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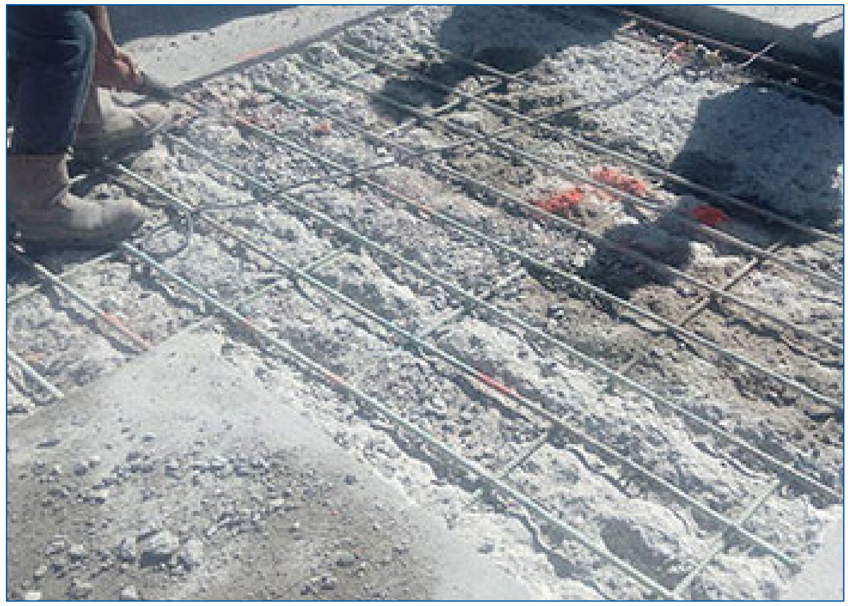
IMPROVED SUSTAINABILITY AND EFFICIENCY OF PARTIAL-DEPTH CONCRETE BRIDGE DECK REPAIR



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16. Abstract

Recently, significant advances have been made in the development of rapid setting cementitious materials for partial-depth bridge deck repair. The rapid set times of these materials allow for traffic to be re-opened onto the bridge deck in several hours versus days once the material has been placed. While this is a substantial improvement in reducing the traffic closure time, much time is still spent on the removal of damaged and deteriorated bridge deck and in preparing the concrete cutouts for placement of the rapid set material. Partial deck removal is a much more delicate process than full deck or pavement roadway removal as the soundness of the concrete surrounding and below the cutout must be maintained. Therefore, the patch preparation process is extremely labor intensive. With the recent development of autonomous machinery, this labor-intensive process may be able to become more efficient. However, prior to developing autonomous machines to prepare the patches, foundational research on methods that reduce the preparation time and that can be easily automated needs to be carried out. Additionally, some removal and preparation methods have more of an environmental impact than others.

The overall objective of this study is to examine different removal methods to decrease traffic closure time due to the preparation process for partial-depth replacement, improve the efficiency of the concrete removal methods, and evaluate the life cycle sustainability of those techniques. The initial portion of the study evaluates the current partial deck removal techniques currently used in practice, including sawing, jackhammering, milling, and hydro-demolition. Each of these methods has advantages and disadvantages when it comes to partial deck removal.

A comparative study of the different concrete removal methods is carried out to identify the least invasive environmental removal technique for partial-depth bridge deck repair. An experimental study is designed to remove the concrete patches using different discretized sawing-jackhammering methods to evaluate those techniques based on removal time, life cycle sustainability, and effect on the concrete surrounding the patch. Furthermore, the different equipment used during the concrete removal process is evaluated to assess minor and major cracks, which could develop because of concrete failure. For example, using a hydro-demolition technique for partial-depth repair causes a punch-through problem. A small-trial water jet experiment that impacts concrete is conducted to investigate the influenced parameters of punch-through occurrence.

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Improved Sustainability and Efficiency of Partial-Depth Concrete Bridge Deck Repair

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August 2024

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ABSTRACT

Recently, significant advances have been made in the development of rapid setting cementitious materials for partial-depth bridge deck repair. The rapid set times of these materials allow for traffic to be re-opened onto the bridge deck in several hours versus days once the material has been placed. While this is a substantial improvement in reducing traffic closure time, much time is still spent on the removal of damaged and deteriorated bridge deck and in preparing the concrete cutouts for placement of the rapid set material. Partial deck removal is a much more delicate process than full deck or pavement roadway removal as the soundness of the concrete surrounding and below the cutout must be maintained. Therefore, the patch preparation process is extremely labor intensive. With the recent development of autonomous machinery, this labor-intensive process may be able to become more efficient. However, prior to developing autonomous machines to prepare the patches, foundational research on methods that reduce the preparation time and that can be easily automated needs to be carried out. Additionally, some removal and preparation methods have more of an environmental impact than others.

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A comparative study of the different concrete removal methods is carried out to identify the least invasive environmental removal technique for partial-depth bridge deck repair. An experimental study is designed to remove the concrete patches using different discretized sawing-jackhammering methods to evaluate those techniques based on removal time, life cycle sustainability, and effect on the concrete surrounding the patch. Furthermore, the different equipment used during the concrete removal process is evaluated to assess the minor and major cracks, which could develop because of concrete failure. For example, using a hydro-demolition technique for partial-depth repair causes a punch-through problem. A small-trial water jet experiment that impacts concrete is conducted to investigate the influenced parameters of punch-through occurrence.

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EXECUTIVE SUMMARY

This research seeks to study different removal methods to decrease traffic closure time due to the preparation process for partial-depth replacement (PDR) as well as evaluates the life cycle sustainability of those techniques. The initial portion of the study evaluates the current partial deck removal techniques discussed in recent literature, currently used by the Utah Department of Transportation (UDOT), and also from other surrounding state departments of transportation (DOTs). A preliminary review of these sources has identified jackhammering, sawing, milling, and hydro-demolition as some commonly utilized methods for concrete removal. Each one of these methods has advantages and disadvantages when it comes to partial deck removal. However, no study could be found that included a combination of methods coupled with their environmental impact. Therefore, a comparative study of the different concrete removal methods is carried out to identify the least environmentally invasive removal technique for partial-depth bridge deck repair. In addition, this study evaluates different concrete removal techniques based on removal time, life cycle sustainability, and the effect on the concrete surrounding the patch. In addition to single techniques, combinations of different techniques are also evaluated. For example, rather than just sawing the edges of the patch location, a discretization of the patch could be sawn, which in theory would reduce the amount of time a jackhammer needs to remove the concrete.

Furthermore, each concrete removal technique uses different equipment, requires specific time, and goes to a certain depth to remove the deteriorated concrete layers. Using any equipment increases the applied loads on the bridge deck and causes minor and/or major cracks, which could develop into concrete failure in some instances. For example, using the hydro-demolition technique for partial-depth repair (PDR) can result in complete punch-through. This study conducts an experiment of water jet impacts on concrete to investigate the influenced parameters of the punch-through occurrence and to develop a model for controlling the removal depth. A subsequent finite element model, using LS-DYNA software, is developed to simulate the concrete behavior under the impacts of the high-pressure water jet, allowing for an optimization analysis of the process parameters.

The overall objective of this project is to study different removal methods to decrease traffic closure time due to the preparation process for PDR, improve the efficiency of concrete removal methods, and evaluate the life cycle sustainability of those techniques. To achieve this objective, the following specific research objectives are identified:

1) Identify from the existing literature commonly used concrete patch removal methods utilized in partial-depth bridge deck repair.
2) Quantify the removal time for commonly used concrete patch removal methods.
3) Identify additional techniques that decrease the removal time of partial deck patches and that may be automated.
4) Determine the environmental sustainability of different concrete removal techniques relative to the partial bridge deck removal.
5) Determine an optimized removal method that accounts for both the time efficiency and environmental impact.

To investigate the environmental impact of each removal method, a comparative study of the different concrete removal methods is conducted to identify the least environmentally impactful removal technique for partial-depth bridge deck repair. The methods are evaluated from an environmental perspective by estimating the air pollutant emission emitted by each method. Five-air pollutant emissions, CO2, CO, NOx, SO2, and PM10, are estimated utilizing the MOVES2014b and GREET models. The results showed that the milling technique produces the largest amount of emissions. The chipping method generated the lowest amount of emissions. CO2 is produced in large quantities among all techniques while SO2 is the smallest compared with other emissions. Additionally, the results indicate that the amount of air emissions increases relative to the utilization time of the removal technique. The values for emissions per cubic foot can also be used to estimate emissions for larger projects for which environmental offsets can be made. Also note that the estimated removal times can also help transportation officials determine the best methods as the goal in partial-depth replacement is typically to re-open the travel lanes to traffic as soon as possible. The results of the study are significant in that they can be used to help state and local transportation officials develop removal standards that include sustainable practices.

To expedite the concrete removal time and decrease traffic closure time due to the preparation process when the saw and patch method is used, an experimental study is carried out. This study evaluates four different discretized sawing and jackhammering methods in terms of removal time, equipment usage, and damage to the surrounding concrete area. The impacts of utilizing this removal equipment on the soundness of the concrete surrounding the patch area are also evaluated. The performance of the removal methods is evaluated in terms of the patch preparation time which directly correlates to the bridge traffic closure time. This study concludes that increasing the saw cutting lines decreases the jackhammering time for the different concrete strengths and increases the concrete removal volume. The saw and patch method can be influenced by many factors such as the operator's skills and health/energy level, saw blade sharpness, and jackhammer pull-off angle. Method IV, which has the largest number of saw-cut lines, is the optimal concrete removal method among the other proposed methods and saves approximately 35% of the required concrete removal time. Also, it has the potential to be automated in the future.

Finally, the hydro-demolition technique, used for the partial-depth bridge deck repair is investigated with the objective to eliminate the occurrence of the punch-through problem. Experimental, statistical, and numerical analyses are performed to analyze the impacts of high-pressure water on concrete as part of the PDR of a concrete bridge deck. Small-scale trials of 15 concrete specimens with varying compressive strengths are tested. Statistical analysis for the experimental data of abrasive water jet on concrete with different compressive strengths is then carried out to develop a predictive model for determining the input parameters to accurately predict concrete removal to a specified depth. Finally, the Arbitrary Lagrangian-Eulerian (ALE) numerical modeling method is applied in the commercial software ANSYS/LS-DYNA to simulate the response of the concrete bridge deck under the impacts of the high-pressure water jet. Explicitly, the goal of this experiment is to develop numerical models of the removal of concrete bridge decks to precise depths as a function of water jet pressure and concrete compressive strength. The experimental study finds that the water pressure, the cutting time, and the compressive strength of concrete influence the cutting depth of the water jet. The statistical analysis provides a multi-regression model that can be employed for the prediction and optimization of response parameters of the hydro-demolition technique. In addition, the numerical model simulates the concrete removal process using the ALE-FEM coupled method, the concrete damage mechanism is explained, and the influence factors are identified. Finally, it is concluded that the punch-through problem can be eliminated and the water jet cutting depth can be controlled by knowing and controlling the process parameters, such as the given water pressure, the cutting time, and the compressive strength of the deteriorated concrete. The results of this study can provide a better understating of the controllability and efficiency of using the hydro-demolition technique for partial-depth concrete bridge deck removal.

1. INTRODUCTION

1.1 Background

Bridges, as fundamental structures, play an essential role within the highway transportation network and over the entire transportation sector. Most bridges were built during the late 1950s through the early 1970s. As of 2019, there were more than 600,000 bridges in existence in the United States (BTS 2019). Increasing population and traffic, code changes, and safety standards mean that there is a frequent need to strengthen, repair, or replace certain structural components of bridges. According to the American Road and Transportation Builders Association, one of every three bridges in service in the United States requires either repair or deck replacement (ARTBA 2021). It is worth mentioning that the total in service bridge deck area is 4 billion square feet, and almost 5% of the bridge deck area is categorized as having a poor condition rating. This equates to approximately 230 million square feet of bridge deck in need of either repair or replacement (BTS 2019). Replacement and repair of bridge decks causes severe traffic disruptions and delays resulting in adverse impacts on the local transportation network. As such, it is imperative that advances be made in concrete bridge deck repair and replacement technology that limit network disruption and traffic delay. One of these methods where advances can still be made is in partial-depth bridge deck repair. Partial-depth repair (PDR) is defined as the removal and replacement of small areas of deteriorated concrete pavement in order to prevent the spread of spalling distresses caused by repeated thermal stresses, freezing and thawing, and traffic loads. PDR is suitable for distress located to a depth of one-third to one-half the bridge deck thickness; the process includes removal of concrete, preparation of repair area, placement of patch material, and application of curing material (Smith et al. 2008).

