Operating weight with carriage and forks	23,722 lb
Load at max height, stabilizers up	4,000 lb
Load at max height, stabilizers down	7,000 lb
Load at max reach, stabilizers up	1,000 lb
Load at max reach, stabilizers down	3,000 lb

3.2 Wheel saw-cutting tools

Conical bits are used on the wheel saws and wheel saw attachments for cutting into the pavement. A variety of teeth is available for varying needs and jobs. Most teeth are made of steel with carbide tips. Replacing teeth is necessary when the carbide bits become worn, particularly after cutting through PCC. A punch tool is used with a mallet to remove the teeth, and the replacement teeth are tapped into place with the mallet, as shown in Figure 18. The following sections describe the cutting teeth evaluated during this study.

Figure 18. Replacing teeth on the SW45 saw.



3.2.1 Caterpillar cutting tools (CAT model 149-5763)

During recent equipment testing conducted at ERDC, the Caterpillar model 149-5763 teeth were determined to be the most efficient teeth to use for saw cutting PCC with the Caterpillar wheel saw attachments (Bell et al. 2014). These teeth are classified as cold planer teeth used for removing asphalt concrete pavement and are not the concrete teeth normally sold for the wheel saws. These conical bits, or teeth, used on the SW45 and SW360B are made with a carbide tip, specifically designed for milling concrete, solid limestone, and ultra-hard rock (Figure 19). The tooth diagram was taken from an email correspondence with Melvin Ottley and John Wood from Caterpillar Inc. (July 10, 2012).

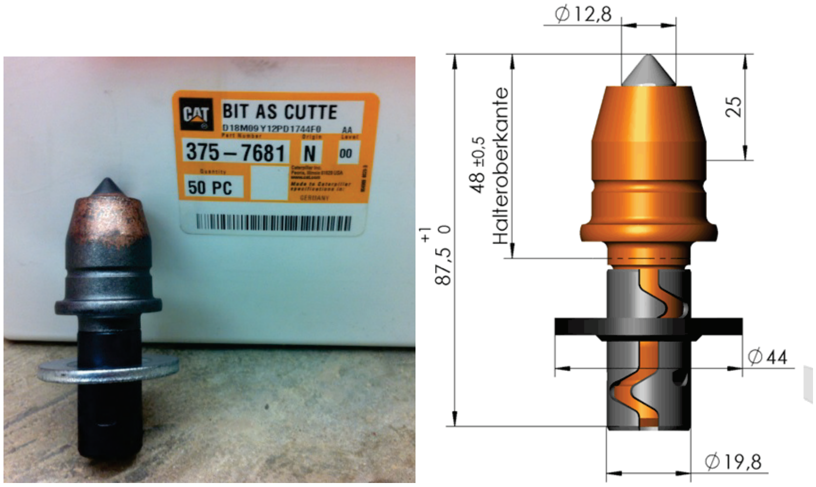
3.2.2 Caterpillar cutting tools (CAT model 375-7681)

The Caterpillar model 375-7681 cutting tools (Figure 20) are primarily used on cold planer equipment but are also designed for use in all Caterpillar wheel saws. The CAT model 149-5763 cold planer teeth were updated to part number 375-7681 because of (1) their improved life expectancy over the previous design due to the carbide tips being a full 0.98 in. (25 mm) in length and (2) the addition of an integral washer under the head that leads to improved tool holder protection, which in turn leads to less machine downtime from premature failure of the tool holder (email correspondence with Melvin Ottley and John Wood, July 10, 2012). The tooth diagram was provided in this email correspondence. At the time of this testing, Caterpillar was no longer manufacturing the CAT model 149-5763 cold planer teeth.

Figure 19. Wheel saw teeth, CAT model 149-5763.

*Measurement unit is mm.

Figure 20. Wheel saw teeth, CAT model 375-7681.



*Measurement unit is mm.

3.2.3 Caterpillar cutting tools (CAT model 227-7340)

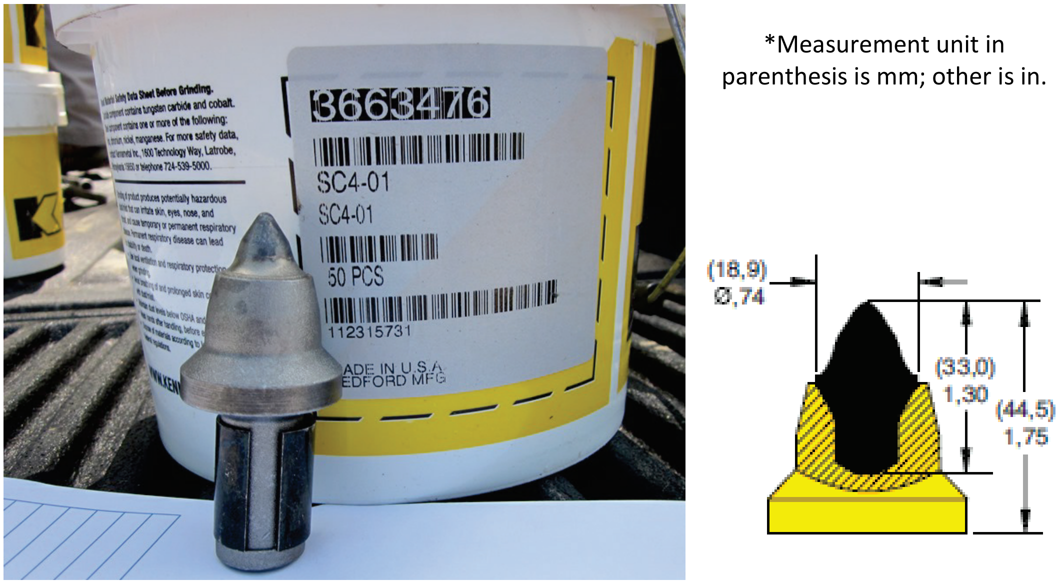
The Caterpillar model 227-7340 concrete cutting tools (Figure 21) are the standard teeth sold with SW45 and SW360B wheel saw attachments. Previous testing (Bell et al. 2014) showed that these teeth produced slightly slower cutting rates than the cold planer teeth (CAT model 149-5763) in a limestone PCC mix. No diagram was available for this tooth.

Figure 21. Wheel saw teeth, CAT model 227-7340.

3.2.4 Kennametal cutting tools (Kennametal model SM08)

The Kennametal model SM08 is a trenching tooth made of forged steel with a tungsten carbide insert with a 0.86-in.-diam shank. The 0.86-in.-diam shank fits in most Vermeer wheel saw attachments. The teeth are designed for use on soft, medium, hard, abrasive, or laminated rock. Figure 22 presents a diagram (Kennametal 2010) and picture of the teeth.

Figure 22. Wheel saw teeth, Kennametal model SM08.



*Measurement unit in parenthesis is mm; other is in.

3.2.5 Kennametal cutting tools (Kennametal model SM04)

The Kennametal model SM04 cutting tools are made of forged steel with a tungsten carbide tip and have a 0.86-in.-diam shank. The teeth fit most Vermeer saw equipment. The teeth are made for cutting through hard asphalt, concrete, or semi-rocky conditions (soft, medium, or abrasive rock). Figure 23 shows a diagram (Kennametal 2010) and picture of the SM04 teeth.

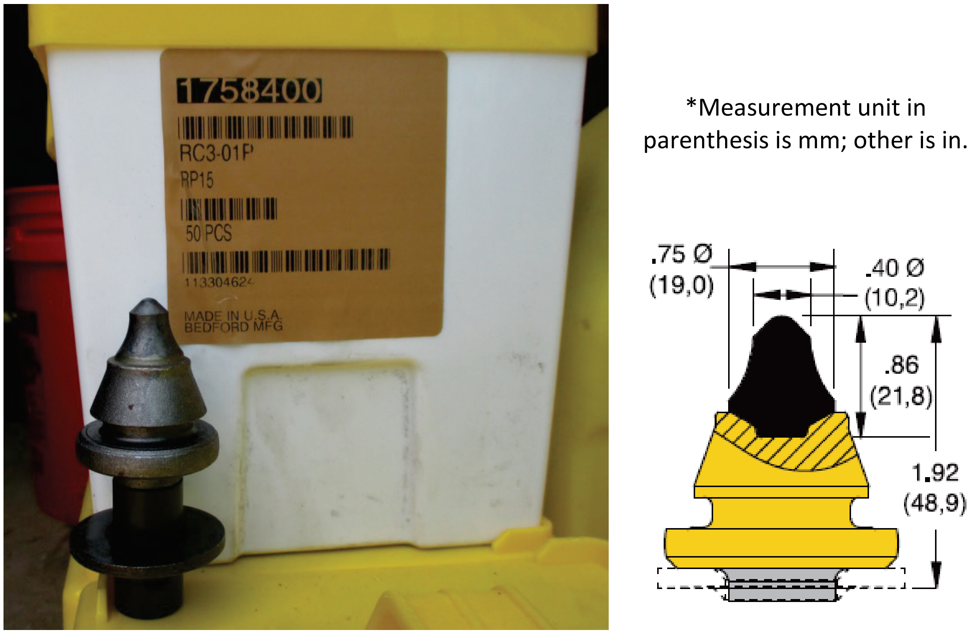
Figure 23. Wheel saw teeth, Kennametal model SM04.

*Measurement unit in parenthesis is mm; other is in.

3.2.6 Kennametal cutting tools (Kennametal model RP15)

The Kennametal model RP15 teeth have a 0.76-in.-diam shank, which fits Caterpillar wheel saws. The cutting tools are made of forged steel with tungsten carbide tips. They are equivalent to the Kennametal model SM04 teeth except that the RP15 teeth have a smaller shank diameter. Common applications for these cutting tools on medium to high horsepower machines include hard to medium asphalt and concrete conditions. Figure 24 shows a diagram (Kennametal 2007) and picture of the RP15 teeth.

Figure 24. Wheel saw teeth, Kennametal model RP15.



*Measurement unit in parenthesis is mm; other is in.

3.3 Anchoring systems

An adhesive anchoring system created during this project with steel box beams, 0.75-in.-diam all thread rods, nuts, and epoxy was evaluated for its ability to excavate the thick concrete. Two different sized box beams were evaluated. One had outer measurements of 4 in. by 8 in., with a 0.5-in.-thick wall (inner measurements of 3 in. by 7 in.), and the other had outer measurements of 4 in. by 8 in. with a 0.25-in.-thick wall (inner measurements of 3.5 in. by 7.5 in.).

The epoxy was Powers Fasteners AC100+Gold. The working times for the epoxy ranged from 1.5 min for hot pavement temperatures (104°F) to 90 min for cold pavement temperatures (14°F), and the cure times ranged from 15 min for hot pavement temperatures (104°F) to 24 hr for cold pavement temperatures (14°F). Table 14 lists the full range of working and curing time for the epoxy (Powers Fasteners 2013). Using any form of anchoring requires that the pavement be saw-cut full-depth at the corners before removal.

Table 14. Working and curing times for Powers Fasteners AC100+Gold.

Temperature of Base Material (°F)	Working Time (min)	Full Curing Time
14	90	24 hr
23	90	14 hr
32	45	7 hr
41	25	2 hr
50	15	90 min
68	6	45 min
86	4	25 min
95	2	20 min
104	1.5	15 min

4 Field Evaluation

The crater repair technologies were evaluated in April, May, and July 2013. Various tests – including the evaluation of tooth wear on each cutting machine, saw-cutting rates, reposition rates, and overcut lengths — were conducted on the PCC test section. The breaking times using an excavator against the weak and strong base materials and adhesive anchoring systems were also evaluated. The variables were tested by using four to eight linear cut lines inside a slab or around an approximate 8.5-ft by 8.5-ft square marked inside the center of the slab as a guide for the saws to follow. Tooth wear and saw-cutting rates were evaluated in the slabs with the straight cut lines. Tooth wear, saw-cutting rates, reposition rates, overcut lengths, anchoring, and/or breaking evaluations were conducted in the slabs with the 8.5-ft cut square. All methods are discussed further in the following sections.

All events were timed to the second. Each method or technology was tested multiple times to obtain average results. Various experienced equipment operators conducted the equipment testing. In the current ADR TTPs, the goal for the saw-cutting rate is 1 ft/min or faster. The goal for breaking is 16 min or less, and the removal process goal is 11 min or less.

4.1 Saw cutting

A key objective of this project was to narrow down the saw and teeth selection to identify the most effective and efficient technologies for small crater repair. Five saws – the SW45 wheel saw, the SW360B wheel saw, the Vermeer RW1236W rockwheel, the Vermeer CC1531 rockwheel, and the Bradco RS24 rock saw– were evaluated for their efficiency and maneuverability of cutting in close proximity to other small craters. Six types of teeth were alternated on the five saws. The teeth were replaced after each set of tests. For the Caterpillar saws, the Caterpillar 299C and 279C CTLs were used. For the Bradco RS24 saw, the Case TV380 and Caterpillar 279C CTLs were used. Table 15 and Table 16 identify the saw-cutting matrix for the 18-in.-thick and 24-in.-thick PCC, respectively. The full test matrix is also represented graphically in the appendix (Figure A4).

Table 15. 18-in.-thick PCC saw-cutting test matrix.

Test No.	Crater No.	Base Material	Saw	Machine	Teeth	Test
1	8	Silt	CAT SW45-A	CAT 279C CTL	CAT 375-7681	Overcut and rate
2	7	Silt	CAT SW45-C	CAT 279C CTL	CAT 149-5763	Overcut and rate
3	1	Silt	CAT SW45-C	CAT 279C CTL	CAT 149-5763	Rate
4	1	Silt	CAT SW360B	CAT 299C CTL	CAT 149-5763	Rate
5	15	Limestone	CAT SW360B	CAT 279C CTL	CAT 149-5763	Rate
8	15	Limestone	CAT SW45-C	CAT 279C CTL	CAT 149-5763	Rate
9	15	Limestone	CAT SW45-C	CAT 279C CTL	CAT 227-7340	Rate
10	15	Limestone	CAT SW45-C	CAT 279C CTL	CAT 375-7681	Rate
	1	Silt				
	8					
	7					
11	8	Silt	CAT SW45-C	CAT 279C CTL	CAT 227-7340	Rate
15	3	Silt	Vermeer RW1236W	Vermeer RTX1250	Kenn SM04	Rate and reposition time
16	2	Silt	Vermeer CC1531	Vermeer CC155	Kenn SM04	Rate and reposition time
17	4	Silt	CAT SW45-C	CAT 279C CTL	CAT 375-7681	Rate and reposition time
18	10	Limestone	CAT SW45-C	CAT 279C CTL	CAT 375-7681	Rate and reposition time
19	5	Silt	CAT SW45-C	CAT 279C CTL	CAT 149-5763	Rate and reposition time
20	11	Limestone	CAT SW45-C	CAT 279C CTL	CAT 149-5763	Rate and reposition time
21	9	Silt	CAT SW45-C	CAT 279C CTL	Kenn SM04	Rate and reposition time
22	12	Limestone	CAT SW45-C	CAT 279C CTL	Kenn SM04	Rate and reposition time
23	14	Limestone	CAT SW45-C	CAT 279C CTL	Kenn SM04	Rate and reposition time
24	17	Limestone	CAT SW45-A	CAT 279C CTL	CAT 149-5763	Rate
25	17	Limestone	Bradco RS24	Case TV380	Kenn RP15	Rate
26	16	Limestone	Bradco RS24	CAT 279C CTL	Kenn RP15	Rate

Table 16. 24-in.-thick PCC saw-cutting test matrix.

Test No.	Crater No.	Base Material	Saw	Machine	Teeth	Test
6	20	Limestone	CAT SW360B	CAT 299C CTL	CAT 149-5763	Rate
7	20	Limestone	CAT SW360B	CAT 279C CTL	CAT 149-5763	Rate
12	19	Limestone	Vermeer RW1236W	Vermeer RTX1250	Kenn SM08	Rate
13	19	Limestone	Vermeer CC1531	Vermeer CC155	Kenn SM04	Rate
	20					
	21					
14	21	Limestone	Vermeer RW1236W	Vermeer RTX1250	Kenn SM04	Rate

The saws were tested for their cutting rates and/or reposition times. The Caterpillar SW45 and SW360B wheel saw attachments were also studied to identify the appropriate lineup and stop locations to achieve the desired overcut lengths. Overcuts lengths are the amount of PCC sawed beyond the marked corners of the crater repair area. Long overcuts (Figure 25) affect the saw times and the repair quality, while short overcuts (Figure 26) or no overcuts run the risk of damaging the parent slab during the remaining repair processes of breaking and removing the existing pavement section. The startup locations were based on a ruler adhered to the base of the saw guard, and saw targets were used for pinpointing where the saw should stop at the end of a cut.

Figure 25. Long overcut lengths, as seen on Crater 8.

Figure 26. Short overcut lengths, as seen on Crater 9.

4.2 Excavation

4.2.1 Excavator

As described in Chapter 2, half of the test section was constructed with a weak foundation composed of compacted silt, while the other half of the test section was constructed with a strong base course composed of compacted crushed limestone. This was done to determine whether the foundation strength affects the time it takes to break up the PCC into pieces small enough to excavate. The Caterpillar M318D with a moil point bit hammer was used to break up the PCC. The removal of the broken PCC and the underlying material was assessed by using a wheeled excavator equipped with a 36-in.-wide bucket with 8-in.-long teeth and a stationary thumb.

Table 17 presents the matrix of the craters used for the breaking and removing evaluation. The overcut range listed is the length of the saw-cut lines beyond the corners of the marked repair areas (beginning and end of each cut).

Table 17. Breaking and removing test matrix.

Crater No.	Estimated PCC Thickness (in.)	Base Material	Overcut Range (in.)
4	18	Silt	0-3
5	18	Silt	0-3
9	18	Silt	3-8
8	18	Silt	>8
10	18	Limestone	0-3
11	18	Limestone	0-3
12	18	Limestone	3-8
14	18	Limestone	>8

4.2.2 Adhesive anchoring systems

Crater 7 was used for evaluating the adhesive anchoring systems. The forklift and front-end loader were used for lifting the PCC. Five different tests were performed involving the Powers Fasteners AC100+Gold epoxy. These were small tests to determine the feasibility of excavating the sawed pavement sections without having to break the PCC into small pieces by using destructive equipment. The working times and cure times are listed in Table 14. Using any form of anchoring requires that the pavement be saw cut full-depth before removal.

Crater 7 was cut out using the SW360B wheel saw attachment on the CAT 279C CTL. The crater was then cut directly in half to make each lifted portion have approximate dimensions of 8.5-ft by 4-ft. The crater was cut to full depth (approximately 18 in.) with each cut having at least an 8-in.-long to 10-in.-long overcut to make sure the slabs would be removed without issues.

Table 18 presents the different anchoring test methods attempted. The epoxy was first placed only on the surface of the pavement. The epoxy was placed in the PCC via a drilled hole in later tests. Box beams were utilized as a method for the lifting equipment of either a Caterpillar TH514 telehandler or a Caterpillar 966K front-end loader to attach to the PCC for removal. The box beams were spaced 3 ft apart in the center of each cut slab. The ambient temperature was used as a conservative measure of surface temperature.

Two pairs of steel box beams with different thicknesses used in these anchoring tests were cut at ERDC's machine shop. One pair of box beams had outer measurements of 4 in. by 8 in., with a 0.5-in.-thick wall (inner measurements of 3 in. by 7 in.), and the other had outer measurements of 4 in. by 8 in. with a 0.25-in.-thick wall (inner measurements of 3.5 in. by 7.5 in.).

Table 18. Anchoring test matrix.

Test No.	Drilled Holes for Each Box Beam	Epoxy Placement	Box Beam	Lifting Method[1]	Ambient Temperature (°F)	Cure Time (min)
1	None	Epoxy applied under box beam pair placed on pavement	0.25-in.-thick wall	Telehandler forks	83	30
2	None	Epoxy applied under box beam pair placed on pavement	0.25-in.-thick wall	Telehandler forks	83	60
3	Four 0.75-in.-diam holes drilled 6 in. deep	Epoxy applied in the four drilled holes and under each box beam placed on pavement	0.25-in.-thick wall	Telehandler forks	86	20
4	One 1-in.-diam hole drilled 6.5 in. deep	Epoxy applied in drilled hole and all thread rod inserted in hole. All thread rod attached to box beam via nut and washer.	0.5-in.-thick wall	Telehandler forks	90	21
5	One 1-in.-diam hole drilled 6.5 in. deep	Epoxy applied in drilled hole and all thread rod inserted in hole. All thread rod attached to box beam via nut and washer.	0.5-in.-thick wall	Front-end loader with chain	90	21

[1] Either a Caterpillar TH514 telehandler or a Caterpillar 966K front-end loader was used.

5 Results and Discussion

Each technology was evaluated multiple times during the evaluation. The saw teeth were replaced for every test to avoid testing with dull teeth. The production rates measured in terms of ft/min or minutes for each evaluated technology are presented as the minimum time, the maximum time, and the average rate or total time depending upon the technology being evaluated. The detailed test matrix with results is listed in Appendix A in Table A1.

5.1 Sawing

The results of the sawing evaluation in the 18-in.-thick and 24-in.-thick PCC are presented in Table 19. The results include the average cutting rates for each piece of equipment tested using the six types of teeth. The total number of cuts (approximately 8.5 ft long per cut) used to determine the average cutting rates is included in the table. All saws were able to consistently cut straight lines.

Two Caterpillar SW45 attachments, labeled as C or A in Table 18, were evaluated to assess the variability in performance for this particular model saw. The results showed that overall the Caterpillar SW45-C and SW45-A wheel saws had comparable saw-cutting rates. The average rate of the SW45-C wheel saw with the CAT model 149-5763 teeth was 25 percent faster than that of the SW45-A; however, the SW45-A was tested only four times, while the SW45-C was tested 15 times. The cutting rates can vary based on teeth wear, operator, and CTL performance. When using the CAT model 375-7681 teeth, the average rate of the SW45-A wheel saw was 10 percent faster than the Caterpillar SW45-C wheel saw, which was opposite of the results using the CAT model 149-5763 teeth.

Table 19. Saw-cutting timing results.

Teeth	Saw	Machine	PCC Thickness (in.)	Avg. Rate (ft/min)	No. Cuts	Min Rate (ft/min)	Max Rate (ft/min)
CAT 149-5763	SW360B[a]	299C CTL[a]	18	0.60	6	0.54	0.66
CAT 149-5763	SW360B[a]	299C CTL[a]	24	0.63	6	0.57	0.75
CAT 149-5763	SW360B[a]	279C CTL[a]	18	0.70	8	0.63	0.75
CAT 149-5763	SW360B[a]	279C CTL[a]	24	0.58	6	0.62	0.62

Teeth	Saw	Machine	PCC Thickness (in.)	Avg. Rate (ft/min)	No. Cuts	Min Rate (ft/min)	Max Rate (ft/min)
CAT 149-5763	SW45 (C)[a]	279C CTL[a]	18	0.57	15	0.49	0.66
CAT 149-5763	SW45 (A)[a]	279C CTL[a]	18	0.72	4	0.67	0.75
CAT 375-7681	SW45 (C)[a]	279C CTL[a]	18	0.58	16	0.48	0.70
CAT 375-7681	SW45 (A)[a]	279C CTL[a]	18	0.53	4	0.50	0.57
CAT 227-7340	SW45 (C)[a]	279C CTL[a]	18	0.40	2	0.35	0.44
Kennametal SM04	RW1236W[b]	RTX1250[b]	18	2.31	4	1.92	2.49
Kennametal SM04	RW1236W[b]	RTX1250[b]	24	1.49	5	1.41	1.56
Kennametal SM04	CC1531[b]	CC155[b]	18	4.45	4	3.64	6.19
Kennametal SM04	CC1531[b]	CC155[b]	24	2.81	8	2.23	3.39
Kennametal SM08	RW1236W[b]	RTX1250[b]	24	0.84	2	0.73	0.96
Kennametal RP15	SW45 (C)[a]	279C CTL[a]	18	0.50	12	0.36	0.66
Kennametal RP15	RS24[c]	TV380[d]	18	0.23	4	0.16	0.33
Kennametal RP15	RS24[c]	279C CTL[a]	18	0.24	4	0.17	0.29

[a]Caterpillar, [b] Vermeer, [c]Bradco, [d]Case

Two common methods of plunging the wheel saw into the pavement with the Caterpillar SW45-C were evaluated in the 18-in.-thick PCC, weak base, using the CAT model 149-5763 teeth. One method, which is recommended by the manufacturer, has the saw starting at a 45-deg angle and plunging into the concrete before rotating parallel to the surface. This method was recommended by the manufacturer to allow the debris to exit the area and allow room for the saw to sit flush on the pavement. The other method, which is commonly employed by ERDC, starts the saw parallel to the ground to plunge into the concrete so that the debris does not fly out and cause harm to spotters or equipment operating in close proximity to the saw-cutting area. The angled method had saw rates of 0.60 ft/min, 0.53 ft/min, and 0.69 ft/min, averaging 0.60 ft/min. The parallel method had saw rates of 0.64 ft/min, 0.59 ft/min, 0.59 ft/min, and 0.66 ft/min, averaging 0.62 ft/min. The two rates were not significantly different, but the parallel method was preferred since the debris was less likely to be ejected from the cut and cause harm to nearby personnel or equipment.

A similar comparison was made for the Caterpillar 279C CTL and the similar Caterpillar 299C CTL by using the Caterpillar SW360B wheel saw in the 18-in.-thick and 24-in.-thick PCC. Table 19 shows that the Caterpillar 279C CTL and 299C CTL had comparable performances. On average, an 8 percent difference in cutting rates was observed between the two CTLs. The same type of teeth (CAT model 149-5763) was used for each test. The 299C CTL was slightly faster than the 279C CTL in the 24-in.-thick PCC, and the 279C CTL was slightly faster than the 299C CTL in the 18-in.-thick PCC.

The CAT model 227-7340 (concrete teeth) and the Kennametal SM08 teeth could be used for only two partial cuts due to the teeth being prematurely worn (Figure 27). The CAT model 227-7340 teeth were not durable enough to finish a complete cut. The cuts were between 5 ft and 8 ft long before the saws were stopped due to the completely worn teeth. The Kennametal SM08 teeth were tested twice and were completely worn after approximately 16 ft of cutting with the Vermeer RW1236W.

Figure 27. Worn concrete teeth after cutting, CAT model 227-7340.

The Caterpillar and Bradco wheel saws did not meet the ADR saw-cutting goal of 1 ft/min in the chert-mixed PCC test section. The Caterpillar SW45 and SW360B wheel saws attached to the Caterpillar CTLs generally met or exceeded the goal of 1 ft/min by cutting 1 ft or more per minute in previous evaluations (Bell et al. 2014); however, this particular PCC mix was stronger than those previously tested. The TTP's goal of 1 ft/min was developed from saws cutting in PCC with limestone aggregate, which is a softer aggregate. The PCC used for this testing was mixed with a chert aggregate. The 28-day flexural strength was 600 psi, and the 28-day compressive strength was 6,500 psi. The chert aggregate was very hard, making it difficult for the saw teeth to cut through the PCC. The saw-cutting results presented are considered conservative cutting rates.

The Caterpillar SW45 wheel saw specifications indicated that it had the ability to cut to a maximum depth of 18 in. The Caterpillar SW360B and Bradco RS24 specifications indicated that these pieces of equipment had the ability to cut to a maximum depth of 24 in. However, each wheel saw consistently cut 1.5 in. less than its published maximum depth. Several attempts were made to help the saws achieve the maximum depths, but none were successful. The attempts included angling the saw backwards or frontwards, clearing PCC dust away from the saw as it cut, and adjusting the guard on the wheel saw.

The Vermeer saws were able to exceed the 1 ft/min goal. Using the Kennametal SM04 teeth, the RW1236W had average cutting rates of 2.31 ft/min and 1.49 ft/min on the 18-in.-thick and 24-in.-thick PCC, respectively. The CC1531 had almost double the rate of the RW1236W, averaging 4.45 ft/min and 2.81 ft/min on the 18-in.-thick and 24-in.-thick PCC, respectively. The faster cutting rates may be partially attributed to the saw size. These saws were much larger than the Caterpillar and Bradco saws.

The performances of the Caterpillar SW45 and SW360B wheel saws on the 18-in.-thick PCC were similar. Table 18 shows that, on average, in the 18-in.-thick PCC, the SW360B (0.65 ft/min) cut approximately 8 percent faster than the SW45 (0.60 ft/min). According to the equipment operators, the disadvantage of the SW360B compared to the SW45 is that the SW360B is more cumbersome to maneuver around craters.

The Bradco RS24 wheel saw had the slowest cutting rate when compared to all other saws. The Bradco RS24 is similar to the Caterpillar SW360B wheel saw; however, the cutting rate of the Caterpillar SW360B wheel saw was approximately 2.5 times faster. Also, the performance of the Bradco RS24 wheel saw was not affected by the carrier machine. The saw rates were similar using the Case TV380 CTL (0.23 ft/min) or the Caterpillar 279C CTL (0.24 ft/min).