Recently, significant advances have been made in the development of rapid setting cementitious materials for partial-depth bridge deck repair. The rapid set times of these materials allow for traffic to be re-opened onto a bridge deck in several hours, versus days, once the material has been placed (Sorensen et al. 2018). While this is a substantial improvement in reducing traffic closure time, a significant amount of time is still spent on removing the damaged and deteriorated bridge deck patches and in prepping the concrete cutouts for placement of the rapid set material. Partial deck removal is a much more delicate process than full deck or pavement removal as the soundness of the concrete surrounding and below the cut out must be maintained; therefore, the patch preparation process is extremely labor intensive. With the recent development of autonomous machinery, this labor-intensive process may be able to become more efficient. However, prior to developing autonomous machines to prep the patches, foundational research on methods that reduce preparation time and that can be easily automated needs to be carried out.

In addition to the large amount of time it takes to prepare the patches, and with the objective of identifying potentially automated methods, it is noteworthy that some removal and preparation methods have a greater environmental impact than others. Kucukvar and Tatari stated that the construction and maintenance activities of roads, highways, and bridges are major sources of environmental pollutants including air, water, and soil (Kucukvar and Tatari 2013). In general, the transportation sector is the second-largest emissions contributor after the building sector (Liu et al. 2014). The U.S Environmental Protection Agency (EPA) reported that the transportation sector accounts for nearly 28% of U.S greenhouse gas (GHG) emissions, which means it is the largest contributor to GHG emissions. From 1990 to 2018, the GHG emissions from the transportation sector increased rapidly when compared with other sectors (EPA 2020). Improving sustainability and reducing the pollutants from transportation is a primary objective of the Utah Department of Transportation (UDOT) and other state departments of transportation (DOTs).

1.2 Problem Statement and Scope

This research seeks to study different removal methods to decrease traffic closure time due to the preparation process for partial-depth replacement as well as evaluates the life cycle sustainability of those techniques. The initial portion of the study evaluates the current partial deck removal techniques discussed in recent literature, currently used by UDOT, and also from other surrounding state DOTs. A preliminary review of these sources has identified jackhammering, sawing, milling, and hydro-demolition as some commonly utilized methods for concrete removal. Each of these methods has advantages and disadvantages when it comes to partial deck removal. However, no study could be found that included a combination of methods coupled with their environmental impact. Therefore, a comparative study of the different concrete removal methods is carried out to identify the least environmentally invasive removal technique for partial-depth bridge deck repair. In addition, this study evaluates different concrete removal techniques based on removal time, life cycle sustainability, and effect on the concrete surrounding the patch. In addition to single techniques, combinations of different techniques are also evaluated. For example, rather than just sawing the edges of the patch location, a discretization of the patch could be sawn, which in theory would reduce the amount of time a jackhammer needs to remove the concrete.

Furthermore, each concrete removal technique uses different equipment, requires a specific time, and goes to a certain depth to remove the deteriorated concrete layers. Using any equipment increases the applied loads on the bridge deck and causes minor/major cracks, which could be developed to concrete failure in some instances. For example, using the hydro-demolition technique for partial-depth repair (PDR) can result in complete punch-through. In this study, an experiment of water jet impacts on concrete is conducted to investigate the influenced parameters of the punch-through occurrence and to develop a model for controlling the removal depth.

The research results will help guide transportation agencies tasked with repairing bridge decks on the most time efficient and minimally environmentally invasive methods of removal for partial bridge deck repair. It is anticipated that the removal method will reduce the amount of time spent in repairing bridge decks as well as the time the bridge is closed to traffic. This results in reduced construction costs and improved productivity from traffic flows. Additionally, the quantification of the sustainable life cycle impact of the removal methods will also help to drive responsible environmental planning.

1.3 Research Objective

The overall objective of this project is to study different removal methods to decrease traffic closure time due to the preparation process for partial-depth replacement, improve the efficiency of the concrete removal methods, and evaluate the life cycle sustainability of those techniques. To achieve this objective, the following specific research objectives are identified:

1) Identify from the existing literature commonly used concrete patch removal methods used in partial-depth bridge deck repair.
2) Quantify the removal time for commonly used concrete patch removal methods.
3) Identify additional techniques that decrease the removal time of partial deck patches and that may be automated.
4) Determine the environmental sustainability of different concrete removal techniques relative to the partial bridge deck removal.
5) Determine an optimized removal method that accounts for both the time efficiency and environmental impact.

1.4 Study Organization

The organization of this study contains seven chapters. Chapter 1 gives the general background, the problem statement and scope, and the objectives of the research study. Chapter 2 contains an overview of the relevant research works, including the PDR techniques and the construction procedure of those techniques, the sustainability and the environmental life cycle assessment, and the influenced parameters of hydro-demolition/water jet. Chapter 3 presents the air emission pollutants comparison of different partial-depth concrete bridge deck removal techniques. Chapter 4 contains the experimental study to determine concrete removal time and efficiency for different removal techniques. Chapter 5 is the experimental study of the hydro-demolition/high-pressure water jet technique impacting concrete for partial-depth concrete bridge deck repair. Chapter 6 presents an optimization study of the high-pressure water jet impact on concrete for partial-depth concrete bridge deck repair. Finally, Chapter 7 provides a summary of this research work, shows the main conclusions drawn from the study, and presents some recommendations for further research.

2. LITERATURE REVIEW

2.1 Partial-depth Concrete Removal Techniques

PDR of concrete bridge decks is defined as the removal and/or replacement of a small area or patch of deteriorated concrete, which is then replaced with a repair material. The removal depth is typically limited to the top one-third of the slab thickness (Smith et al. 2008). Therefore, it can be used for certain types of concrete distresses: spalling caused by the intrusion of incompressible materials into the joints; spalling caused by poor consolidation, inadequate curing, or improper finishing practices; spalling caused by weak concrete, clay balls, or mesh reinforcing steel located too close to the surface; and spalling caused by an inadequate air void system (Frentress and Harrington 2012). The PDR boundaries should extend 2 to 6 inches outside the deteriorated area (Wilson et al. 1999). FWHA (2017) guidelines include specifications that the removal area should be square or rectangular with a minimum 12-inch length and minimum 4-inch width, and the repair limits should extend outside the deteriorated area by 3 to 4 inches.

Frentress and Harrington (2012) identified three main types of PDRs for spalls, joints, and cracks. Type (1) is considered for a repair spot length between 15 inches and 6 feet and Type (2) when the length of the repair area exceeds 6 feet along a longitudinal or transverse joint or crack. Type (3) occurs when the repair area extends full depth at joint intersections or slab edges for short areas. Type (1) is commonly performed to a small, isolated area of deteriorated concrete areas. These repair areas are less than 6-ft. long and around a 2-in. depth with a tapered edge (30–60 degrees) to the bottom of the joint or the crack. Also, Type (1) is typically addressed to repair mid-slab surface spalling or cracking, joint spalling, severe surface scaling, and joint reservoir issues. Type (2) is considered when the repair areas are longer than 6 feet and extending as deep as one-half the depth of the concrete slab in transverse and longitudinal joints or cracks. Type (3) is mainly a full-depth corner repair and used to repair the deteriorated slab edges and corners for a short distance of approximately 18 inches. Bottom-half repairs performed at the outer edges of a slab should not be more than 18 inches in the transverse direction at the bottom of the repair. In longitudinal joints it can extend 18 inches along the longitudinal joint. Figure 2.1 shows the three types of PDRs.

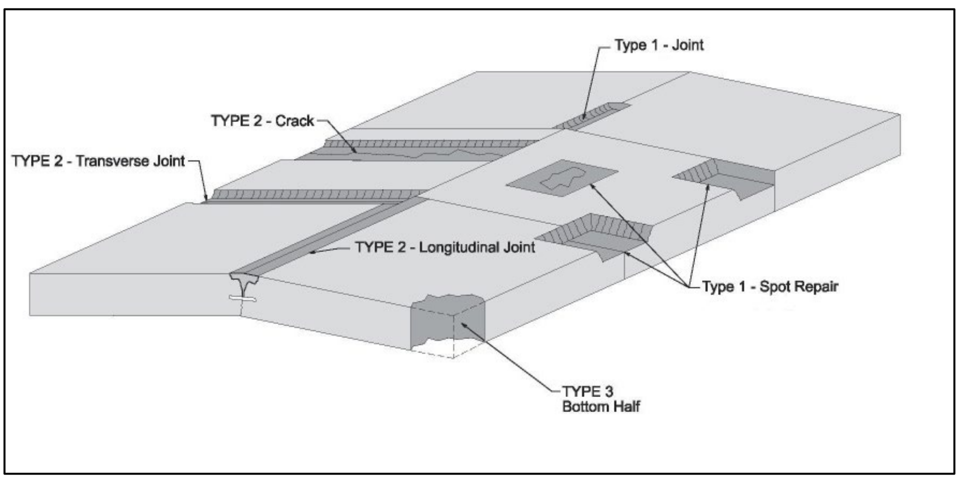


Figure 2.1 Partial-depth repair types (Frentress and Harrington 2012)

Several methods and techniques can be used to remove the deteriorated concrete. The American Concrete Institute (ACI) standard ACI 546R-14/130.1R-09, Guide to Concrete Repair, classifies concrete removal methods based on the removal process in five categories: blasting, cutting, milling, abrading, presplitting, and impacting methods (ACI 2014). The ACI 555R-01 report, Removal and Reuse of Hardened Concrete, classifies the concrete removal methods according to the tools and equipment into nine methods: hand tools, hand-operated power tools, drills and saws, water-jet blasting, explosive blasting, vehicle-mounted equipment, nonexplosive demolition agents, and mechanical splitter demolition of concrete structures by heat (ACI 2001). The Federal Highway Administration (FHWA) considers five removal methods: saw and patch, chip and patch, mill and patch, water-blast and patch, and clear and patch (Wilson et al. 1999). Similarly, another FHWA study utilized the previous methods with the exclusion of the clear and patch method (FHWA 2017). ACI defined the sawing method and milling method as the two most common PDR methods (ACI 2017). In practice, chipping and water-blasting are the most common concrete removal methods (Galecki et al. 2001). From this literature review from different sources, four common concrete removal methods are identified: saw and patch, chip and patch, mill and patch, and waterblast and patch. These four methods are considered in this study and a discussion of the different removal techniques utilized in this study follows.

2.1.1 Saw and Patch

Saw and patch is the most frequently used method. It starts by using a diamond-bladed saw to outline the repair patch boundaries at a cutting depth of approximately 2 inches (Smith et al. 2008). For larger repair patches, sawing may include the interior concrete of the repair area to facilitate the removal process (Smith et al. 2014). After sawing, a light jackhammer with a maximum weight of 15 pounds is used to complete the removal process. A jackhammer with a maximum impact force of 35 pounds could be permitted if damage to non-deteriorated concrete is avoided (Wilson et al. 1999). Finally, a jackhammer is used to remove the polished vertical saw cutting edge by chipping out the concrete 2 inches beyond the saw cutting to produce an angle between 30 and 60 degrees. This creates a rough surface, which enhances the bonding of the repair material to the existing concrete (Frentress and Harrington 2012). Figure 2.2 shows the saw and patch approach. Frentress and Harrington (2012) state that most repair crews are familiar with the saw and patch method, and it is cost-effective for small projects in general. Wilson and others (1999) point out other advantages, such as the fact that saw cutting makes vertical edge boundaries and is isolated to the concrete repair area, so the applied chipping forces do not severely affect the surrounding the sound, non-detiorated, concrete. On the other hand, this method has drawbacks such as the fact that without proper care during jackhammering operations, spalling may occur outside the saw cutting boundaries. This method is also time consuming and not cost-effective for large repair projects (Smith et al. 2014; Frentress and Harrington 2012).

(a) (b)

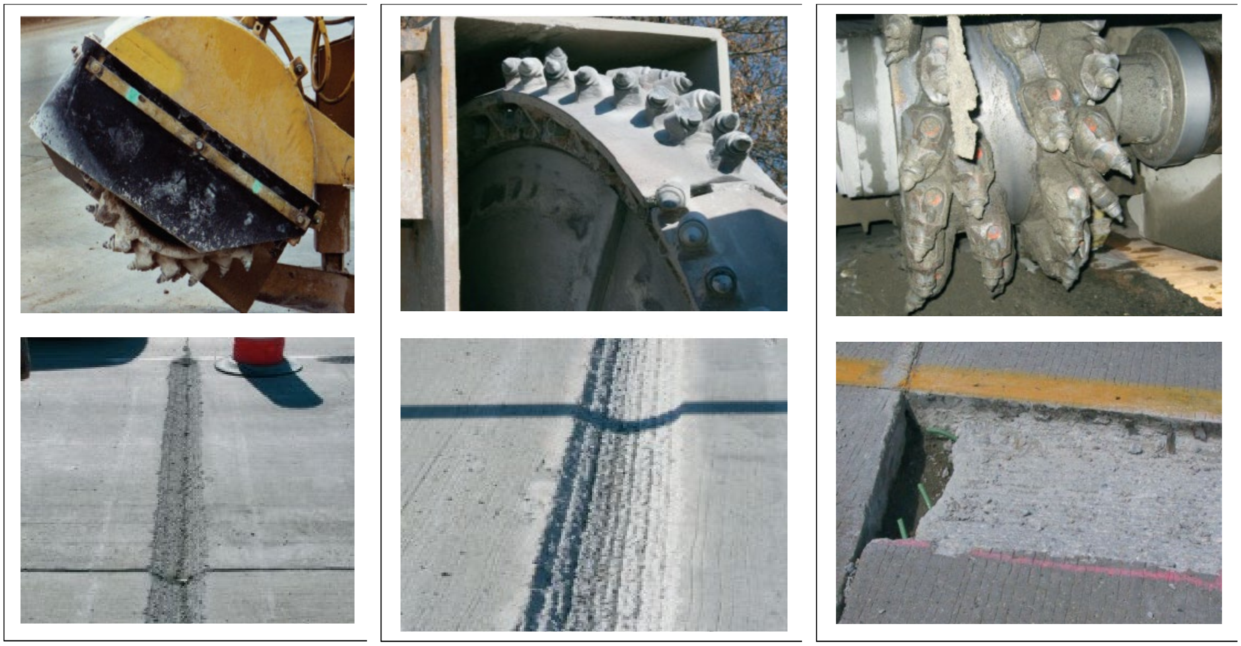
Figure 2.2 (a) sawing the repairing boundaries and (b) removing the repairing area using jackhammer (Wu et al. 2001)

2.1.2 Chip and Patch

The chip and patch method is slightly different from the saw and patch method as the patch boundaries are not sawed. The removal starts from the inside of the repair area toward the edges using a light jackhammer with a maximum impact force of less than 35 pounds with the chisel point always directed toward the inside of the patch (Frentress and Harrington 2012). The chip and patch method may be faster and quicker than the saw and patch method as it has fewer steps (i.e., no sawing for the repair area boundaries and no saw overcut to be cleaned and sealed). In addition, the rough edges promote bonding, and spalling is more controlled through the use of a lighter jackhammer (Wilson et al. 1999). The disadvantages of chip and patch include difficulty to achieve vertical sides and using the jackhammer may cause feathered repair area edges (Wilson et al. 1999).

2.1.3 Mill and Patch

The mill and patch method, also known as the carbide milling method or cold milling method, is another common PDR method (ACI 2017). Milling machines with 12-inch-wide to 18-inch-wide milling heads are used to remove the deteriorated concrete (FHWA 2017). The milling heads should be designed with a mechanism that will stop break-through of the concrete at a preset depth (Smith et al. 2014). The milling operation can be either parallel to a joint or across a joint. The industry produces three milling head types: the “V” head, rounded head, and the vertical edge, as shown in Figure 2.3, all of which can be used on longitudinal and transverse joints and cracks (FHWA 2014). Milling with the V-head or rounded head has been used very successfully on transverse joints without any additional sawing and with only minor chipping at the edge of the repair where a tapered edge with a taper angle between 30 and 60 degrees to the bottom of the joint is the preferred shape. However, the vertical edge head can increase chipping at the top edge (as shown in Figure 2.3c), making it more commonly used when highway agencies require saw cutting for all transverse joints repaired with partial-depth milling (Frentress and Harrington 2012). The advantages of the mill and patch method are that it is an economical and effective method with large repair areas, leaves a rough, irregular, surface that promotes bonding, and it requires less labor than other methods (Frentress and Harrington 2012). The drawbacks of this method are that it may not match with the site because the milling has a standardized size, extra milling may be required to widen the original milled channel when milling along cracks, and it is not cost-effective for small projects due to high costs of required equipment and mobilization (Frentress and Harrington 2012).



(a) (b) (c)

Figure 2.3 Milling head types (a) "V" Head, (b) Rounded head, and (c) Vertical edge head (Frentress and Harrington 2012)

2.1.4 Waterblast and Patch

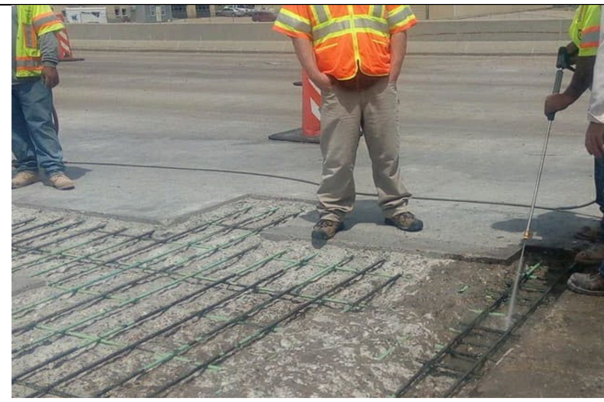
The waterblast and patch method, or hydro-demolition, is a water jet technique used to remove the deteriorated concrete using a high-water pressure machine (15,000–30,000 psi), as shown in Figure 2.4. The water-blasting machine should have the ability to remove damaged concrete within an acceptable production rate. It is typically automated and has filtering and pumping units (Wilson et al. 1999). The advantages are that it does not require many crewmembers to operate, it only removes the weak concrete, and there is no need for hauling milled or chipped concrete residual. Moreover, it produces rough and irregular surfaces, enhancing the bond between the repair material and existing concrete. The disadvantages are that it leaves the surfaces saturated with water, which causes a delay in the placement of the repair material; environmental processing of the resulting fine slurry is necessary; it requires shields to protect concurrent traffic; it is difficult to control the depth and size of the removal concrete area; and the production rate can be reduced due to the presence of coarse aggregate in the jet path (Wilson et al. 1999).

Figure 2.4 Hydro-demolition procedure

2.2 The Construction Procedure of the Partial-depth Repair

The PDR construction procedure has some typical steps, which include removal of concrete, preparation of repair area, placement of patch material, and application of curing material. These steps are shown in Figure 2.5.

1. Remove concrete using jackhammer



2. Prepare area using pressure washer

3. Place new concrete patch

4. Apply curing material

Figure 2.5 Construction steps of partial-depth repair for concrete bridge deck

2.3 Sustainability and Environment Assessment

2.3.1 Life cycle Assessment

Life cycle assessment (LCA) is a comprehensive “cradle-to-grave” approach commonly used for analyzing and assessing the environmental impacts of a product, system, or a service, considering its entire life cycle, from materials extraction, manufacturing, use, and maintenance until the end-of-life (EOL) disposition (Finkbeine et al. 2006). The U.S. EPA describes LCA as, “It can help avoid a narrow outlook on environmental concerns by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential impacts associated with identified inputs and releases, and making a more informed decision by interpreting the results” (EPA 2006). Balaguera et al. (2018) stated that the key features of LCA are: 1) it is an analytical approach, 2) it follows a step-by-step procedure, and 3) it considers the environmental impacts of a product or service in each life cycle stage. The international standards ISO 14040 and ISO 14044 provide the general specification for LCA processes and rules without detailed instructions for how to perform the LCA in practice (ISO 2006). However, these general standards have been developed by the relevant industries with specific guidance (Fava 2011). According to ISO 14040, the LCA has four phases: 1) the goal and scope definition phase,

2) the life cycle inventory (LCI) phase, 3) the life cycle impact assessment (LCIA) phase, and 4) the interpretation. These four phases are depicted in Figure 2.6. In LCA, a product or a service can be assessed by determining all of its inputs and outputs. For example, input can be material and output can be material waste. When those inventory flows have been quantified, the outcomes can be interpreted. Interpretation can show which phase of a product's life causes the most pollution and can show the environmental performance of the different systems under consideration (Hauschild 2018).

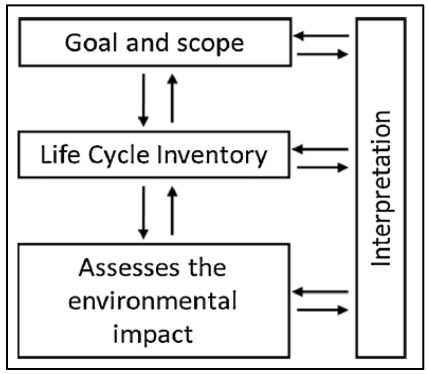


Figure 2.6 LCA phases according to ISO 14044 (ISO 2006)

LCA can be conducted through three various approaches: (1) process-based LCA, (2) input-output LCA, or (3) hybrid LCA. Each approach has its own advantages and limitations (Santero et al. 2011). A discussion of each is presented in the following sections.

2.3.1.1 Process-based LCA

Process LCA is an environmental approach quantifying the inputs and the outputs of each individual process within the life-cycle system boundary of a given product or service (Inyim et al. 2016). In this approach, every environmental output released from individual processes in the product's or service's life cycle is analyzed and evaluated instead of assessing their environmental impacts. Practically, it is a bottom-up method to quantify the environmental impacts of a product or service. Santero and others (2011) stated that the process LCA approach was developed based on the Society of Environmental Toxicology and Chemistry (SETAC) and EPA approach; therefore, it is often referred to as the SETAC-EPA approach (Santero et al. 2011). The accuracy of this approach is determined based on the life cycle details of the product or service. As such, process LCA gives a straightforward and detailed process that analyzes specific product or service requirements. Meanwhile, each product or service has specific characteristics, which means conducting process LCA requires extensive data, time, and labor. Thus, process LCA is considered a time consuming and expensive approach, particularly in complex systems that have a massive number of processes (Jiang and Wu 2019). Additionally, there is a high possibility of excluding some inputs for upstream processes, which might have a serious effect on the entire process (Choi et al. 2016). A product or service supply chain is a continuous process depending, either directly or indirectly, upon other industrial sectors. Therefore, it is hard to examine an infinite upstream process leading to setting an arbitrary system boundary for process LCA analysis, which obviously will affect the results of the analysis. This is defined as a truncation error, and it might reach 50% in some analyses (Santero et al. 2011).

2.3.1.2 Input-Output LCA

Input-Output LCA (IO-LCA) is an environmental model based on an economic model input-output model developed in 1936 by Wassily Leontief, who was awarded the Nobel Prize in 1973 for this accomplishment. The model describes itself as an interdependency model due to its ability to quantify the interrelationships across sectors of an economic system meanwhile defining the economic inputs. The economic model has been used for environmental impacts along with the supply chain processes (Choi et al. 2016). The IO-LCA is a top-down approach that comprises the entire supply chain of a product or a service in various environmental sectors. IO-LCA assesses all economic sectors by identifying the input flows of goods and services between distinct sectors to produce a unit of output from a given economic sector. The IO-LCA outputs include global warming potential (GWP), CO_2 emissions, and energy consumption (Inyim et al. 2016). The substantial advantage of IO-LCA over the process LCA approach is its ability to analyze entire supply chains without truncation error. Conversely, IO-LCA has other associated errors, which include: 1) uncertainties of basic source data due to data collection, 2) uncertainties due to input assumptions, 3) uncertainties of aggregation for input-output data over different producers and suppliers for products in the same industry (Lenzen 2001).