The wheel saws were also evaluated for their ability to maneuver around small craters by measuring their reposition times. The reposition time includes the time it takes for a saw to rotate and line up for a second cut once it has finished its first cut. Normally, the second cut is the one connecting and perpendicular to the current cut. The goal for repositioning is 1 min. The average reposition time for the Caterpillar SW45 was 1.05 min. The reposition time of the Caterpillar SW60 was not measured during this evaluation but is assumed to be the same as the SW45 since both wheel saws utilize the same prime mover. The Vermeer CC1531 and RW1236W wheel saws had average reposition times of 1.57 min and 1.63 min, respectively. The saws are larger and more cumbersome than the Caterpillar wheel saws, so the additional 30 sec of reposition time was expected.

5.1.1 Overcuts

Overcuts were estimated by using the saw target system with the Caterpillar wheel saws in the 18-in.-thick and 24-in.-thick PCC. Figures 28 to 33 show the overcuts achieved at the beginning or end of the cut, based on where the saw was lined up using the ruler or how far the target was placed away from the marked corner for the end of the cut. The overcut lengths affect the saw time, breaking time, removing time, and the final repair quality.

When the Caterpillar SW45 and SW360B wheel saws begin cutting, the saws move backwards as they plunge through the PCC, so lining up the saws can be deceiving for the spotter. More scatter was seen in the starting overcut data, likely due to the variability in the length as the saw moves backwards. To ensure consistency when measuring the starting overcuts, a rookie stick was used to line up the arrow and the marked corner (Figure 10).

Figure 28. Saw placement data for CAT SW45 in 18-in.-thick PCC.

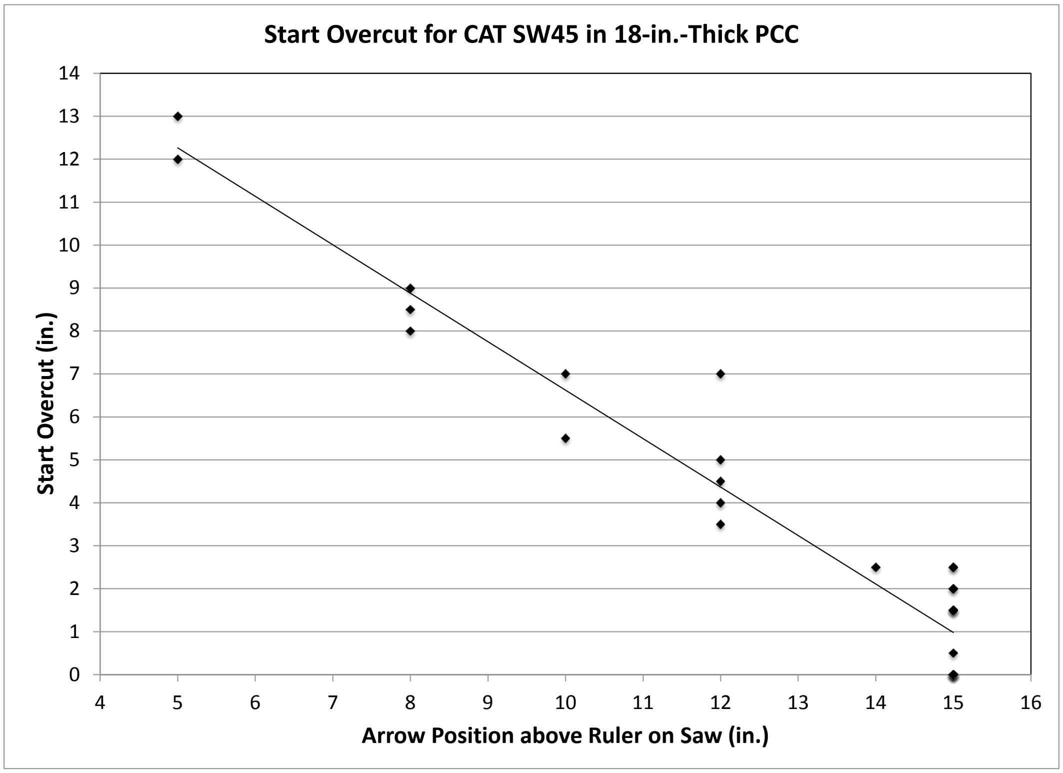


Figure 29. Target placement data for CAT SW45 in 18-in.-thick PCC.

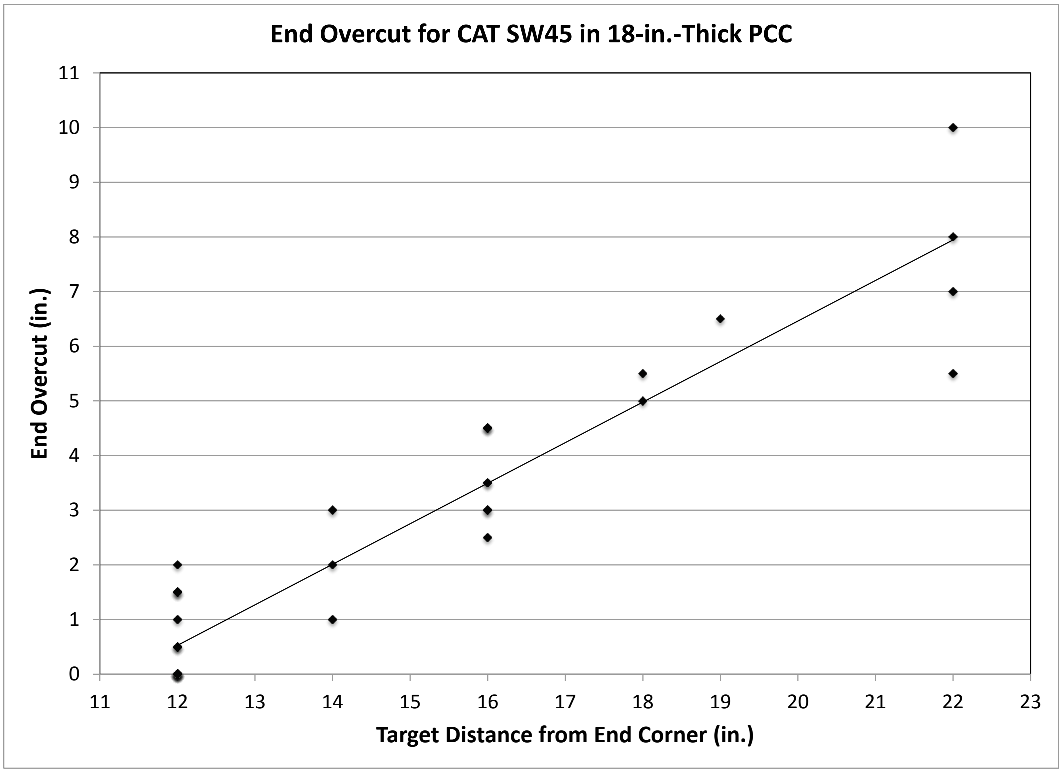


Figure 30. Saw placement data for CAT SW360B in 18-in.-thick PCC.

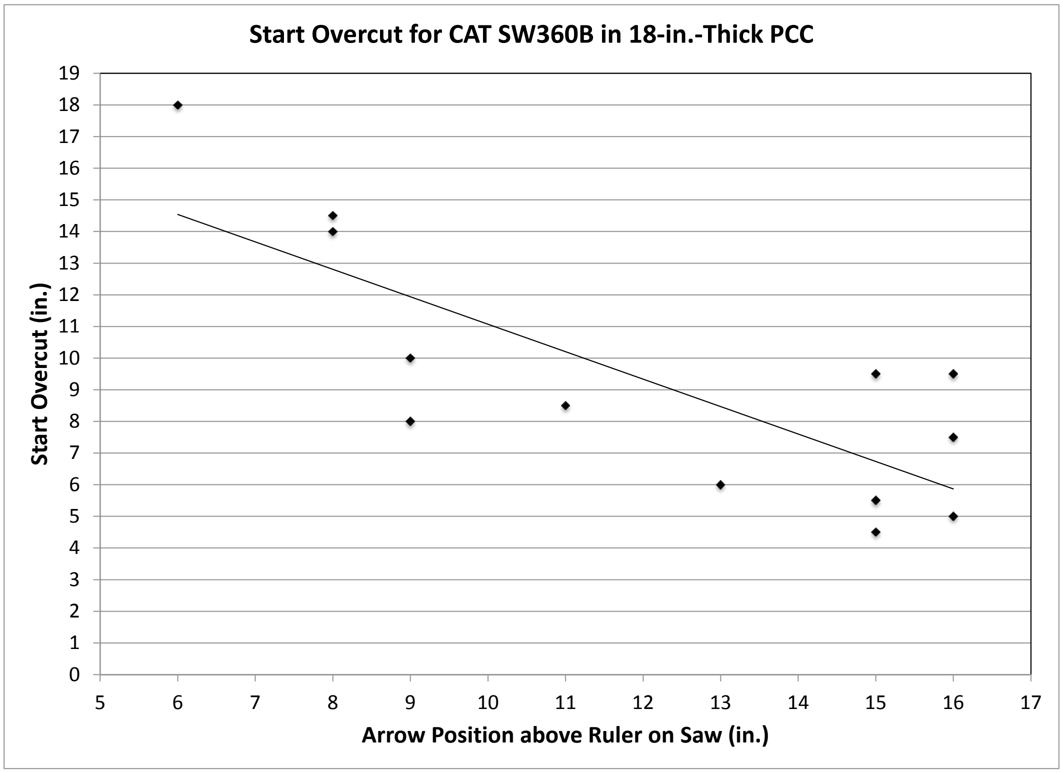


Figure 31. Target placement data for CAT SW360B in 18-in.-thick PCC.

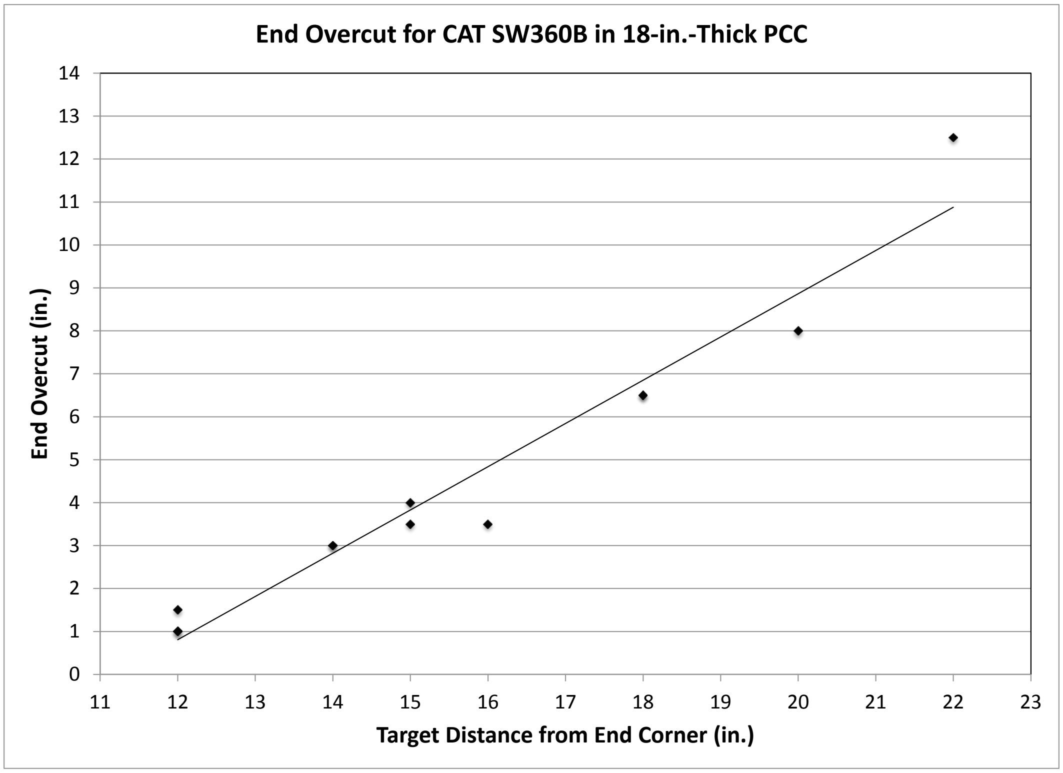


Figure 32. Saw placement data for CAT SW360B in 24-in.-thick PCC.