2.3.1.3 Hybrid LCA

Hybrid LCA is a combined approach for both Process LCA and IO-LCA approaches. Hybrid LCA applies input-output economic and environmental data relating to a specific process chain coupled with the product or service being investigated (Inyim et al. 2016). Hendrickson and others (2010) stated, "Process LCA and IO-LCA approaches are not rivals, but rather have comparative advantages. A hybrid analysis enhances the value of each approach to give better, more confident answers." Hence, hybrid LCA works to use the strength of the IO-LCA approach to fill the shortcomings of Process LCA. The two are used in sequence using process LCA to deal with direct processes and IO-LCA for the indirect processes. Santero et al. (2011) pointed out that the hybrid approach "exploits the primary strengths of process LCA (specificity) and IO-LCA (comprehensiveness) while minimizing the impact of truncation and aggregation errors that occur when using the two approaches independently." The hybrid LCA approach has recently become more widespread in environmental impact studies (Inyim et al. 2016).

2.3.2 Environmental Assessment of Bridge Rehabilitation Phase

In recent years, environmental assessment has become very important to the transportation sector and sustainability aspects have been increasingly investigated. The construction and rehabilitation of a road network is a carbon intensive process (Liu et al. 2014). Kucukvar and Tatari (2013) stated that the construction and maintenance activities of roads, highways, and bridges are major sources of environmental pollutants to air, water, and soil. Park et al. (2003) reported that the environmental emissions and energy consumption in the repair and maintenance stage are relatively high among the other life cycle stages. NOx, SO_2, CO_2 emissions in the maintenance and repair stage of a highway are 39.9% of total life cycle emissions (Park et al. 2003). In addition, bridge maintenance and repair activities cause a traffic disruption and lead to longer driving queues and increased driving distances (Zhang 2010). Chester and Horvath (2009) stated that the traffic disruption associated with road maintenance is a significant factor in environmental assessments (Chester and Horvath 2009). Rasdorf et al. (2015), estimating the air emissions released from heavy-duty diesel equipment used in highway construction projects, describe significant relationships between air emissions and a highway construction project's scope, schedule, and budget by analyzing two case study projects.

The majority of sustainability and environmental assessment studies have focused on the building sector while relatively less attention has been given to the transportation sector (Zhang 2010) and all of the corresponding environmental impacts. Furthermore, these studies are more engaged in design and construction phases than maintenance and rehabilitation phases (Zhang et al. 2011). A Weiland and Muench (2010) study compared three repair alternatives to replace concrete pavement. The studied alternatives were to remove and replace with asphalt, remove and replace with concrete, and crack and seat with asphalt. The study results show that the replace with concrete option generated the highest amount of CO_2 emissions, meanwhile also stating its lifespan will be four years longer than other methods

(Weiland and Muench 2010). Chui et al. (2007) conducted an LCA study to evaluate the environmental impact of using different recycled materials to rehabilitate asphalt pavements. Three recycled materials (recycled hot mix asphalt, asphalt rubber, and glassphalt) and the traditional hot-mixed asphalt were compared. This study found that using both recycled hot mix asphalt and asphalt rubber could reduce the environmental impact by 23%; while glassphalt increases it by 19% (Chui et al. 2008). Yu and Lu (2011) compared environmental effects of three overlay systems, including Portland cement concrete (PCC) overlay, hot mixture asphalt (HMA) overlay, and crack, seat, and overlay (CSOL). The LCA study includes six modules: material, distribution, construction, congestion, usage, and EO. The study showed that the material module, congestion module, and usage module have high contribution to energy consumption and air pollutant emissions. Moreover, using the recycled materials reduces energy consumption compared with HMA options (Yu and Lu 2011).

2.4 Hydro-demolition/water Jet Technique

Water jet cutting technology has been dramatically improving over the last years. It is a non-traditional cutting process that uses the impacts of high water pressure to cut the materials with different strengths and thicknesses. The technology is widely used in the industry, and it has many applications and uses. In civil engineering, the high-pressure waterjet used for concrete removal is called the hydro-demolition technique (Lewis 1990). The hydro-demolition technique is an innovative technology widely used in rehabilitation of highway infrastructures (Bazanov 2019), and particularly in bridge deck rehabilitation where the preservation of the reinforcement steel is required and the damage is only in the upper concrete layer (Sitek et al. 2011). This technique is becoming increasingly common for partial-depth concrete removal of bridge deck repair (Roper 2018). Silfwerbrand (2009) stated that hydro-demolition is the best technique for concrete removal. Wenzlick (2002) argued that hydro-demolition does not cause damage to the unsounded concrete left in place compared with other conventional methods, such as jackhammering and milling, which can generate micro-fracturing in the surface of the concrete and can lead to premature loss of bond in the concrete patching or overlay material (Wenzlick 2002). Furthermore, the hydro-demolition technique has competitive operational advantages, including a dust-free, vibration-free, and heat-free construction zone (Momber 2001). McCabe (2014) highlights that hydro-demolition can be done in a directional manner, which means it has the selective concrete removal capability.

2.4.1 Influence Parameters of Hydro-demolition/water Jet

A standard water jet machine has a high-pressure pump, water supply unit, orifice, an abrasive system, mixing chamber system, and nozzle system, as shown in Figure 2.7.

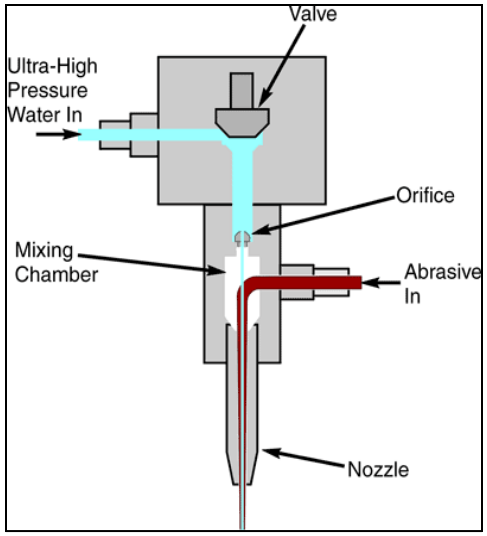


Figure 2.7 Components of water jet

The parameters of the hydro-demolition process can be divided into hydraulic parameters and performance parameters. The hydraulic parameters describe the nozzle-pump-system such as the pressure, the flow rate, and the nozzle diameter. The performance parameters characterize the cutting process including the stand-off distance, traverse velocity, impact angle, number of passes, and the targeted material (Momber 2011; ElTobgy 2007). In the case of abrasive water jet usage, there are another two input parameters—the abrasive parameter and the mixing parameter—and the output parameters, which include cutting depth, cutting width, surface roughness, waviness, and removal rate of material (Xu 2006). Figure 2.8 shows the input and output parameters of the water jet process.

The hydro-demolition process is influenced by the variability of the parameters listed above. The efficiency and the quality of the cutting process is therefore a function of those parameters. Therefore, optimization of those parameters is essential for a successful water jet cutting. A detailed discussion about the effects of the most crucial parameters follows in the subsequent sections.

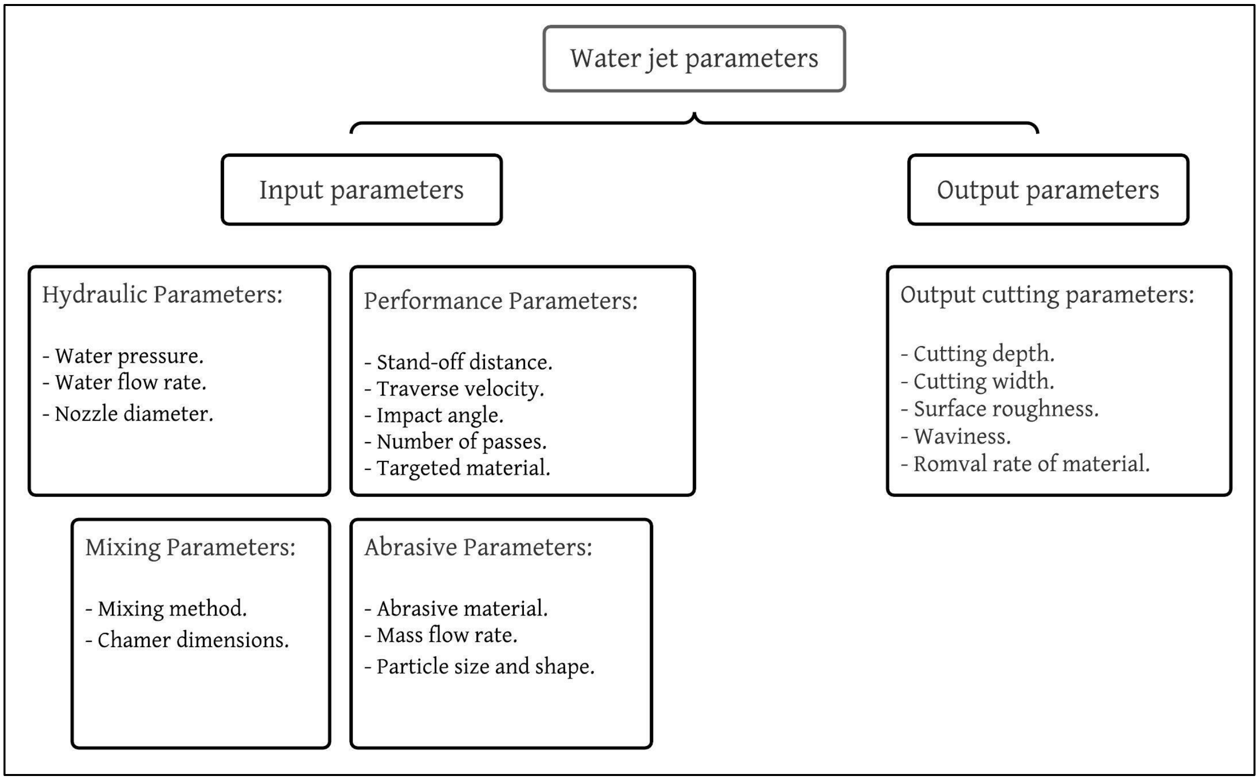


Figure 2.8 The input and output parameters of the water jet process

2.4.1.1 The effect of the water pressure

Many studies have investigated the relationship between water pressure and the cutting depth (Laurinat et al. 1992; Momber and Kovacevic 1997; Wang et al. 2002; Selvan et al. 2011). These studies indicate that the water pressure and the cutting depth have a direct proportional relationship, which means that increasing water pressure has a positive effect on the cutting depth. One experimental study conducted to examine the water jet cutting depth found that increasing water pressure is the most effective way to increase the cutting depth (Kovacevic 1992). This is explained because increasing the water pressure leads to an increase of the water velocity passing through the nozzle, as described by Bernoulli's equation (see Eq 2.1). This increased velocity has a higher energy impact, which results in deeper cutting. Researchers have noticed that, in ductile materials such as steel, the relationship between the water pressure and the cutting depth is a linear relationship (Anwar 2013), while in brittle materials, such as concrete, the relationship is non-linear (Momber and Kovacevic 1997).

$$V_w = \sqrt{\left(\frac{2P}{\rho}\right)} \qquad Eq. 2.1$$

Where: V_w: velocity of the watejet passing through the orifice, P: water pressure, ρ: water density.

2.4.1.2 The effect of the standoff distance

The standoff distance is the distance between the workpiece and the nozzle exit. Many studies have investigated the influence of the standoff distance, and it has been reported that the depth and width of the cutting are significantly influenced by changing the standoff distance (Kovacevic 1992). An increase of the standoff distance results in decreased cutting depth linearly due to the decrease in the transmitted amount of energy to the targeted material surface. On the other hand, increasing the standoff distance increases the cutting width due to the divergence and widening of the water jet diameter, which increases the exposed area on the target material (Srinivasu et al. 2009).

2.4.1.3 The effect of the nozzle traverse velocity

The nozzle traverse velocity is one of the important cutting process variables that affects the cutting depth by controlling the exposure time of the water to the target material (Anwar 2013). The relation between the traverse velocity and the cutting depth is a negative and non-linear one, where the increase in traverse velocity decreases the cutting depth and material removal rate (Momber and Kovacevic 2012). The reason behind this relationship is because increasing the traverse velocity decreases the water and abrasive particles impacting the target material per unit time, which results in a reduction in the transferred kinetic energy to a specific position and limits the ability of the water to penetrate the target material (Momber and Kovacevic 2012).

2.4.1.4 The effect of the nozzle diameter

Previous studies have shown that the relationship between the nozzle diameter and the cutting depth is positively correlated. The cutting depth increases as the nozzle diameter increases (Momber and Kovacevic 2012). This trend is dominant with small-sized and medium-sized nozzle diameters (0.25 mm and 0.30 mm). However, with the large-sized nozzle diameter (0.40 mm), this effect is less significant (Jegaraj and Babu 2005).

2.4.1.5 The effect of the abrasive mass flow rate

Increasing the abrasive mass flow rate increases the cutting depth due to the increased number of abrasive particles hitting the target material per unit area. But this fact is only true at a given water pressure and for a low rate of abrasive mass flow (Momber and Kovacevic 1997). In contrast, at a high rate of abrasive mass flow, particles colliding in the mixing chamber and turbulence in the water jet leads to decreased cutting depth and material removal (Hashish 1992). In addition, the limited available kinetic energy of the water jet must be distributed over a larger number of particles and the results lead to a decrease in the kinetic energy for each single particle (Momber and Kovacevic 2012).

2.4.2 Water Jet Impacts on Concrete

Many experimental studies have been conducted to investigate the impacts of using high-pressure water on concrete and the influential parameters of using hydro-demolition techniques. Momber (2003) examined the erosion of cementitious composites such as concrete by high-speed water jets. The study showed specific characteristics of the nonlinear fracture behavior of the concrete, like micro-cracking, and as a result, the fracture parameter might be used to estimate the erosion resistance of the concrete. Yazdi and others studied the effects of the concrete removal techniques on the bonding between the repair mortar and substrate surfaces. The study revealed that removing concrete using the water jet technique with a pressure of 19,000 psi gave the roughest surface, while the jackhammering technique left the surface with significant micro-cracks (Yazdi et al. 2020). An experimental study has compared the cutting of concrete using a continuous water jet and modulated/pulsed water jet (Sitek et al. 2003). The study concluded that the pulsed jet cutting was deeper in general. The cutting depth in concrete by pulsed jet was approximately 1.5 times larger than that using a continuous jet. This is because the continuous jet has stagnation pressure with low dynamic factor impacts, while the pulsed jet has intensive fatigue stress impacts on the targeted material (Sitek et al. 2003). Similarly, Foldyna et al. (2017) tested continuous and pulsing jets on concrete composite carbon nanotubes (CNT). The study findings indicate that CNT concrete does not have any significant difference compared with normal PCC regarding their physical and mechanical properties. On the other hand, CNT concrete shows higher resistance when impacted by either continuous jet or pulsing jet (Foldyna et al. 2017). Zhao and Wu (2004) conducted an experimental study on mixed abrasive and high-pressure water jet cutting of concrete.

Two abrasive materials and three kinds of concrete with different pressure-resistance intensities were studied. The study examined the impacts of the standoff distance, jet pressure, and velocity on the cutting depth. In addition, the effect of the jet moving velocity on the cutting surface was investigated. The study found that the abrasive material has some lashing energy that has a positive impact during the cutting process; the strength of the concrete is an influential factor on the cutting depth, and the jet moving velocity had some effects on the concrete surface appearance (Zhao and Wu 2004).

Other researchers investigated the effects of changing the abrasive concentration (10% to 20%) on the jets' performance using the smooth particle hydrodynamics (SPH) method and finite element analysis (FEA) simulations to model for abrasive jet impacted concrete. The results showed that the cutting rate, cutting depth, and the internal energy of concrete tend to increase relative to the abrasive concentration (Liu et al. 2019). Liu et al. (2017) analyzed the stress state in concrete under the impact of high-pressure water jets at different times. Moreover, the paper measured the damage rate along the radial direction of the water jet (Liu et al. 2017). For this purpose, a 3-D simulation model was built and verified using experimental and theoretical analysis. The study found that the damage shape of concrete develops faster along the radial direction of the water jet, and it evolves from a small diameter cylinder to a funnel and becomes a large diameter cylinder (Liu et al. 2017). In addition, Liu et al. (2021) evaluated the propagation of cracks in concrete with pre-cracks under water jet impacts. The results show that the existing pre-cracks led to developing cracks in all directions and increased the penetration dimension compared with normal PCC (Liu et al. 2021).

2.5 Summary

This chapter provides a comprehensive literature review of the relevant research and studies of the partial-depth concrete removal techniques of bridge decks and the environmental assessment of using those techniques. The beginning of the chapter presents a brief overview of the PDR techniques of a concrete bridge deck. The main partial-depth concrete removal methods are saw and patch method, chip and patch method, mill and patch, and water-blast and patch method. Moreover, the review shows the advantages and disadvantages of each technique.

A detailed summary of the sustainability and environmental assessment of the past bridge rehabilitation phase has been conducted, and it indicates the research gaps that must be filled. Most of the studies have focused on the material and construction phases while the rehabilitation and maintenance phase has been neglected. Few studies considered bridge deck replacement based on comparisons among different alternatives, and none of these studies investigated minor concrete rehabilitation such as crack sealing and PDR.

At the end of this chapter, water jet technology and its advantages were briefly reviewed. This was followed by the input and output parameters of the water jet process, in addition to the effect of those parameters on water jet performance. A detailed review of previous studies focused on using water jet technology in the concrete industry was provided. The existing studies are limited to investigating and analyzing the water jet impact on concrete behavior. Few studies focused on studying the impacts of a water jet in terms of the cutting depth, the material removal rate, and the cutting time. Furthermore, none of the existing studies examine the impacts of the water jet on different strengths of concrete and the change of the water jet parameters in that case.

3. AIR EMISSION OF DIFFERENT PARTIAL-DEPTH CONCRETE BRIDGE DECK REPAIR TECHNIQUES: A COMPARATIVE STUDY

3.1 Introduction

In recent years, environmental assessment has become very important to the transportation sector and sustainability aspects have been increasingly investigated. The construction and rehabilitation of a road network is a carbon intensive process (Liu et al. 2014). Kosovar and Tatari (2013) stated that the construction and maintenance activities of roads, highways, and bridges are major sources of environmental pollutants, including air, water, and soil. In general, the transportation sector is the second-largest emissions contributor after the building sector (Liu et al. 2014). The EPA reported that the transportation sector accounts for nearly 28% of U.S greenhouse gas (GHG) emissions, making it the largest contributor to GHG emissions. From 1990 to 2018, GHG emissions from the transportation sector increased rapidly when compared with other sectors (EPA 2020). Bridges, as fundamental structures, play an essential role within the highway transportation network and over the entire transportation sector. Most bridges were built during the late 1950s through the early 1970s. In 2019, there were more than 600,000 bridges in the United States (BTS 2019). Increasing population, increasing traffic, changing codes, and safety standards mean there is a frequent need to strengthen, repair, or replace certain structural components of bridges. According to the American Road and Transportation Builders Association, one of three U.S bridges in service require either repair or deck replacement (ARTBA 2021). Note that the total in-service bridge deck area is 4 billion square feet, and almost 5% of this bridge deck area is categorized as having a poor conditions rating. This equates to approximately 230 million square feet of bridge deck in need of either repair or replacement (BTS 2019). The rapid increase of construction and maintenance activities raises many concerns from the public, governmental authorities, and stakeholders about the sustainability and environmental performance of these activities, which has led to the growing interest to minimize their impacts on the environment. Park and others (2003) reported that the emissions and energy consumption in the repair and maintenance stage are relatively high among the other life cycle stages. NOx, SO_2, CO_2 emissions in the maintenance and repair stage of highways are 39.9% of total life cycle emissions (Park et al. 2003). In addition, bridge maintenance and repair activities cause traffic disruptions and lead to longer driving queues and increased driving distances (Zhang 2010). Chester and Horvath (2009) stated that the traffic disruptions associated with road maintenance are a significant factor in an environmental assessment (Chester and Horvath 2009).

The life cycle of bridges is divided into four phases: material manufacture, construction, use and maintenance, and demolition/end life (Du and Karoumi 2014). The majority of the sustainability and environmental assessment studies have focused on the material manufacture and construction phases while relatively less attention has been given to the use and maintenance phase (Zhang et al. 2011). Maintenance and rehabilitation activities are commonly addressed from an economic perspective without taking into consideration the environmental impacts of this stage (Alam et al. 2019). Li et al. (2019) studied the environmental impacts of air emissions of a highway project located in China and found that the maintenance phase has 1.7% of the emissions compared with other life cycle phases (Li et al. 2019). Alam et al. (2019) compared four different maintenance techniques of asphalt pavement, including patching, rout and sealing, hot in-place recycling, and cold in-place recycling to assess the environmental impacts of each technique. The study indicated that patching and hot in-place methods have higher environmental impacts compared with the rout and sealing and cold in-place techniques (Alam et al. 2019). Weiland and Muench (2010) compared three repair alternatives to replace concrete pavement. The suggested alternatives include remove and replace with asphalt, remove and replace with concrete, and crack and seat with asphalt. The study result shows that the replace-with-concrete option generated the highest amount of CO_2 emissions (Weiland and Muench 2010). In addition, Rasdorf et al. (2015) estimated the air emissions released from heavy-duty diesel equipment used in highway construction projects and found the relationships between the air emissions and the highway construction project scope, schedule, and budget by analyzing two case study projects (Rasdorf et al. 2015). Note that most of the environmental studies related to maintenance and rehabilitation of concrete roads and bridges have not considered minor concrete rehabilitation such as crack sealing and partial-depth repair (PDR) (Wang and Gangaram 2014). Similar to pavement repair, partial-depth bridge deck repair is a commonly used approach to replace deteriorated concrete that is located in the upper one-third of a bridge deck. In this approach, only those areas on the bridge deck that have deterioration are removed down to a partial amount of the total bridge deck. The resulting patches are then filled with new concrete materials. This method requires the use of equipment to remove the deteriorated concrete patches, which results in pollutant emissions. Construction and maintenance equipment and transportation vehicles, both on-road and non-road, are sources of air emissions due to the burning of fossil fuels by their engines (Rasdorf et al. 2015). Any engine that burns carbonaceous fuel is producing a net amount of carbon dioxide (CO_2). Additionally, vehicles and equipment powered by diesel engines generate other emissions, including carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM10), hydrocarbons (HC), and a small amount of sulfur dioxide (SO_2) (Lewis et al. 2009). Such air pollution emissions have significant negative effects on natural ecosystems, climate, and human health (Marco et al. 2019).

The objective of this study is to compare four partial concrete repair methods to identify the least environmental impact removal technique used for partial-depth bridge deck repair. The environmental comparison is conducted by estimating the air pollutant emissions from construction equipment and transportation vehicles used in each removal method. This study contributes to the analysis of life-cycle sustainability of bridges with the specific objective to reduce air pollutant emissions due to bridge maintenance activities. Previous studies only consider the time of construction. No study could be found that included a combination of methods coupled with their environmental impact. Improving the entire life-cycle sustainability of bridges can only be achieved by reducing the environmental impacts of the life cycle components, including maintenance. This study aims to reduce the pollutant emissions of one commonly used maintenance and life cycle extension method for bridge structures.

3.2 Research Methodology

In this study, four different partial-depth concrete removal methods for a bridge deck have been compared by means of environmental assessment. The study estimates the emissions of CO_2, CO, NOx, SO_2, and PM10 that are associated with construction equipment and transportation vehicles used in each method. The removal process steps and the equipment required for each method in this study are shown in Figure 3.1. The construction procedure of PDR has been previously discussed in Section 2.2 of this study.