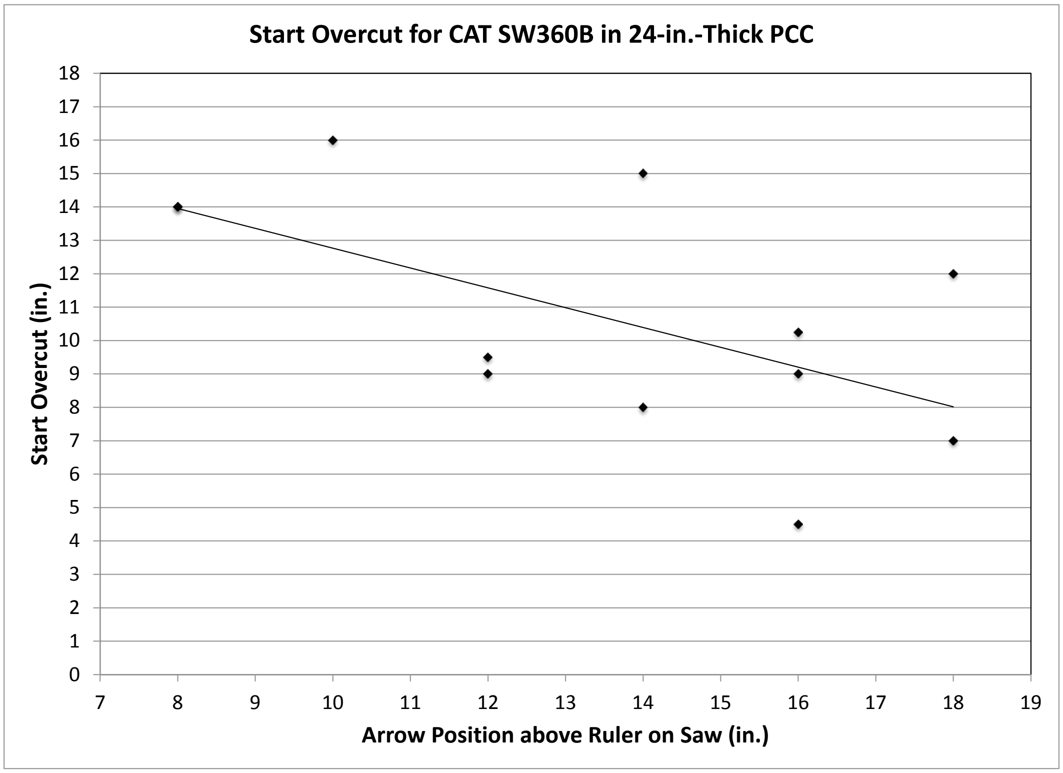
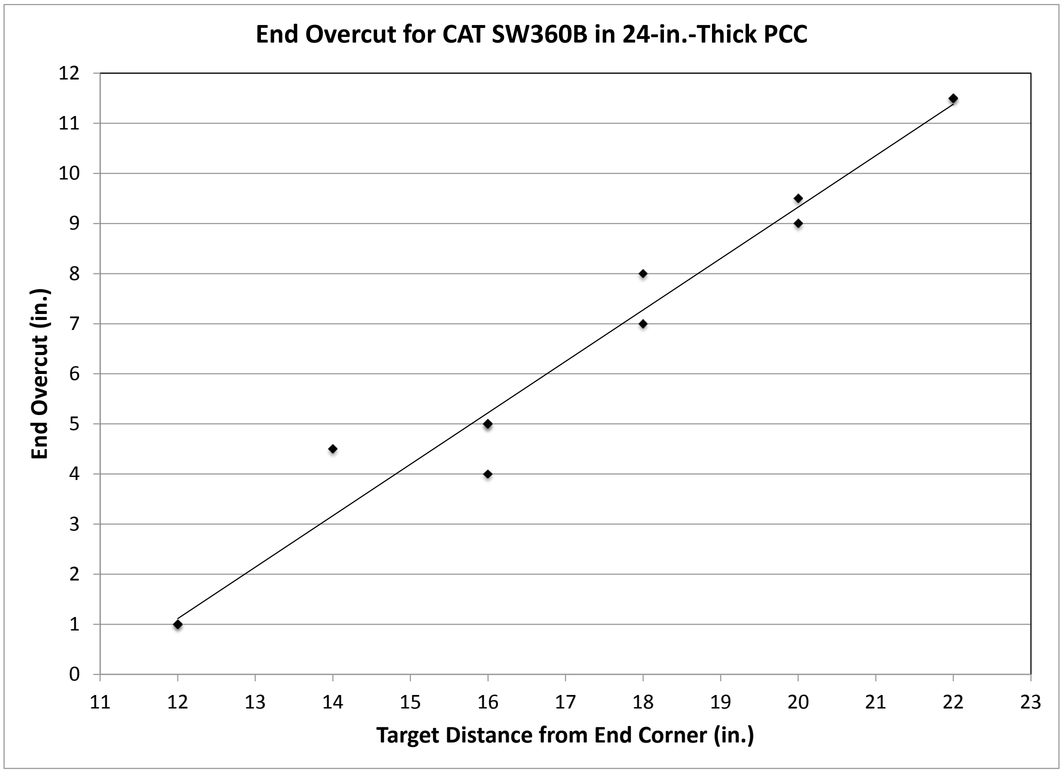


Figure 33. Target placement data for CAT SW360B in 24-in.-thick PCC.



The end overcuts were determined by placing the target at various distances away from the corner located at the end of the cut. The saw operator stopped the saw as soon as the machine bumped the target. Once all data were obtained, linear regressions were used to show approximately where the saws should be lined up to achieve the desired overcut.

Based on the testing, the 4-in. to 8-in.-long overcut range appeared to be optimal, as discussed later in the excavation section. Overcuts that were short, less than 4 in., ran the risk of cracking the surrounding pavement. Longer overcuts, greater than 8 in., required more material during capping, and often the material that naturally gravitated towards the overcuts had a high water content. The high water content led to a weaker repair in that area, generating an area with a high risk of FOD formation.

To achieve an overcut in the 4- to 8-in.-long range in 18-in.-thick PCC with the Caterpillar SW45 wheel saw, it is recommended to put the arrow on the saw at 12 in. (Figure 28). Figure 29 shows that the target should be placed 18 in. away from the end of the marked corner to achieve an overcut in the 4-in. to 8-in.-long range in 18-in.-thick PCC using the Caterpillar SW45 wheel saw. Figures 30 to 33 show the overcut data for the Caterpillar SW360B saw for both 18-in. and 24-in. PCC. The start overcut data were scattered, and more data points will be required for a more precise trendline. In the meantime, for overcuts in the 4-in.-long to 8-in.-long range, it is recommended that the arrow on the Caterpillar SW360B saw be placed at 18 in. on the saw ruler and the target be placed 16 in. away from the end of the marked corner. The recommendation can be applied for both 18-in.-thick and 24-in.-thick PCC.

5.1.2 Teeth durability

The lengths of the wheel saw teeth evaluated were measured with calipers before cutting began and at various cut lengths throughout the testing. Measuring the tooth length after various cut lengths gave an indication of the durability of each tooth. The same set of 10 teeth, marked prior to cutting, were measured for each test.

The results are presented in Figures 34 to 39. Each test began with new teeth, which ranged from 1.81 in. (46 mm) to 2.09 in. (53 mm) long. The Kennametal SM08 and CAT model 227-7340 teeth (Figure 27) were limited on their results because they were not able to finish a test; therefore, little durability data were collected due to fear of damaging the teeth pockets on the wheel saw. A bar graph showing the average slope of each tooth type is shown in Figure 40. The slope indicates the rate of decline of tooth wear as the cut length increases. A lower value slope indicates a better performance. It is important to note that the machine used does generally have an effect on teeth durability.

The Kennametal SM04 wheel saw teeth used on the Vermeer machines were the most durable and had similar wear to the Kennametal RP15 and CAT model 149-5763 teeth used on the Caterpillar machines. The Kennametal RP15 wheel saw teeth had poor performance on the Bradco RS24 wheel saw. The teeth did not wear down at the same rate; most of the teeth lasted about 45 ft along the 18-in.-thick PCC. Once all teeth were worn to approximately 1.38 in. (35 mm) (approximately 40 percent decrease), they were no longer durable enough to cut through the thick PCC. The Kennametal SM04 wheel saw teeth used on the Vermeer machines and the Kennametal RP15 wheel saw teeth used on the Caterpillar machine were never tested until the teeth were completely worn.

Figure 34. CAT model 149-5763 tooth length versus cut length.

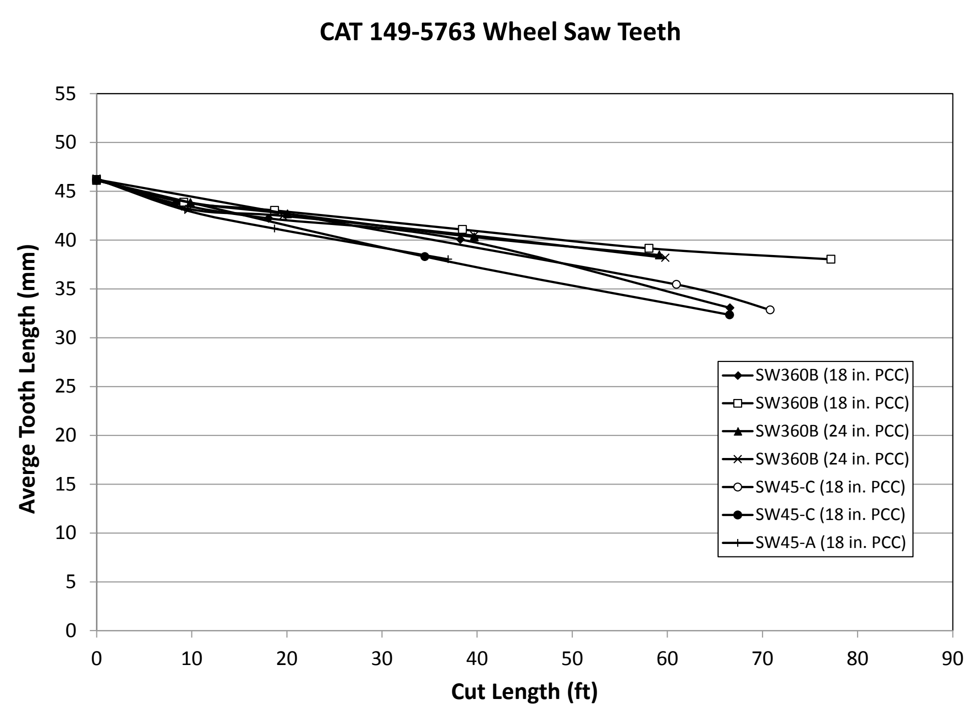


Figure 35. CAT model 375-7681 tooth length versus cut length.

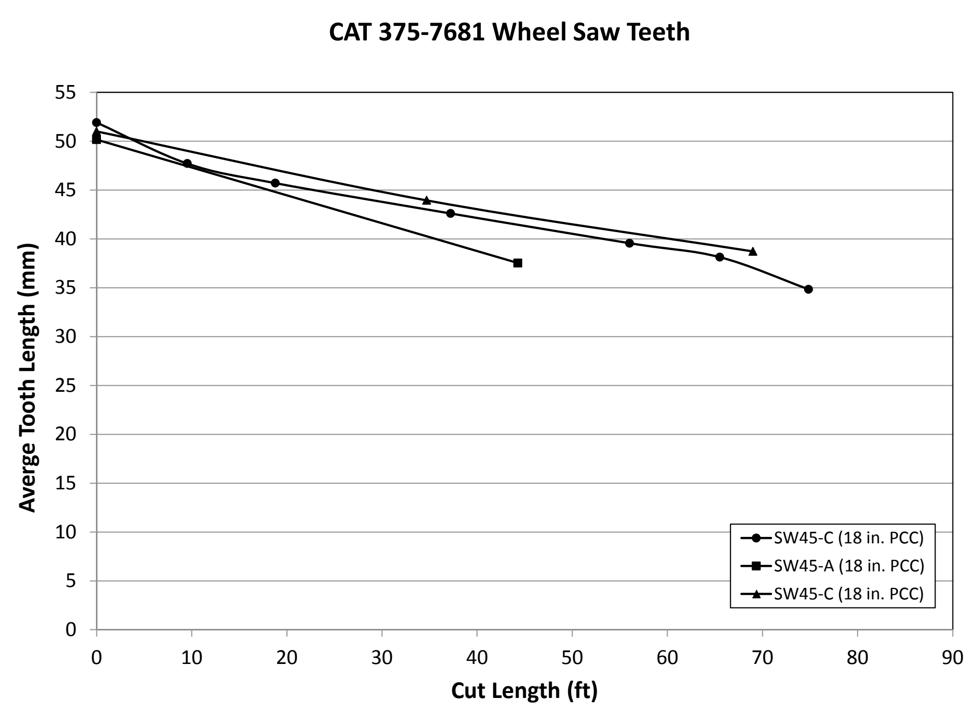


Figure 36. CAT model 227-7340 tooth length versus cut length.

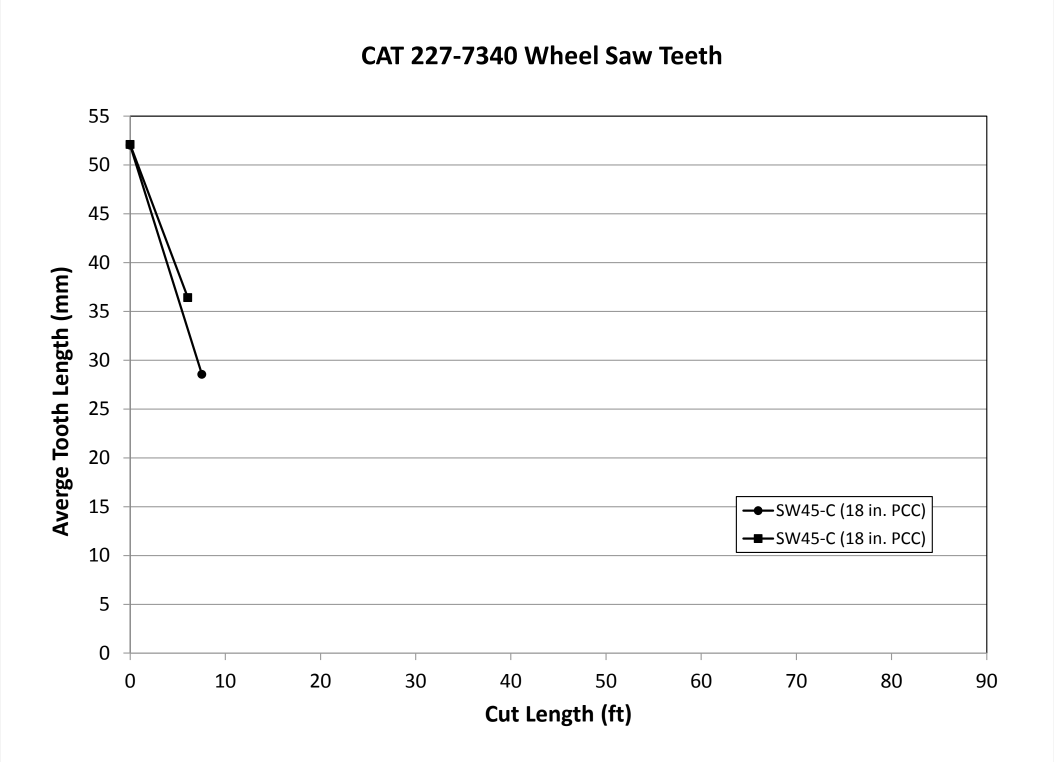


Figure 37. Kennametal model SM08 tooth length versus cut length.