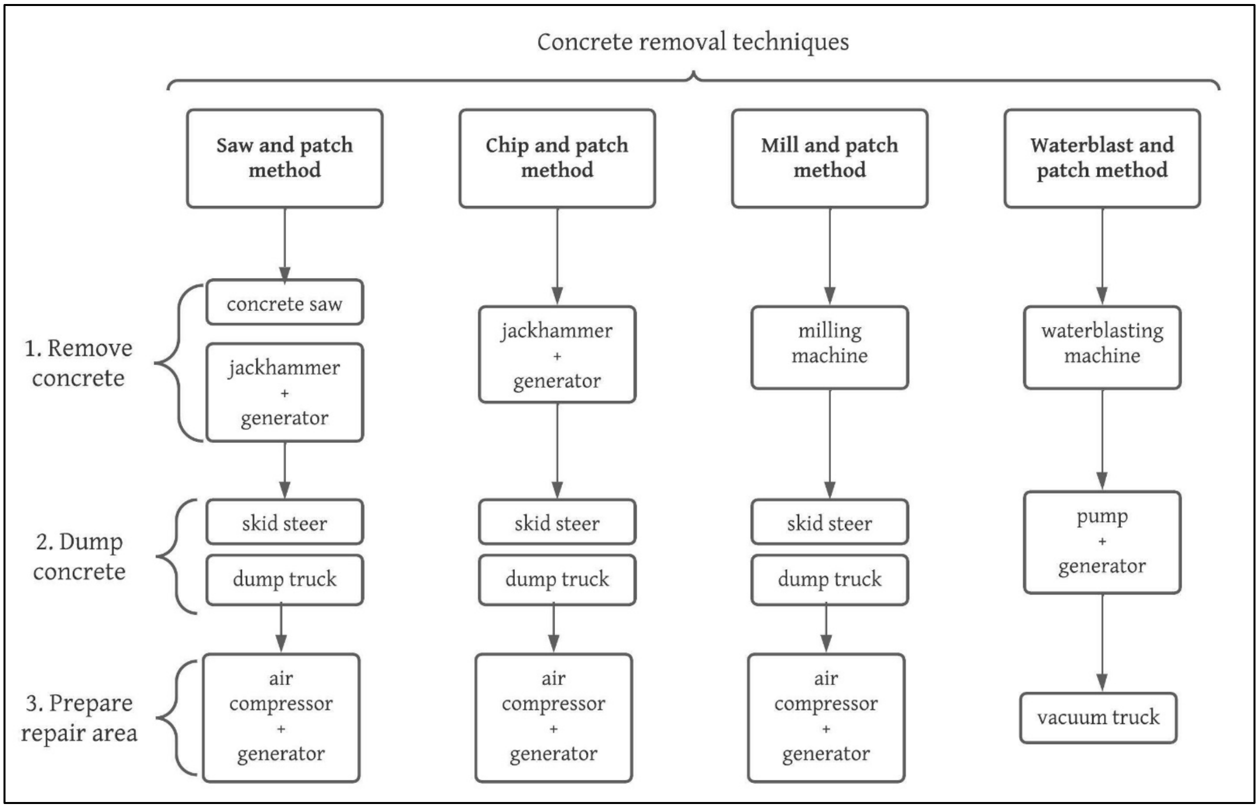


Figure 3.1 Process and equipment of concrete removal methods

The main data sources in this study are two environmental models: the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, and the U.S. EPA's Motor Vehicle Emission Simulator (MOVES) model. GREET is a tool developed at Argonne National Laboratory to analyze the life-cycle impacts of vehicle fuels, products, and energy systems (Wang et al. 2018). The GREET model can determine the total energy consumption, air emissions, greenhouse gas emissions, and water consumption for on-road vehicular transportation (Wang et al. 2018). In this study, version 2019 of GREET is utilized. The EPA's MOVES model is designed to estimate air emissions from mobile sources. It estimates the exhaust and evaporative emissions from all types of on-road vehicles and non-road equipment (EPA 2019).

This section identifies the vehicles and emissions for equipment commonly used in partial-depth bridge deck repair. Table 3.1 shows two on-road vehicles commonly used: a dump truck and a vacuum truck and their GREET model categorization (Wang et al. 2018).

Table 3.1 GREET model for on-road vehicles

Equipment	Typical equipment	GREET model category	Fuel used
Dump truck	Ford-F750, 5–6-yard diesel payload capacity (17,300 lb)	HD truck: combination short-haul-LS diesel	Low-sulfur diesel
Vacuum truck	Rampart Vacuum Truck	HD truck: combination short-haul-LS diesel	Low-sulfur diesel

The emission factor data for these on-road vehicles are obtained from the GREET model database. The dump truck and vacuum truck are the only trucks used in this study. Based on GREET model categories, both are classified as HD trucks: combination short-haul CIDI-RDII 100 from Distributed Conventional Petroleum Refinery. Table 3.2 shows the emission factors of CO_2, CO, NOx, SO_2, and PM10 expressed in grams/mile (g/mile) for the vehicles listed in Table 3.1.

Table 3.2 Emission factors for on-road vehicles

Equipment	CO_2 emission rate (g/mile)	CO emission rate (g/mile)	NO_x emission rate (g/mile)	SO_2 emission rate (g/mile)	PM_{10} emission rate (g/mile)
Dump truck	2,280.00	0.92	2.04	0.40	0.84
Vacuum truck	2,280.00	0.92	2.04	0.40	0.84

Emissions data for all non-road equipment are obtained from the EPA's MOVES2014b model. The model provides emissions factors for ranges of horsepower, so an estimate of the engine horsepower is made for each type of construction equipment.

Table 3.3 shows what equipment is used with the rated horsepower and the MOVES2014b NONROAD category used to approximate that equipment's emission factors. The remaining equipment is operated by electrical power. It is assumed for this study that electrically powered equipment does not create any air pollution emissions during concrete bridge deck repair. Examples of such equipment are the jackhammer/concrete breaker HILTI-TE 1000-AVR and the water-blasting machine Conjet robot 327. The pollutant emissions for this equipment are accounted for by the generator, which provides the electricity for this equipment.

Table 3.3 MOVES2014b model non-road equipment

Equipment	Typical equipment	Horsepower (hp) rating	MOVES2014b model category
Concrete saw	EDCO SS-26 31D	31	Concrete/industrial saws ($25 < hp \leq 40$)
Skid steer	CAT skid steer-216B3	51	Skid steer loaders ($50 < hp \leq 75$)
Air compressor	XATS 138 compressor	65	Air compressor ($50 < hp \leq 75$)
Generator	Generac 6864, 5000 running watts	7	Generator sets ($6 < hp \leq 11$)
Milling machine	SCHIBECI-RM350	200	175 HP crushing/proc. equipment ($100 < hp \leq 350$)
Generator	Generac 16 KW	21.5	Generator set ($16 < hp \leq 25$)
Pump	HAMMELMANN-power pack20	315	Pump ($300 < hp \leq 600$)

Table 3.4 shows the emission factors of CO_2, CO, NOx, SO_2, and PM10 expressed in g/hr for the non-road equipment listed in Table 3.3.

Table 3.4 Emission factors for non-road equipment

Equipment	**CO_2 emission rate (g/hr)**	**CO emission rate (g/hr)**	**NOx emission rate (g/hr)**	**SO_2 emission rate (g/hr)**	**PM_{10} emission rate (g/hr)**
Concrete saw	18,970.50	317.52	28.89	0.12	1.93
Skid steer	8,399.99	792.23	62.62	0.14	2.13
Generator	2,128.59	11.52	16.69	0.02	1.46
Air compressor	15,411.22	23.42	83.16	0.12	3.31
Milling machine	55,082.78	23.78	98.64	0.22	3.74
Pump	90,701.15	141.54	444.69	0.74	21.90
Generator	5,391.15	18.80	39.13	0.05	2.48

Note that MOVES2014b and GREET do not give the total air emissions directly. Instead, they give the emission factors, which the EPA defines as "A representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant" (EPA 2019). MOVES2014b provides a general equation with emission factors to estimate the air emission, as shown in Equation (1) (EPA 2019).

$$E = A \, x \, EF \, x \left(1 - \frac{ER}{100}\right) \qquad (1)$$

where: E = air emissions gram, A = activity rate hour, EF = emission factor gram/hr., and ER = overall emission reduction efficiency (%).

The equation shows that air emission (*E*) is equal to the activity rate (*A*) of this equipment multiplied by emission factor (*EF*), multiplied by the percentage of the emission reduction (*ER*). Emission (*E*) is the amount of any type of pollutant emitted by a process or equipment with units of mass per time such as gram per hour. Activity rate (*A*) is the productivity rate of the equipment, and it is expressed in units per time such as cubic feet per hour. The emission factor (*EF*) is the most important variable in the equation, and it takes time to develop in different ways, such as using the MOVES2014b model. It is expressed in terms of mass per time, such as grams per hour. The last term in the equation is the emission reduction efficiency, which reflects the emission control efficiency of the equipment itself, and for simplification it has been neglected in this study.

3.3 Case Study Analysis

3.3.1 Case Description

This case study is modeled based on a PDR project of Utah SR-193 bridge over US-89 (Structure Number 0F 575) located in Layton, Utah. The SR-193 bridge is a concrete bridge built in 1995 with a total length of 178.5 feet and a 65.3-ft width (https://bridgereports.com/1570708). The total surface area of the repaired patches is 3,946 square feet and the average removal depth is 3 inches. A table and map of repair area are provided in Appendix A (Maguire et al. 2021).

3.3.2 Equipment Designation

This section outlines the emissions specific to the equipment used in the removal of the concrete patches in the partial bridge deck repair process.

3.3.2.1 Concrete saw

In the saw-cut method, a diesel-powered concrete saw is the main equipment utilized. The saw is used to outline the deteriorated concrete patch boundaries. For this study, a concrete saw model EDCO SS-26 31D is utilized for the analysis. This model of saw has a 31-hp engine with a productivity rate of 800 linear feet per hour (Wang et al. 2016). The total linear saw cut length is equal to 2,402 linear feet. Using this cutting length and an additional 25% for uncertainty, the total saw utilization time is 3.75 hours. Using Equation (1) and emission factors from Table 3.4, the emissions released by using a concrete saw can be estimated as seen in Table 3.6.

3.3.2.2 Skid steer

After the concrete in a patch is broken up, the resulting pieces are removed from the site and loaded onto a truck with a small front loader typically referred to as a skid steer. A Caterpillar skid steer-216B3 is the equipment designated in this study to perform this task. The Caterpillar 216B3 has a 51-hp engine and can load 978 cubic feet of material per hour working at 75% efficiency (London 2017). At this rate, it would take 1.48 hours for a skid steer to load the total project's amount of 1,086 cubic feet of removal concrete. Considering that the amount will not be removed at the same time, a 25% increase factor is added for the required time, resulting in a total time of 1.85 hours. Using Equation (1) and the emission factors from Table 3.4, the emissions released from the skid steer are calculated and shown in Table 3.6.

3.3.2.3 Air compressor

During the demolition of the deteriorated concrete patches, concrete debris is generated, which results in concrete and aggregate waste in a variety of sizes. The larger pieces are removed by hand while the dust and small pieces are blown away with an air compressor. For this activity, a XATS 138 compressor is designated to be used. The compressor has a 65-hp engine with a 11,654 cf/hour productivity rate working at 75% efficiency (Copco 2017). At this rate, considering a 25% increase factor due to discontinuous use, the air compressor's required time of use is calculated to be 0.16 hours. Using Equation (1) and the emission factors from Table 3.4, the emissions released from the air compressor are calculated and shown in Table 3.6.

3.3.2.4 Generator

A generator is used to provide electricity to the jackhammer in the chip and patch method and for the water blasting machine in the waterblast and patch method. Two types of the generator are used with different productivity rates. The Generac 6864 generator is designated to operate the jackhammer HILTI-TE 1000-AVR (Generac 2016). Generac 6864 has a 7-hp engine and requires the same utilization time as the jackhammer. A 25% increase factor is added for time uncertainty due to discontinuous use. This results in a total usage time of 82.32 hours. A Generac 16 KW generator is designated to run the water blasting machine Conjet robot 327 and the vacuum. It has a 21.5-hp engine (Generac 2018) and its working time is taken as the same as the water blasting machine. A total time of 44.85 hours is calculated. Using Equation (1) and the emission factors from Table 3.4, the emissions released from the generator are calculated and shown in Table 3.6.

3.3.2.5 Milling machine

In the mill and patch method, a milling machine is used to remove the deteriorated concrete. For this study, a SCHIBECI-RM350 is used. The milling machine is approximated using the crushing/process equipment from the MOVES2014b MODEL. This equipment has a 200-hp engine and can remove 137 square feet of material per hour (SCHIBECI 2018). In the concrete case, it has a designated efficiency of 70%. The required time to remove the total concrete surface area of 3,946 square feet with 25% added time for uncertainty is determined to be 51.44 hours. Using Equation (1) and the emission factors from Table 3.4, the emissions released from the milling machine are calculated and shown in Table 3.6.