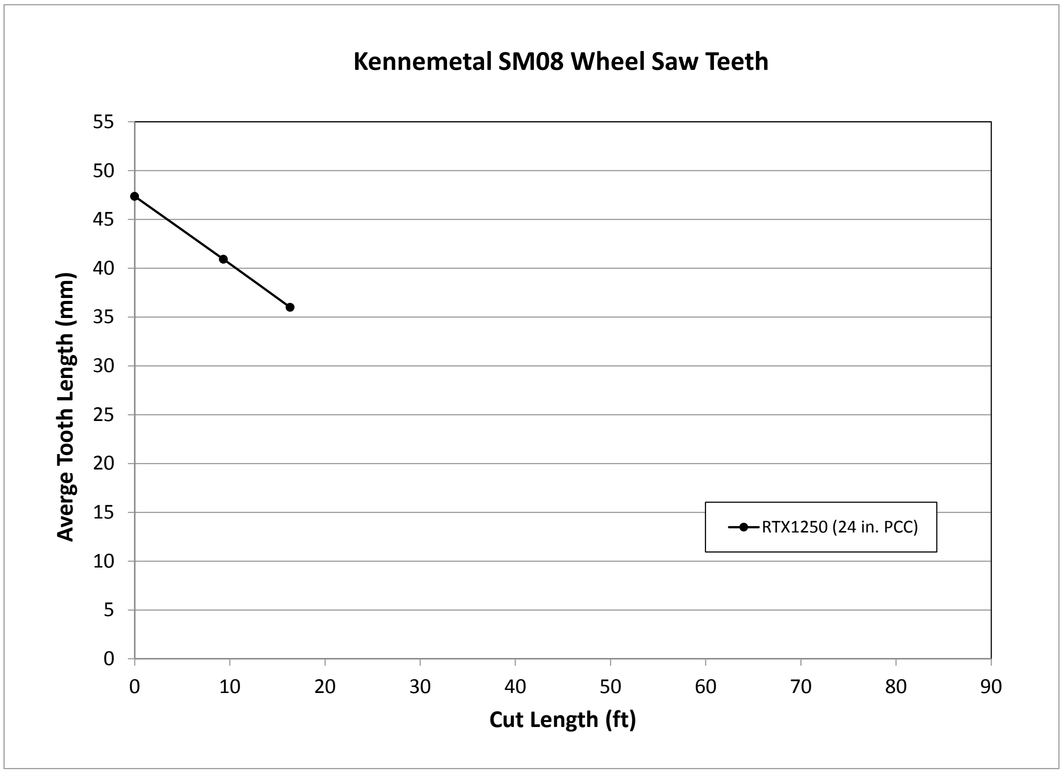


Figure 38. Kennametal model SM04 tooth length versus cut length.

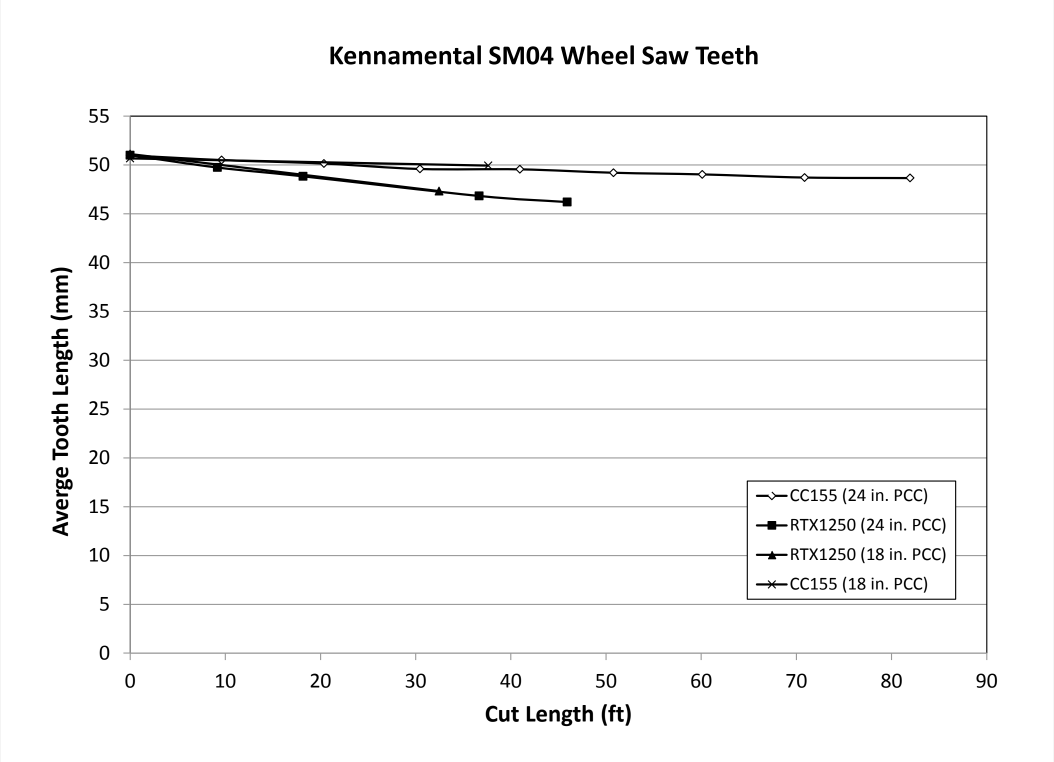


Figure 39. Kennametal model RP15 tooth length versus cut length.

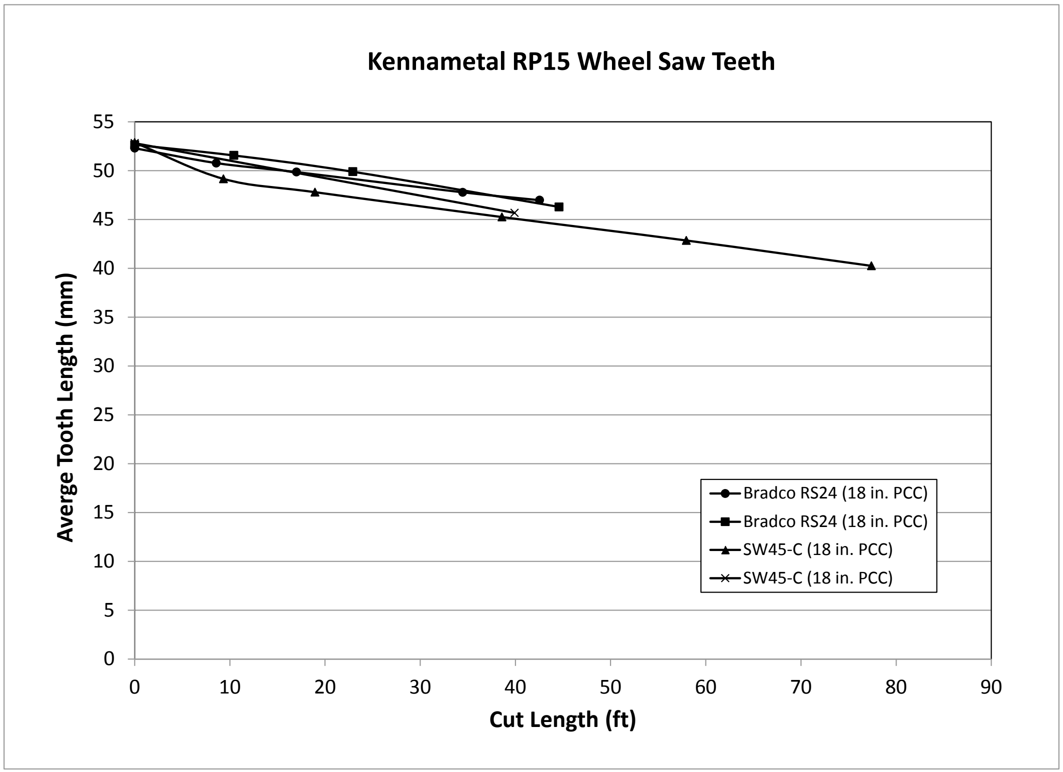
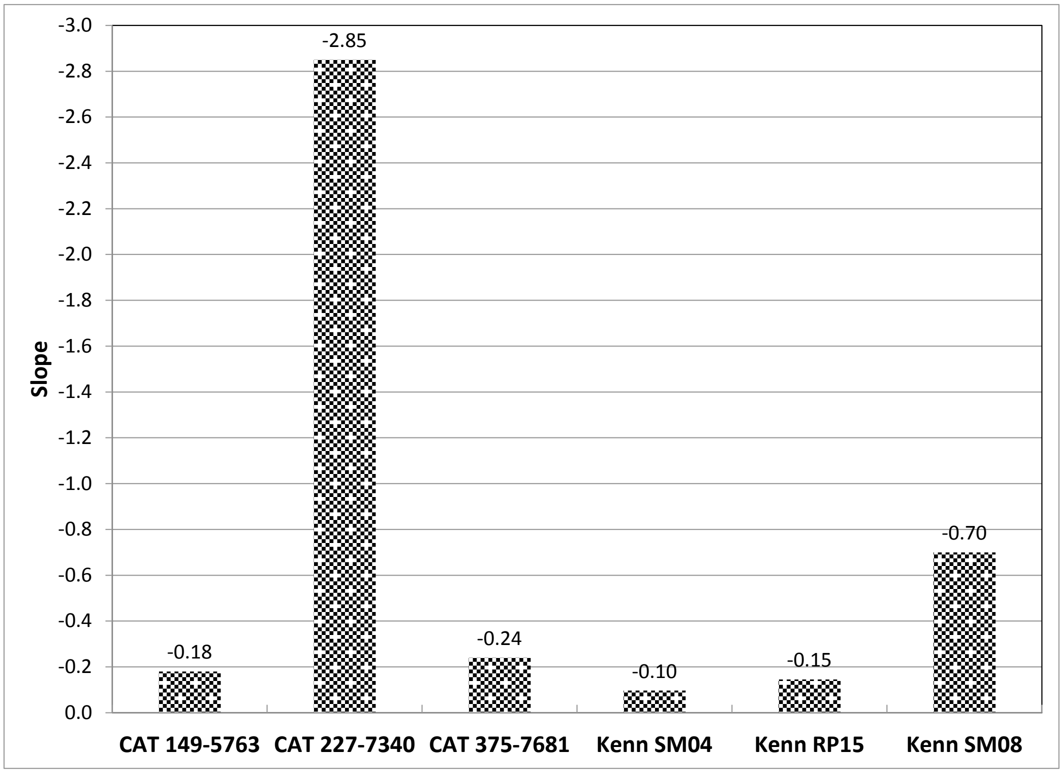


Figure 40. Slope of teeth wear with cut length.



The Kennametal SM08 wheel saw teeth used on the Vermeer RTX1250 machine and CAT model 227-7340 wheel saw teeth tested on the Caterpillar machines were not durable enough for sawing through 18-in.-thick and 24-in.-thick PCC. Also, the preexisting CAT model 149-5763 wheel saw teeth (slope of -0.18) were slightly more durable than the newer CAT model 375-7681 teeth (slope of -0.24). These data are considered conservative due to the chert aggregate used in the PCC mix.

5.2 Excavation

5.2.1 Breaking and removing

The PCC was broken with the Caterpillar H120E hammer attached to the Caterpillar M318D wheeled excavator. The Caterpillar M318D excavator with the H120E hammer with a 36-in.-wide bucket or its equivalent was determined to be the most efficient combination of tools to use for breaking and removing PCC and underlying debris of small craters (Bell et al. 2014). The hammer used in this study had a moil point tip.

The purpose of the breaking evaluation was to identify the effects of breaking with varying overcut lengths and to determine whether the base material affects the breaking times. The same wheeled excavator with a 36-in.-wide bucket and 8-in.-long teeth was used to remove the broken PCC and underlying material to an approximate depth of 34 in. The hammer was removed to attach the bucket, a process that took 36 min. The excavator used did not have the quick disconnects for the hydraulic lines, resulting in a longer time to change attachments.

Table 20 and Figures 41 and 42 present the breaking and removing results. The number of breaks was the number of times the excavator hammer was moved to produce a new breaking point in the pavement. Craters 2 and 3 were not included in the comparisons graphs because the start and end overcuts varied drastically due to the difficulty of controlling the starting locations of the larger Vermeer saws.

Table 20. Breaking and removal timing results.

Crater No.	PCC Thickness (in.)	Base	Overcut Range (in.)	Number of Breaks	Breaking Time (min)	Removal Time (min)	Notes
4	19.00	Weak	0-3	12	8.25	9.25	Not full-depth cut (15.5 in.)
5	19.00	Weak	0-3	6	7.25	9.73	PCC still attached on 2 edges
9	18.75	Weak	3-8	4	3.32	6	PCC still attached on sides
8	18.00	Weak	>8	5	3.8	6.35	Excavated wet soil
10	20.00	Strong	0-3	21	19.5	9.77	Not full-depth cut (15.5 in.)
11	18.50	Strong	0-3	8	7.5	10	
12	18.75	Strong	3-8	3	2.82	6.08	
14	19.00	Strong	>8	3	3.33	6.12	
2	18.00	Weak	0-18	8	3.83	6.25	Vermeer CC1531
3	18.00	Weak	0-8	9	5.42	6.68	Vermeer RW1236W

Figure 41. Breaking results.

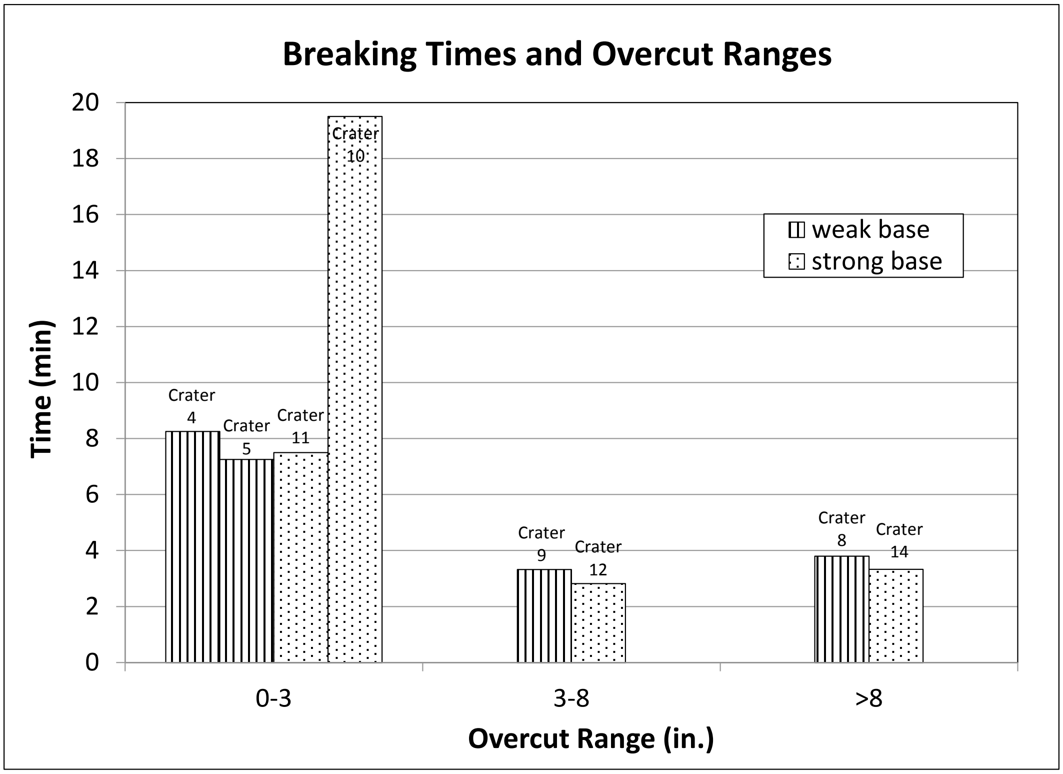
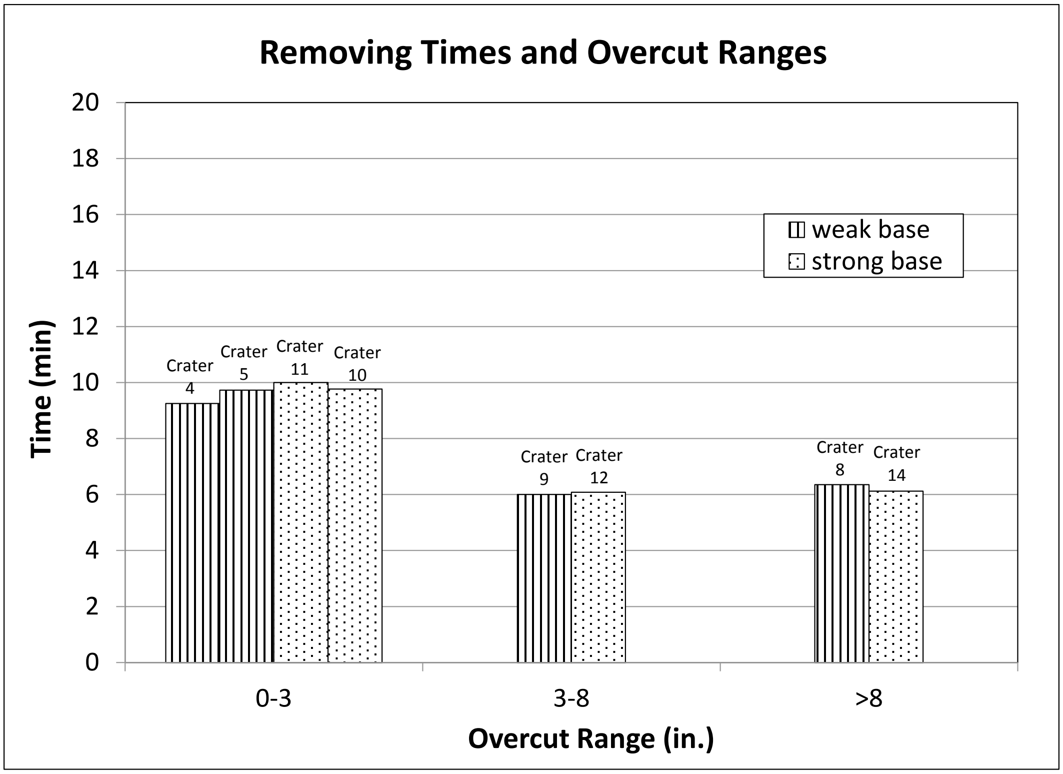


Figure 42. Removing results.



The PCC was cut to a depth of 15.5 in. for Craters 4 and 10. This was purposely done to see what effect the 2.5-in. less-than-full-depth cut had on the breaking and removal times. The breaking time required for Crater 4 was 8.25 min, which was the second longest break time. The less-than-full-depth cut and the little-to-no overcuts (less than 2 in.) caused an increase for the breaking time of Crater 4 because of the need for more breaks with the excavator hammer. The breaking of this crater also cracked the four corners of the parent slabs. Two of the corner breaks spread to the adjacent slabs and cracked to their existing cut lines. As a result, the excavator operator began breaking in the center of the sawed area for the remaining craters. The removal time was longer than most others due to the amount of small PCC debris.

The breaking time for Crater 10 was the longest in this set of testing; however, this was due to the hammer operator's being unsure whether the sawed area was loose during the breaking due to the lack of overcuts and less-than-full-depth cut. These two factors caused an excessive number of breaks (Figure 43), resulting in a longer than necessary breaking time. The hammer operator broke the four corners first. There were no resulting cracks in the parent slab. The removal time was also longer than most others due to the large number of small pieces of PCC required to be removed.

Figure 43. Crater 10, with no overcuts and less-than-full-depth cuts.

The 0-in.-long to 3- in.-long overcuts for Craters 4, 5, 10, and 11 left attached PCC remnants which began at the corners and broadened to the base of the repair. Figure 44 shows the attached PCC in the corners of a removed PCC section. This attached PCC also contributed to the longer breaking and removal times. It was difficult to get the 36-in.-wide bucket in the hole and remove the debris with PCC still attached in the corners.

Figure 44. Crater 10, with attached PCC at the corners.

The combination of the less-than-full-depth cut and small overcuts (0-3 in.) did not prevent the successful removal of PCC and underlying debris but more than doubled the breaking time (adding at least 7 min), increased the removal time by adding at least 3 min, and increased the operator's uncertainty in terms of knowing when to stop breaking. The short overcuts alone (0-3 in.), as seen in Craters 5 and 11, increased the breaking and excavation time (Figure 45 and 46, respectively). With the exception of Crater 10, where the operator was uncertain about the breaks, the breaking and excavation times of the craters with short overcuts (0-3 in.) and less-than-full-depth cuts differed by at most 1 min. Short overcuts often led to cracking of the corners of the parent slabs.

Craters 2 and 3 were cut with the larger Vermeer saws, and the overcuts had a wide range. For Crater 2, there were no end overcuts, as the saw stopped at the corner of the crater but did not cut full-depth at that corner (Figure 47). The average depth of the cuts at those corners, at the end of the cuts, was 5.2 in., resulting in the excavator operator's using the bucket to detach the corner pieces (Figure 48).

Figure 45. Crater 5, with short overcuts.

Figure 46. Crater 11, with short overcuts.

Figure 47. Crater 2, not fully sawed at corners.

Figure 48. Crater 2, corners broken with bucket.

Crater 9 had 3-in.-long to 8-in.-long overcuts, which left some PCC still attached to the corners (Figure 49). These were small corners, and the PCC pieces attached were easy to break off and remove. Crater 9 had one of the fastest breaking times and the fastest removal time.

The base material of Craters 2, 3, and 8 was wet due to rain falling into the saw cut lines the day before the PCC was broken and removed. The excavator operator noted that the wet subgrade made the removal of the soil easier than when dry because the material tended to clump together. The base material strength did not affect the breaking and removal times.

Figure 49. Crater 9 with 3-in. to 8-in. overcuts and PCC attached at corners.

The breaking and removal evaluation proved that longer overcuts decrease the breaking and removal times. The most efficient overcuts were determined to be 4 in. to 8 in. long. This range helped alleviate the risk of cracking the parent slab while decreasing the breaking and removal times. As mentioned in the overcut section, to obtain the 4-in.-long to 8-in.-long overcut range on the Caterpillar SW45, it is recommended that the target be set to 12 in. on the saw and 18 in. on the pavement at the end of the cut. For the Caterpillar SW360B, it is recommended that the target be set to 18 in. on the saw and 16 in. on the pavement at the end of the cut. The actual overcut length will vary because spotters' perceptions vary and also because the wheel saw moves back during the initial part of cutting.

5.2.2 Anchoring

Anchoring was tested as a possible alternative to breaking and removing with an excavator. An alternative to the conventional excavation with the excavator is necessary when there is not an available excavator or when a supplemental tool to assist in accelerating the crater repair process is desired. At the beginning of the ADR scenario, there may be additional manpower available while the initial saw cutting and excavation of the craters is being completed. During this time, the available manpower could potentially utilize supplemental tools to aid in opening more craters for repair while the excavators are working on other craters.

The first anchoring test consisted of simply placing the epoxy on the pavement underneath the box beam pair with the 0.25-in.-thick wall (Figure 50). One 10-fl.-oz. tube of the epoxy was used for each box beam. The box beam surface was ground prior to the test to remove rust and debris. The box beams were placed 3 ft apart to allow for adequate spacing for the forks on the telehandler. The ambient temperature was 83°F, so the epoxy was cured for 30 min. After the cure time had passed, the forks on the telehandler were set in place and were used to pick up the box beams and slab. The bond of the epoxy to the box beams failed. The box beams were lifted without the slab, while all the epoxy stayed on the PCC (Figure 51).

Two other variations of this method were tested. The second test consisted of a longer cure time of 1 hr but was not successful. The third test consisted of four 0.75-in.-diam holes drilled 6 in. deep into the pavement with epoxy placed in the holes and on top of the pavement (Figure 52). The box beams were placed on top of the epoxy and cured for 25 min. The holes took 1.5 min each to drill, and they were completed to increase the probability of the epoxy adhering to the box beams. However, this test was not successful in ensuring adhesion.

Figure 50. Application of epoxy below steel box beam.

Figure 51. Epoxy on pavement failed to hold.

Figure 52. Four drilled holes filled with epoxy.

The fourth anchoring test consisted of using an all thread rod (0.75-in.-diam, 9-in. length) placed in a drilled hole with epoxy for each box beam. A 1-in.-diam opening was drilled on the bottom of both box beams for the all thread rod. A nut (0.75-in.-diam, 1-in. width across the flats, 0.5-in. height) and washer were fitted to the top of each all thread rod and tightened to ensure that the rod remained attached to the box beams (Figure 53). A Bosch hammer drill was used to drill two 1-in.-diam holes 6.5 in. deep within the PCC slab and 3 ft apart. The total drill time for each hole was approximately 2.5 min. One and a half tubes of epoxy (total ~15 oz) was used to fill the two holes to the top of the existing PCC. The box beam was placed on top of the pavement with the all thread rod inserted into the epoxy-filled hole. Because the air temperature averaged 90°F, the epoxy set quickly, after 1 min, and an additional 20 min of cure time was added to ensure the epoxy was fully cured. The forks on the telehandler were placed within the box beams (Figure 54), and the slab was successfully lifted out of the crater (Figure 55). The entire process took approximately 40 min.

Figure 53. All thread rod with nut, inserted through opening on the bottom of the box beam and placed into drilled hole in PCC.

Figure 54. Placing the telehandler forks into the box beams attached with all thread rods with bolts and nuts.

Figure 55. Successful removal of PCC using the box beam with all thread rod.

The fifth anchoring test was completed to determine whether the Caterpillar 966K front-end loader with a 4-yd^3 bucket could be used to lift the slab. Since the PCC crater repair section of Crater 7 had already been lifted out of the parent slab, this test was conducted simply by lifting the PCC section off the ground. A 14-ft-long tow chain was used to thread through the box beam already attached from the fourth anchoring test. The chain was attached to the front-end loader bucket using the eye holes on the bucket of the front-end loader, as shown in Figure 56. The chain was also tested wrapped around the teeth of the front-end loader, as shown in Figure 57. Both of these attachment techniques were successful in lifting the 4.25-ft by 8.5-ft section of PCC.

The anchoring system consisting of the box beams, epoxy, all thread rod, nut, and washer should be considered in the event that no excavator is readily available or a supplemental method of excavation is desired.

Figure 56. Successful lifting of PCC using eye holes on the front-end loader.

Figure 57. Successful lifting of PCC using the teeth on the front-end loader.

6 Conclusions and Recommendations

ERDC performed full-scale field evaluations of crater repair equipment to identify methods for increasing the efficiency and production rates for sawing, breaking, and excavating small craters for repair purposes. It should be noted that the concrete mix had a large effect on the saw-cutting rates and possibly the breaking times as well. Pavement constructed of different mixes will likely produce drastically different rates and efficiencies. The 18-in.-thick and 24-in.-thick PCC test sections were constructed of chert aggregate with concrete that had an average 90-day UCS of 6,700 psi and flexural strength of 810 psi. Results in this study differed from those in a previous study (Bell et al. 2014), in which the PCC mix aggregate was limestone. The following sections present the conclusions and recommendations resulting from the study.

6.1 Conclusions

- The Caterpillar Sw45 and SW360B wheel saws were not capable of cutting their maximum advertised depths of 18 and 24 in., respectively. During these tests, the SW45 and SW360B wheel saws were effective at cutting to maximum depths of only 16.5 in. and 22.5 in., respectively. The Bradco RS24 wheel saw was also not capable of cutting its maximum advertised depth of 24 in. In these tests, the maximum depth achieved was only 22.5 in.
- The Bradco RS24, Caterpillar SW45, and Caterpillar SW360B wheel saws did not meet the saw-cutting goal of 1 ft/min in the 18-in.-thick or 24-in.-thick PCC mixed with chert aggregate. Tests have not been conducted in this type of PCC mix before this project. The saw-cutting results presented in this report should be considered as the worst case scenario given the hard aggregate used in the concrete mixture.
- The performances of the Caterpillar SW45 and SW360B wheel saws on the 18-in.-thick PCC were similar. On average, the SW360B wheel saw cut approximately 8 percent (0.05 ft/min) faster than the SW45 wheel saw in the 18-in.-thick PCC.
- The Bradco RS24 wheel saw attached to the Caterpillar 279C CTL or Case TV380 CTL was not efficient enough for ADR scenarios. The average cutting rate of the comparable Caterpillar SW360B wheel saw attached to the Caterpillar 279C CTL (0.61 ft/min) was about 2.5 times faster than the Bradco RS24 wheel saw (0.24 ft/min).

- The Vermeer CC155 with the CC1531 concrete cutter using the Kennametal SM04 teeth was faster than all other evaluated saws. On average, the CC1531 concrete cutter's cutting rate of 4.45 ft/min was almost twice as fast as the Vermeer RTX1250 tractor with the RW1236W wheel saw rate (2.31 ft/min) and approximately 7.5 times faster than the Caterpillar SW45 and SW360B wheel saws (0.60 ft/min) in the 18-in.-thick PCC. The CC1531 (2.81 ft/min) was approximately twice as fast as the RW1236W (1.49 ft/min) in 24-in.-thick PCC.
- Both of the cold planer Caterpillar teeth evaluated (CAT model 375-7681 and CAT model 149-5763) had similar cutting rates on the Caterpillar SW45 wheel saw on 18 in.-thick-PCC. The newer CAT model 375-7681 cutting teeth were considered comparable to the expiring CAT model 149-5763 cutting teeth and can be used as a substitute to the CAT model 149-5763, which are no longer manufactured.
- The Kennametal SM04 teeth used on the Vermeer saws were the most durable cutting tools tested, followed by the Kennametal RP15 teeth on the Caterpillar saws, and then the cold planer teeth on the Caterpillar (CAT model 375-7681 and CAT model 149-5763) saws. The Kennametal RP15 cutting bits were equivalent to the Kennametal SM04 bits but with a smaller shank diameter, which was required for the Caterpillar saws.
- The Caterpillar concrete teeth (CAT model 227-7340) tested on the Caterpillar wheel saws had the slowest rate and were the least durable. The teeth were able to cut only approximately 7 ft before the carbide tips were completely worn.
- The Kennametal SM08 teeth used on the Vermeer RW1236W wheel saw were able to cut only approximately 16 ft before the carbide tips were completely worn. It is expected that the teeth, or their equivalent, would be less durable on the Caterpillar wheel saws.
- The most efficient overcut lengths were determined to be 4 in. to 8 in. long. Shorter overcuts increased the breaking and removal times and presented a greater risk of cracking the parent slab. Longer overcuts decreased the breaking and removal times; however, they increased the saw time and decreased the overall repair quality after capping.
- Weak or strong foundation materials had no discernible effect on the sawing, breaking, or removal times.
- One-half of a repair slab (8.5 by 4.25 ft by 18 in.) could be removed using the Power Fasteners AC100+Gold epoxy if the adhesive

anchoring system using all thread rods was implemented. This adhesive anchoring system required drilling two 1-in.-diam holes 6.5 in. deep and 3 ft apart in the PCC. An all thread rod was placed into each drilled hole with epoxy. A box beam with a 1-in.-diam opening was drilled on the bottom of both box beams for the all thread rod to fit through the box beam, and a nut and a washer were fitted to the top of each all thread rod and tightened to ensure that the rod remained attached to the box beams. To remove the PCC slabs, the forks on the Caterpillar TH514 telehandler were placed within the box beams, and the slab was successfully lifted out of the crater.