3.3.2.6 Pump

One of the main pieces of equipment in the waterblast and patch method is the water pump. The water pump is used to pump water with high pressure from a water source to the water blasting machine. In this study, HAMMELMANN Power Pack 20 with a 315-hp engine is used (HAMMELMANN 2017). The pump is expected to work the same amount of time as the water blasting machine. The water blasting machine Conjet robot 327 removes an average of 110 square surface feet per hour (Conjet 2018). This results in a required time of 44.85 hours, accounting for a 25% increase factor for uncertainty. Using Equation (1) and the emission factors from Table 3.4, the emissions released from the pump are calculated and shown in Table 3.6.

3.3.2.7 Dump truck

The broken concrete from each patch is removed from the work site via a dump truck. The waste material is loaded into the truck via skid steer, and then needs to be transported to a dumpsite or a location where it can be processed for other uses. It is assumed that the distance of this disposal site is 10 miles away from the job site. This might be an underestimate for many construction sites but is more accurate for a site in or close to an urban population. The density of a typical concrete bridge deck is 150 pounds per cubic foot. This means that the weight of removed concrete is approximately 162,986 pounds, which is divided by the 17,300-lb payload capacity of the truck; requiring 10 total round trips and a total distance traveled of 200 miles with a 60 mph average driving speed. The total calculated time is 4.17 hours with 25% additional time for uncertainty. This task is accomplished using an HD truck that is a combination short haul CIDI-RDII 100 from the Distributed Conventional Petroleum Refinery in the GREET model. Using Equation (1) and the emission factors from Table 3.2, the emissions released from the dump truck are calculated and shown in Table 3.6.

3.3.2.8 Vacuum truck

Water blasting requires the use of a vacuum truck to clean up waste materials post demolition. The working hours are taken as the same as the water blasting machine’s 44.85 hours. The truck reaches its capacity after 1.5 hours of water blasting machine work. As such, the truck will reach its full capacity five times. Once the truck is full, it has to stop working and leave the site to dump the wastewater. Assuming the dumping area is five miles away, the truck will travel a total of 300 miles. This task is also represented using an HD truck: combination short-haul CIDI-LS diesel from the GREET model. Using Equation (1) and the emission factors from Table 3.2, the emissions released from the vacuum truck are calculated and shown in Table 3.6. Note here that the calculations included in this study do not include the environmental impact of treating the wastewater. This is a viable assumption if the wastewater is disposed of in a settling tank and allowed to evaporate. As such, only the remaining concrete waste is left and no wastewater treatment is required.

3.3.3 Utilization Time

Time is an important factor when comparing different bridge deck removal techniques. The time for each concrete removal method is estimated based on the utilization time of each piece of equipment used in that method, and the equipment working time is calculated based on the productivity rate of the equipment with 25% added time for uncertainty due to discontinuous use, as explained previously in Section 4.2. Of note is that the generators are used to supply power to the electrical equipment such as jackhammer and water-blasting machine. For the purpose of this study, it is assumed that the generators are in use for the same amount of time as the electrical equipment. As such, the demolition time for the electrical equipment is calculated, and that time is then taken as the generator running time. Table 3.5 shows the total removal time for each removal method. Note that the waterblast method is the fastest method, while the saw and patch method requires the most time.

Table 3.5 The removal time of each removal method

Saw and patch method		Chip and patch method		Mill and patch method		Waterblast and patch method	
Equipment	**Time (hours)**	**Equipment**	**Time (hours)**	**Equipment**	**Time (hours)**	**Equipment**	**Time (hours)**
Concrete saw	3.75	Jackhammer*	82.32	Milling machine	51.44	Water-blasting machine*	27.41
Jackhammer*	82.32	Generator		Skid steer	1.85	Generator	
Generator		Skid steer	1.85	Air compressor	0.16	Pump	
Skid steer	1.85	Air compressor	0.16	Dump truck	4.17	Vacuum truck	6.25
Air compressor	0.16	Dump truck	4.17				
Dump truck	4.17						
Total (hours) =	**92.24**	**Total (hours) =**	**88.49**	**Total (hours) =**	**57.61**	**Total (hours) =**	**33.66**

* Electrical power equipment time used to calculate generator run time.

3.4 Results and Discussion

Table 3.6 shows the different quantities of emissions produced for the multiple techniques used for concrete removal that are evaluated in this study. The emissions evaluated include CO_2, CO, NOx, SO_2, and PM10 measured in grams. Comparing the different techniques, the results indicate that the milling method generates the highest CO_2 emission amount, which in total is 5,756 kg. The main contribution of this high emission is related to the milling machine, which is powered by diesel fuel and has a 200-hp engine. Meanwhile, the water-blasting technique is ranked second in releasing CO_2, but it is the highest in terms of other released air pollutant emissions. In contrast, the table illustrates that the chip and patch method had the lowest air emissions. In the chipping method, the electric jackhammer is used as the main demolition equipment. The jackhammer is powered by electricity and does not emit any air pollution. As seen, the chipping method produces 649 kg of CO_2, which is considered significantly low as compared with the amount of CO_2 released from milling and water-blasting methods. The last concrete removal technique is the saw and patch method, which can be ranked as the second-lowest generator of air emissions. Note that applying the saw and patch method includes the same equipment and vehicles used in the chip and patch method except it includes an extra piece of equipment, the concrete saw. The concrete saw has a 31-hp engine and is powered by diesel. The saw is categorized as small equipment and increases the amount of CO_2 produced for the assumed project by 71 kg. This amount is the difference between the total CO_2 emission from the saw and patch method, which is 720 kg, and the total CO_2 emission from the chip and patch method. which is 649 kg.

Table 3.6 Air pollutant emissions calculations by removal methods

Method	Equipment	CO_2 (kg)	CO (kg)	NO_X (kg)	SO_2 (kg)	PM_{10} (kg)
Saw and patch method	Concrete saw	71.139	1.191	0.108	0.0005	0.007
	Jackhammer	-	-	-	-	-
	Skid steer	15.540	1.466	0.116	0.0003	0.004
	Air compressor	2.466	0.004	0.013	0.0000	0.001
	Dump truck	456.000	0.184	0.408	0.0800	0.168
	Generator	175.226	0.948	1.374	0.0017	0.120
	Total emissions (kg) =	**720.371**	**3.792**	**2.019**	**0.0824**	**0.300**
Chip and patch method	Jackhammer	-	-	-	-	-
	Skid steer	15.540	1.466	0.116	0.0003	0.004
	Air compressor	2.466	0.004	0.013	0.0000	0.001
	Dump truck	456.000	0.184	0.408	0.0800	0.168
	Generator	175.226	0.948	1.374	0.0017	0.120
	Total emissions (kg) =	**649.231**	**2.602**	**1.911**	**0.0819**	**0.293**
Mill and patch method	Milling machine	5,282.439	2.281	9.460	0.0211	0.359
	Skid steer	15.540	1.466	0.116	0.0003	0.004
	Air compressor	2.466	0.004	0.013	0.0000	0.001
	Dump truck	456.000	0.184	0.408	0.0800	0.168
	Total emissions (kg) =	**5,756.444**	**3.934**	**9.997**	**0.1014**	**0.531**
Waterblast and patch method	Water-blasting machine	-	-	-	-	-
	Generator	147.771	0.515	1.073	0.0014	0.068
	Pump	2,486.119	3.880	12.189	0.0203	0.600
	Vacuum truck	684.000	0.276	0.612	0.1200	0.252
	Total emissions (kg) =	**3,317.890**	**4.671**	**13.874**	**0.1417**	**0.921**

Figure 3.2 presents the total pollutant emissions from the four different concrete removal methods in logarithmic scale. The amount of CO_2 emitted using the milling method is the largest compared with the other methods followed by the water-blasting method, the chipping method, and the sawing method in decreasing order. Furthermore, the amount of CO_2 is significantly larger than CO, NO_X, SO_2, and PM10 emissions in all removal methods. With respect to CO, it can be seen that using the water-blasting method generates the highest CO amount, followed by the milling method, then the saw and patch method, and

finally the chip and patch method. Meanwhile, the distribution of NOx and PM10 is similar to CO distribution in terms of ranking but with a different amount for each of them by each method. Using any removal method generates approximately the same amount of SO_2.

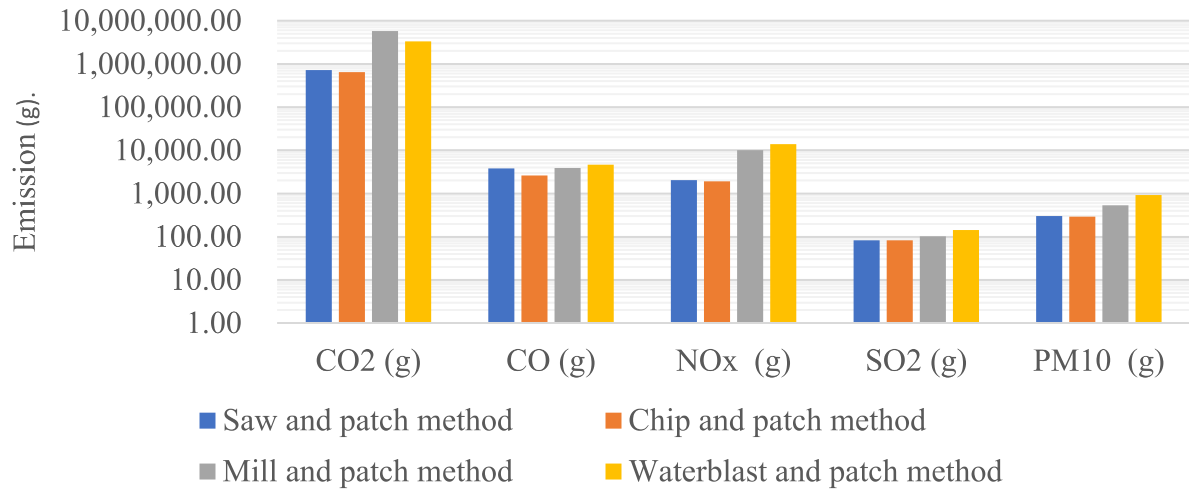


Figure 3.2 Total emissions of each removal technique

Table 3.7 presents an environmental weighted ranking for the four removal methods in order to identify the best overall method. The table shows the rank based on the amount of each released emission from the lowest to the highest amount. The emission from each method and type of pollutant is ranked from one to four, where one represents the lowest amount of the emission while four represents the highest amount of emission. The total summation of the numbers is divided by four (the total number of different pollutants considered) to give a weighted representative number for each method. The table indicates that the methods, ranked from a friendlier environmental perspective (in increasing order), are the chipping method, sawing method, water-blasting method, and lastly the milling method.

Table 3.7 Environmental weighted ranking for the removal techniques

Method	CO^2	CO	NOx	SO^2	PM^{10}	Ranking
Saw and patch method	2	2	2	3	2	2.2
Chip and patch method	1	1	1	2	1	1.2
Mill and patch method	4	3	3	4	3	3.4
Waterblast and patch method	3	4	4	1	4	3.2

Table 3.8 shows the total emissions released per hour for each concrete removal method. It indicates that the emission rates could have effects on the ranking of the methods if they are considered. Because some removal methods take more time, there is direct correlation to the increase in emissions. This result is of interest because in addition to reducing emissions, reducing the preparation time is also of interest to practitioners. The table shows that the chipping method is the lowest released emission method per hour while the milling method is the highest released emission method.

Table 3.8 Total emissions rate (kilogram per hour)

Method	CO_2 (kg)	CO (kg)	NOx (kg)	SO_2 (kg)	PM_{10} (kg)	Total emission (kg)	Total time (hr)	kg/hr
Saw and patch method	720.371	3.792	2.019	0.0824	0.300	726.565	92.24	7.88
Chip and patch method	649.231	2.602	1.911	0.0819	0.293	654.119	88.49	7.39
Mill and patch method	5,756.444	3.934	9.998	0.101	0.531	5,771.008	57.61	100.17
Waterblast and patch method	3,317.890	4.671	13.874	0.142	0.921	3,337.497	33.66	99.15

Another means of evaluating the most sustainable removal method is to express the total emissions per cubic feet of removal concrete for each method. This evaluation is shown in Table 3.9. The removal concrete volume is 1,087 cubic feet in total for this study per patch. The total summation of the five emissions released from each method is divided by the total removal concrete volume to give the emission rate in grams per cubic feet. This information is useful is approximating the emissions for other projects where a known amount of concrete is to be removed.