- The Caterpillar 966K front-end loader with a 4-yd^3 bucket was also capable of removing the half-section slab by using a chain to attach the box beams to the bucket of the front-end loader.
- The process of installing the anchors was slow, but the epoxy anchoring system was determined to be (a) a viable option to use if an excavator is unavailable for breaking the PCC or (b) a supplement if manpower and materials are available to expedite opening additional craters for repair while the excavators are in use.

6.2 Recommendations

- The recommended overcut range is 4 in. to 8 in. long when sawing around upheaval. To achieve these overcuts when using the Caterpillar SW45 on 18 in. to 24 in. PCC, it is recommended that the saw be lined up at 12 in. on the ruler and the end target be placed 18 in. away from the end of the marked line. When using the Caterpillar SW360B on 18 in. to 24 in. PCC, it is recommended that the saw be lined up at 18 in. on the ruler and the end target be placed 16 in. away from the end of the marked line. Due to the perception of the spotter lining up the wheel saw and variability within the saw, the actual overcut length will vary but should be within the desired range.
- For best results on the Caterpillar wheel saw attachments, the Kennametal RP15 or Caterpillar model 375-7681 teeth should be used. The Caterpillar model 149-5763 is no longer available for purchase.
- For best results on the Vermeer saws, the Kennametal SM04 wheel saw teeth should be used.
- The saw spotter should watch the saw teeth to determine when they should be replaced. The teeth should be replaced when they have worn approximately 40 percent of the original length. At this point, the carbide tip will have worn off, and the teeth should be replaced to prevent damage to the saw itself.

- While the installation of anchors is time consuming, this alternative can be utilized if an excavator is not available or if extra manpower is available at the beginning of the repair process. The anchoring process works best on larger slabs that are still intact but should be limited to slabs that are no greater than 8.5 ft by 4.25 ft by 1.5 ft or 54 ft^3. Once installed, the metal box beams can be retrieved for reuse if necessary.

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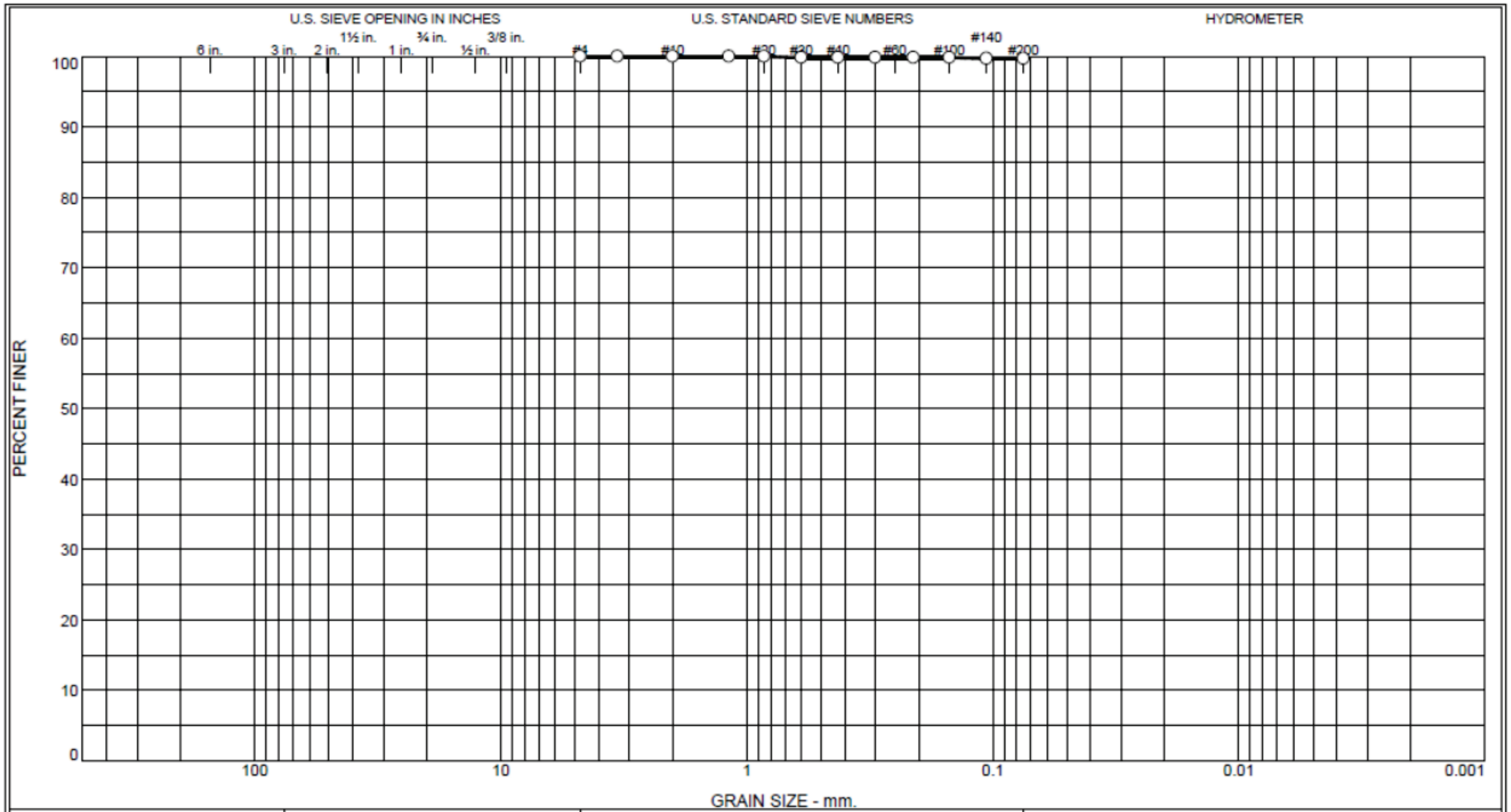
Appendix A: Additional Data

Figure A1. Classification data for silt.



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
○	Silt		Silt (ML), Brown		NV	NP	NP

Project Poor House Road

Area

Boring No.

Date: 8/14/2013

Particle Size Distribution Report

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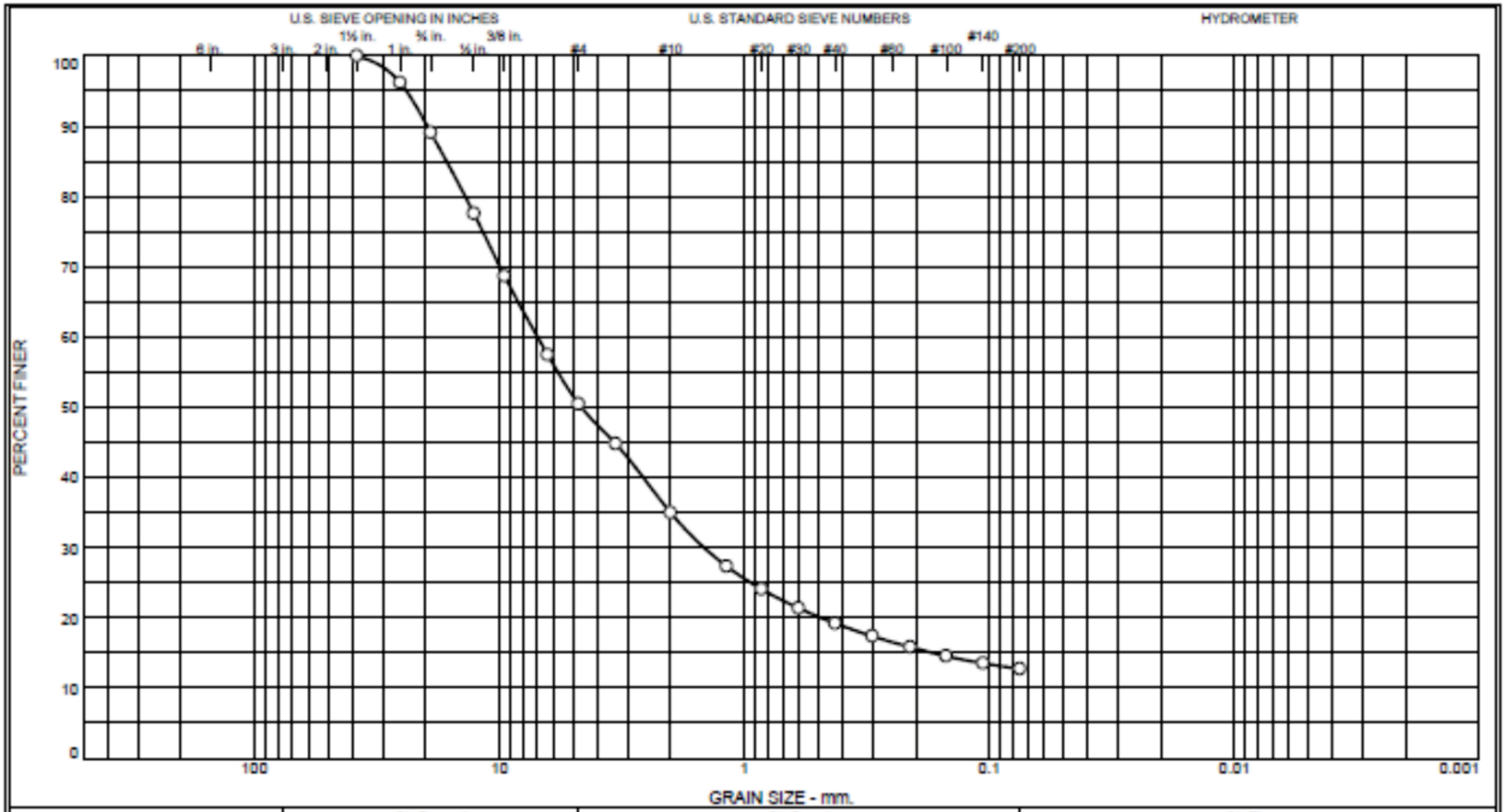
Figure A2. Classification data for limestone.



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

	Sample No.	Elev or Depth	Classification	Nat w%	LL	PL	PI
○	Limestone		Silty Clayey Gravel (GC-GM) with Sand		NV	NP	NP

Project Poor House Road

Area

Boring No.

Date: 8/14/2013

Particle Size Distribution Report

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Figure A3. Mix design for PCC section.

Construction Type: Interior

Constructor: Dark Horse

Mix Number: V4010661

Specified Slump: 6" inches

Project Description: Eval Saw

Concrete Supplier: MMC Materials

Specified Compressive Strength: 4000 psi.

Specified Air Content Non-AEA %

Material Properties and Source

Cementitious Material		Type		Source		Specific Gravity
Portland Cement		II		Holcim		3.15
Fly Ash		C		Headwaters		2.59
GGBFS (Slag)						

Admixtures		Name		Supplier		Dosage, Fl. Oz.
Mid-Range		997		BASF		5-8 per cwt.
Note: Dosage rate will require adjustments for field and environmental conditions.						

Aggregate Size	Type	Supplier	Sp. Gr. SSD	Sp. Gr. OD	Absorption, %	F.M.
# 57	Coarse	Green Bro.	2.52	2.48	1.67	7.07
Sand	Natural	Green Bro.	2.60	2.58	0.66	2.65

Batch Quantities

Material	Quantities lb/yd^3 SSD	Absolute Volume ft^3
Cement, lb.	451	2.29
Fly Ash, lb	113	0.70
Mix Water, lb.	266	4.26
Slag, lb.		
Coarse Aggr., lb.	1850	11.76
Fine Aggr., lb.	1251	7.71
Air Content, %	1	0.27
Total Mass, lb.	3931	27.00

Water / cementitious material ratio: 0.47

Mix Design Information:

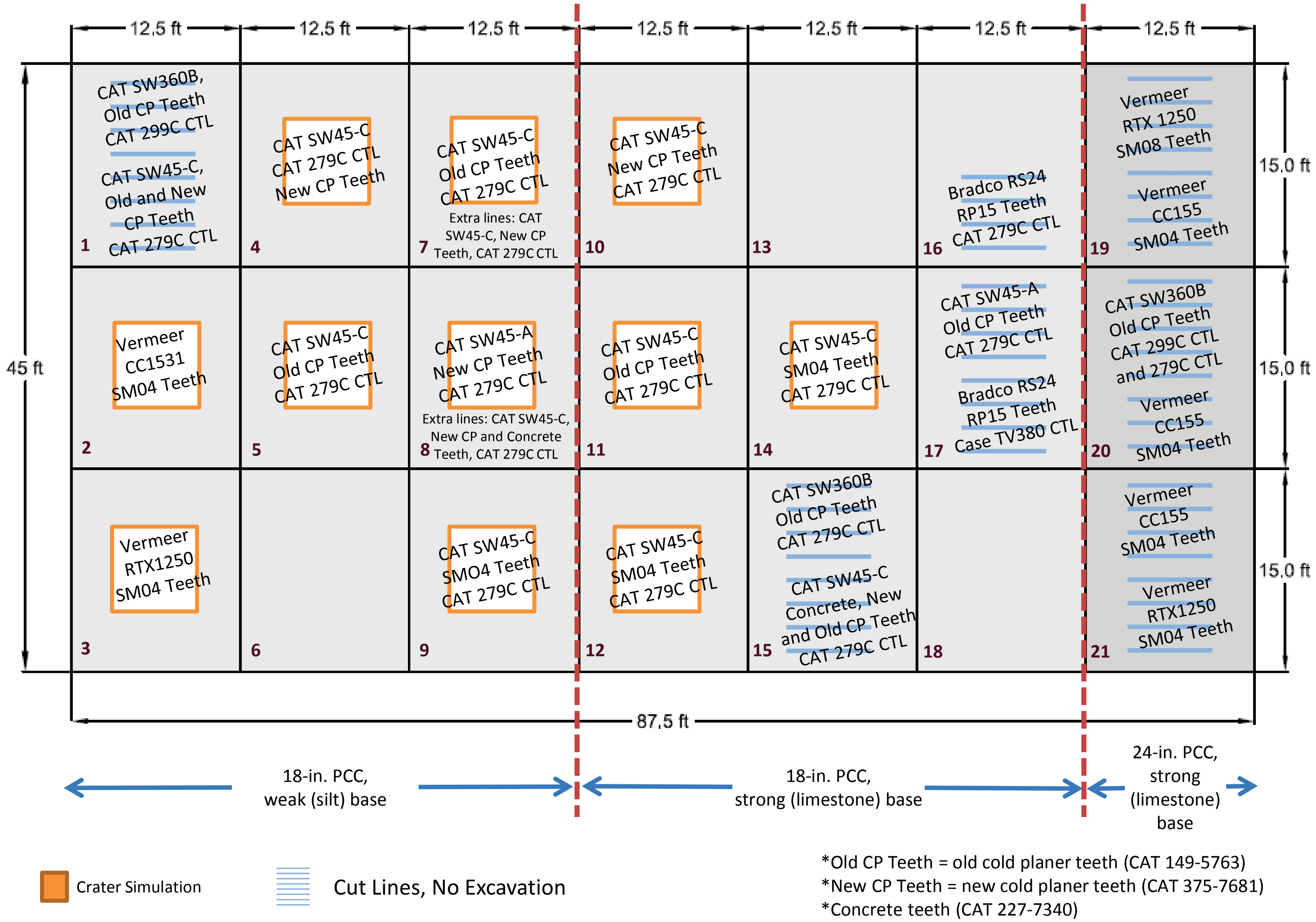
Mix Class 4000 psi. Non-Air
Comments: with Mid-Range

Designed by: Andrew Lester
Title: Regional QA Manager

Organization: MMC Materials

The above mix will meet the specified strength in 28 days when tested, placed, and handled in accordance with current ASTM and ACI standards and recommended practices. Please include this office on the distribution list for concrete test reports.

Figure A4. Test matrix.



*Old CP Teeth = old cold planer teeth (CAT 149-5763)
*New CP Teeth = new cold planer teeth (CAT 375-7681)
*Concrete teeth (CAT 227-7340)

Table A1. Test matrix details with results (continued).

Test No.	Crater No.	PCC Thickness (in.)	Base	Saw	Machine	Machine Operator	Spotter	Test	Teeth	Plunge Time (min)	Saw Time (min)	Reposition Time (min)	Cut Length (in.)	Cumulative Cut Length (ft)	Saw Rate (ft/min)
1	8	18	weak	SW45 - A	279C CTL	Jay	Jason & Don	overcut	new cold planer	5.03	22.62	2.58	138.0	11.5	0.51
										5.77	21.87	2.60	131.0	22.4	0.50
										5.95	19.80	1.90	132.5	33.5	0.56
										4.90	18.95	n/a	130.0	44.3	0.57
2	7	18	weak	SW45 - C	279C CTL	Jay	Don & Matt	overcut	old cold planer	3.00	17.88	n/a	138.0	11.5	0.64
										5.42	17.37	n/a	122.5	21.7	0.59
										5.65	16.87	3.03	120.0	31.7	0.59
										5.68	14.63	n/a	116.0	41.4	0.66
3	1	18	weak	SW45-C	279C CTL	Dante	none	rate	old cold planer	n/a	16.37	n/a	117.0	51.1	0.60
										n/a	18.62	n/a	118.0	61.0	0.53
4				SW360B	299C CTL					n/a	12.07	n/a	100.0	8.3	0.69
						Jay	Don			5.50	14.67	n/a	117.0	18.1	0.66
							none			7.50	19.00	n/a	124.5	28.5	0.55
										5.95	15.23	n/a	117.5	38.3	0.64
										7.00	18.28	n/a	119.5	48.2	0.54
										5.93	18.57	n/a	120.0	58.2	0.54
										7.67	21.08	n/a	100.5	66.6	0.40
5	15	18	strong	SW360B	279C CTL	Jay	none	rate	old cold planer	5.17	13.53	n/a	110.0	9.2	0.68
										6.00	13.97	n/a	114.5	18.7	0.68
										5.53	14.75	n/a	117.5	28.5	0.66
										5.57	15.80	n/a	119.5	38.5	0.63
										5.67	12.77	n/a	115.5	48.1	0.75
										6.95	13.83	n/a	120.0	58.1	0.72
										5.20	13.33	n/a	118.0	67.9	0.74
										5.60	12.83	n/a	111.5	77.2	0.72
6	20	24	strong	SW360B	299C CTL	Jay	none	rate	old cold planer	6.90	16.97	n/a	118.5	9.9	0.58
										5.75	14.85	n/a	122.5	20.1	0.69
										6.38	15.55	n/a	118.0	29.9	0.63
										7.75	17.23	n/a	117.5	39.7	0.57
										5.62	14.08	n/a	116.0	49.4	0.69
										5.28	15.33	n/a	117.5	59.2	0.64
7					279C CTL					4.78	16.13	n/a	117.0	9.8	0.60
										6.75	19.62	n/a	118.0	19.6	0.50
										5.97	15.93	n/a	114.0	29.1	0.60
										6.00	18.78	n/a	127.5	39.7	0.57
										5.67	16.70	n/a	119.5	49.7	0.60
										5.70	16.40	n/a	121.5	59.8	0.62
8	15	18	strong	SW45-C	279C CTL	Jay	none	rate	old cold planer	5.83	18.62	n/a	118.3	69.6	0.53
9	15	18	strong	SW45-C	279C CTL	Jay	none	rate	concrete	6.38	21.33	n/a	90.5	7.5	0.35

Table A1. Test matrix details with results (continued).

Test No.	Crater No.	PCC Thickness (in.)	Base	Saw	Machine	Machine Operator	Spotter	Test	Teeth	Plunge Time (min)	Saw Time (min)	Reposition Time (min)	Cut Length (in.)	Cumulative Cut Length (ft)	Saw Rate (ft/min)
10	15	18	strong	SW45-C	279C CTL	Jay	none	rate	new cold planer	7.33	18.60	n/a	114.5	9.5	0.51
										8.45	18.13	n/a	111.0	18.8	0.51
										7.00	16.25	n/a	111.0	28.0	0.57
	1									8.13	16.78	n/a	110.0	37.2	0.55
										7.47	16.50	n/a	115.3	46.8	0.58
										9.30	18.08	n/a	110.5	56.0	0.51
	8									5.78	16.20	n/a	114.0	65.5	0.59
	7									7.53	17.77	n/a	112.0	74.9	0.53
11	8	18	strong	SW45-C	279C CTL	Jay	none	rate	concrete	6.07	13.85	n/a	72.8	6.1	0.44
12	19	24	strong	RW1236W	RTX1250	Jim (Vermeer)	Vermeer	rate	SM08	7.33	9.75	n/a	112.0	9.3	0.96
										-----	9.57	n/a	84.0	16.3	0.73
13	19	24	strong	CC1531	CC155	Doug (Vermeer)	Ty (Vermeer)	rate	SM04	2.47	3.82	n/a	115.5	9.6	2.52
										1.50	4.42	n/a	129.0	20.4	2.43
										3.00	4.53	n/a	121.0	30.5	2.23
										2.23	3.55	n/a	126.0	41.0	2.96
										2.40	3.93	n/a	118.0	50.8	2.50
	20									1.90	2.75	n/a	112.0	60.1	3.39
	21									1.80	3.20	n/a	129.0	70.9	3.36
										1.57	3.63	n/a	133.0	82.0	3.05
14	21	24	strong	RW1236W	RTX1250	Jim (Vermeer)	Zach (Vermeer)	rate	SM04	5.33	6.5	n/a	110.0	9.2	1.41
										-----	5.77	n/a	108.0	18.2	1.56
										5.23	6.35	n/a	115.0	27.8	1.51
										5.42	5.97	n/a	107.0	36.7	1.49
										5.08	6.32	n/a	111.0	45.9	1.46
15	3	18	weak	RW1236W	RTX1250	Jim (Vermeer)	Zach (Vermeer)	rate, reposition times	SM04	2.72	4.30	1.33	99.0	8.3	1.92
										2.67	3.67	1.87	104.0	16.9	2.36
										2.40	3.08	1.68	92.0	24.6	2.49
										2.43	3.18	n/a	94.5	32.5	2.48
16	2	18	weak	CC1531	CC155	Doug (Vermeer)	Ty (Vermeer)	rate, reposition times	SM04	1.33	3.02	1.58	132.0	11.0	3.64
										0.75	2.35	1.45	113.0	20.4	4.01
										1.00	1.42	1.68	105.5	29.2	6.19
										1.43	2.12	n/a	101.0	37.6	3.97
17	4	18	weak	SW45-C	279C CTL	Jack	none	rate, reposition times	new cold planer	5.65	18.00	1.17	104.0	8.7	0.48
										4.55	13.67	1.33	104.0	17.3	0.63
										6.00	14.58	0.97	104.0	26.0	0.59
										5.83	15.33	n/a	104.5	34.7	0.57
18	10	18	strong	SW45-C	279C CTL	Jack	none	rate, reposition times	new cold planer	4.75	13.57	0.70	104.5	43.4	0.64
										4.33	11.85	0.93	99.5	51.7	0.70
										4.25	12.00	0.90	101.0	60.1	0.70
										5.00	13.73	n/a	106.5	69.0	0.65

Table A1. Test matrix details with results (concluded).

Test No.	Crater No.	PCC Thickness (in.)	Base	Saw	Machine	Machine Operator	Spotter	Test	Teeth	Plunge Time (min)	Saw Time (min)	Reposition Time (min)	Cut Length (in.)	Cumulative Cut Length (ft)	Saw Rate (ft/min)
19	5	18	weak	SW45-C	279C CTL	Jack	none	rate, reposition times	old cold planer	6.33	14.30	1.47	104.0	8.7	0.61
										6.37	14.08	1.58	100.5	17.0	0.59
										7.43	16.83	2.83	105.0	25.8	0.52
										5.95	13.52	n/a	104.5	34.5	0.64
20	11	18	strong	SW45-C	279C CTL	Jack	none	rate, reposition times	old cold planer	7.25	16.28	0.82	103.0	43.1	0.53
										7.33	16.37	1.30	103.5	51.7	0.53
										7.25	15.92	0.95	103.0	60.3	0.54
										7.00	12.78	n/a	75.0	66.5	0.49
21	9	18	weak	SW45-C	279C CTL	Jack	none	rate, reposition times	RP15 (Kennemetal)	6.53	16.03	1.50	112.0	9.3	0.58
										6.55	17.92	1.33	115.5	19.0	0.54
										7.83	22.42	0.98	117.0	28.7	0.43
										7.63	24.37	n/a	118.5	38.6	0.41
22	12	18	strong	SW45-C	279C CTL	Jack	none	rate, reposition times	RP15 (Kennemetal)	7.50	27.82	0.60	120.0	48.6	0.36
										7.58	23.42	1.00	112.5	58.0	0.40
										7.50	20.22	0.93	114.0	67.5	0.47
										5.13	17.55	n/a	119.5	77.4	0.57
23	14	18	strong	SW45-C	279C CTL	Jack	none	rate, reposition times	RP15 (Kennemetal)	3.58	15.42	1.00	119.0	9.9	0.64
										4.67	15.00	0.70	118.0	19.8	0.66
										4.75	19.75	0.77	119.0	29.7	0.50
										6.83	21.63	n/a	123.0	39.9	0.47
24	17	18	strong	SW45-A	279C CTL	Jack	none	rate	old cold planer	3.75	12.33	n/a	111.5	9.3	0.75
										4.50	14.08	n/a	113.0	18.7	0.67
										3.77	12.67	n/a	111.0	28.0	0.73
										4.07	12.50	n/a	108.0	37.0	0.72
25	17	18	strong	Bradco RS24	Case TV380	Les	none	rate	RP15 (Kennemetal)	10.00	26.03	n/a	103.0	45.5	0.33
										n/a	32.77	n/a	101.0	54.0	0.26
										n/a	37.48	n/a	105.5	62.8	0.23
										n/a	48.97	n/a	104.0	71.4	0.18
										n/a	50.00	n/a	97.0	79.5	0.16
26	16	18	strong	Bradco RS24	279C CTL	Les	none	rate	RP15 (Kennemetal)	10.00	59.72	n/a	125.0	10.4	0.17
										12.43	43.03	n/a	150.0	22.9	0.29
										9.25	39.62	n/a	123.0	33.2	0.26
										11.87	51.83	n/a	137.0	44.6	0.22

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
May 2015

2. REPORT TYPE
Report 2 of a series

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Improved Concrete Cutting and Excavation Capabilities for Crater Repair, Phase 2

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center
Geotechnical and Structures Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/GSL TR-14-8

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, Air Force Civil Engineer Center
Tyndall Air Force Base, FL 32403-5319

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Army Engineer Research and Development Center was tasked by the U.S. Air Force Civil Engineer Center to further improve the saw cutting and excavation production rates and robustness of crater repairs in thick portland cement concrete (PCC) pavements for airfield damage repair (ADR) scenarios. The Vermeer concrete cutting saws (CC1531 and RW1236W) were investigated and compared to the previously tested concrete saws (Caterpillar SW45, Caterpillar SW60, and Bradco RS24). Several methods of excavation were compared in terms of production rate and ease of execution. The current ADR techniques, tactics, and procedures (TTPs) indicate cutting of pavement around a small crater should be completed in 22 min or less, and excavation (breaking and removal) of the repair area should be completed in 23 min or less for an 8.5-ft by 8.5-ft crater. Various equipment and methods were evaluated for sawing and removing concrete and base course materials in 18-in.-thick and 24-in.-thick PCC pavements. The effects of base course strength and overcut lengths on excavation production rates were of particular interest for this investigation. This report presents the technical evaluation of various models of sawing and excavation equipment and various methods for improving the efficiency of removing damaged pavement associated with crater repair.

15. SUBJECT TERMS
Crater
Concrete
Saw cutting
Excavation

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		83	

19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18