Table 3.9 The total emissions per cubic feet of removal concrete (kilogram per cubic foot)

Method	CO_2 (kg)	CO (kg)	NOx (kg)	SO_2 (kg)	PM_{10} (kg)	Total emission (kg)	Total removal concrete (ft^3)	kg/ft^3
Saw and patch method	720.371	3.792	2.019	0.0824	0.300	726.565	1,086.57	0.67
Chip and patch method	649.231	2.602	1.911	0.0819	0.293	654.119	1,086.57	0.60
Mill and patch method	5,756.444	3.934	9.998	0.101	0.531	5,771.008	1,086.57	5.31
Waterblast and patch method	3,317.890	4.671	13.874	0.142	0.921	3,337.497	1,086.57	3.07

3.5 Impacts of Repair Method on Traffic

Maintenance and rehabilitation activities of the roads frequently require lane closures, which cause an increase in traffic crashes and delays due to capacity reduction of the loads. The decrease is due to fewer traffic lanes, narrower lanes, and construction zone speed limits (Schrank at el. 2019). For example, in Utah, the average capacity of one lane is 560 vehicles/hour at 65 miles/hour (Mashhadi and Rashidi 2021). The impact of using the four different PDR methods is evaluated by calculating the traffic delays due to one lane closure, as shown in Table 3.10. In general, the results indicate that the method that requires more time causes more traffic delays and has more negative impacts on the traffic. For example, using the saw and patch method causes traffic delay for 51,654 vehicles while using the hydro-demolition method causes traffic delay for 18,850 vehicles. The difference between using those two methods is significant. Therefore, the decision-makers at UDOT should consider the impact of using each PDR method to minimize traffic congestion and delay.

Table 3.10 Traffic delays

Method	Required time (hour)	Average lane capacity vehicle/hour	Total traffic delay (vehicle)
Saw and patch method	92.24	560	51,654
Chip and patch method	88.49	560	49,554
Mill and patch method	57.61	560	32,262
Waterblast and patch method	33.66	560	18,850

3.6 Conclusion

In this study, the environmental assessment of different concrete removal techniques for partial-depth repair of a concrete bridge deck is conducted using comparative analysis to identify the most sustainable method. The methods are evaluated from an environmental perspective by estimating the air pollutant emissions from each method. Five air pollutant emissions of CO_2, CO, NOx, SO_2, and PM10 are estimated by employing the MOVES2014b and GREET models. The results showed that the milling technique produces the largest quantity of emissions. The chipping method generated the lowest quantity of emissions. CO_2 is produced in large quantities among all techniques while SO_2 is the smallest compared with other pollutants. Additionally, the results indicated that the amount of air emissions are increasing relative to the utilization time of the removal technique.

The results of the study are significant in that they can be used to help state and local transportation officials develop removal standards that include sustainable practices. Obviously, the sustainability of the removal technique is just one piece of information that goes into the decision-making process, but by utilizing the information in this study, better environmental policies and standards can be developed. The values for emissions per cubic foot can also be used to estimate emissions for larger projects for which environmental offsets can be made. Also note that the estimated removal times can help transportation officials determine the best methods, as the goal in partial-depth replacement is typically to re-open the travel lanes to traffic as soon as possible.

4. IMPROVED REMOVAL EFFICIENCY OF PARTIAL BRIDGE DECK REPAIR PATCHES USING THE SAW AND PATCH METHOD

4.1 Introduction

The saw-and-patch removal method is considered the primary and the most frequently used method for partial-depth concrete bridge deck repair (Frentress and Harrington 2012). The procedure of the saw and patch method begins with using a diamond blade saw to cut the perimeter of the patch area to a certain required depth. Then a light jackhammer with an impact force of 10 to 35 pounds is used to chip out the deteriorated concrete inside the patch area (Smith et al. 2014). Using this method gives a rough concrete surface which strengthens the bonds between the existing concrete and the newly placed repair material. In addition, most construction crews are familiar with the saw and patch method (Frentress and Harrington 2012). A Federal Highway Administration (FHWA) study determined that the saw and patch method is cost-effective (Wilson et al. 1999) and has advantages over other removal techniques in terms of accessibility to the small and isolated areas of deteriorated concrete on the bridge deck where large equipment used in the other removal methods cannot access (Vorster et al. 1992). The saw and patch method can remove irregular concrete patches and effectively remove concrete under, between, and around steel reinforcement bars (Ramcharitar 2005). The major concerns about the saw and patch method are the required time and labor to remove the deteriorated concrete patches. As such, it is a time-consuming and labor-intensive method (Smith et al. 2014). Consequently, a significant amount of time is still spent on the removal of damaged and deteriorated bridge deck patches. During the repairing time, one or more bridge lanes are closed, which causes many traffic problems and travel delays.

A recent comparative study estimated the utilization time required to remove deteriorated concrete for a partial-depth bridge repairing project with a total removal volume of approximately 990 ft^3 (Abu Shanab and Sorensen 2022). In the study, the removal time is calculated based on the equipment used for four different methods, including saw and patch, chip and patch, milling and patch, and hydro-demolition. The results indicate that saw and patch is the slowest method, and it requires more time compared with the other removal techniques. This suggests that when a bridge is repaired using the saw and patch method, the time closure increases, which causes traffic congestion and increases car crash vulnerability because the available lanes are not sufficient for the traffic demand (ASCE 2021). Therefore, there is a need for foundational research on methods to reduce the saw and patch method concrete removal time. Along with that, the labor-intensive process could be more efficient if part of it can be automated. The present study investigates methods to reduce the removal time and identify methods that can easily be automated for additional future studies. In 2017, the Missouri Department of Transportation conducted a study about the best current practices of partial-depth repair (PDR) and concrete removal techniques. The study discusses case studies from many U.S states including California, Georgia, Minnesota, Missouri, Utah, and Washington. The states' PDR procedures and specifications have evolved over many years to become more efficient for long-term bridge deck performance. One of the main aspects to achieve that is the selection of the proper concrete removal techniques and equipment. Traditionally, saw and patch has been the most common method used for removing the bridge deck's deteriorated concrete. Currently, Utah, Washington, and Georgia use the saw and patch technique because it is a fast and cost-effective approach (Darter 2017). Another survey conducted at Ryerson University in Canada evaluated the current bridge deck rehabilitation. A detailed questionnaire was sent to many DOTs in North America (the U.S. and Canada) and included questions on the most common tools and methods to remove concrete from bridge decks. The survey results showed that the jackhammer was the most utilized piece of equipment (35% of the time) because it is cheap, applicable to most bridge types, and can be used vertically or horizontally (Lachemi et al. 2007).

4.2 Methodology

This study aims to experimentally evaluate and improve the saw and patch procedure to expedite concrete removal time in order to decrease traffic closure time due to the preparation process for partial-depth concrete bridge deck repair. This objective also includes identifying techniques that may be automated for future studies in reducing patch preparation time. This study presents an experimental evaluation of different sawing and jackhammering methods to partially remove concrete from the bridge deck repair area. The utilization impacts of this removal equipment on the soundness of the concrete surrounding the patch area are also evaluated. The performance of the removal methods is evaluated in terms of the patch preparation time, which directly correlates to the bridge traffic closure time. More precisely, the experimental portion of this study evaluates four different discretized sawing and jackhammering methods in terms of the removal time, equipment usage, and damage to the surrounding concrete area.

4.3 Experimental Setup and Procedure

4.3.1 The Experimental Design

Four unreinforced concrete slabs measuring 5-ft wide by 5-ft long by 10-ins. deep were cast at the SMASH lab at Utah State University, as shown in Figure 4.1. Each slab's concrete had a different mix design and resulting compressive strength with target strengths between 5,000 and 7,000 psi. The compressive strength of hardened concrete is examined by testing 4-in. diameter by 8-in. tall cylinders according to ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM 2018).

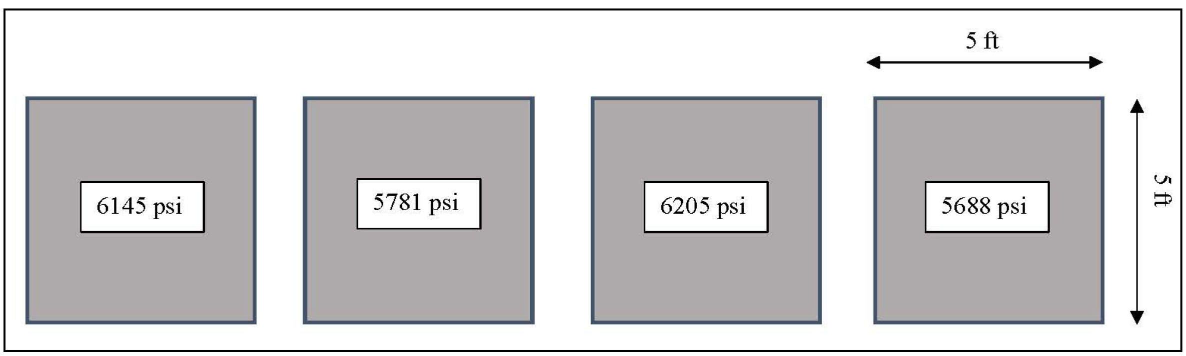


Figure 4.1 Concrete test slabs with respective 28 days compressive strengths (f'c)

Each concrete slab was divided into four equal areas of dimensions 2 ft by 2 ft, and the concrete was removed using four different discretized sawing-jackhammering methods. Three-inch deep patches are removed from the slab. For each method, the removal and equipment usage times for the experiments are measured.

The four sawing-jackhammering methods are:

1. **Method I** involves saw cutting the four edges of the concrete patch with a gas-powered concrete saw, as shown in Figure 4.2(a), then uses only a jackhammer to remove the interior of the concrete.
2. **Method II** involves saw cutting the four edges of the concrete patch and two perpendicular cutting lines at the center of the patch, as shown in Figure 4.2(b). A jackhammer is then used to remove the four pieces of concrete of 12 in. by 12 in. dimension.
3. **Method III** involves saw cutting the four edges of the concrete patch and four perpendicular cutting lines inside the patch, as shown in Figure 4.2(c). Then using the jackhammer, the nine pieces of concrete with 8-in. by 8-in. dimensions are removed.

4. **Method IV** involves saw cutting the four edges of the concrete patch and six perpendicular cutting lines inside the patch, as shown in Figure 4.2(d). The jackhammer then removes 16 concrete pieces of 6-in. by 6-in. dimensions.

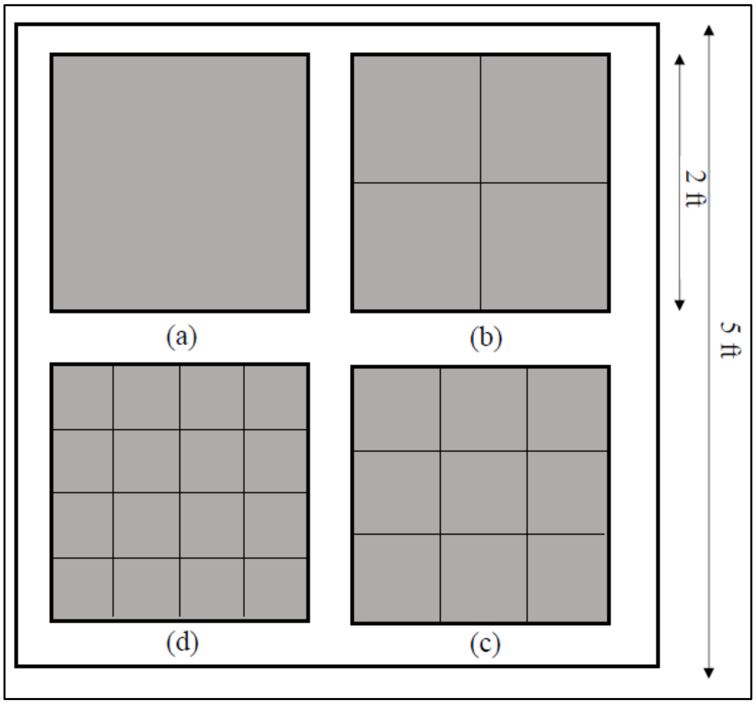


Figure 4.2 The four discretized methods of partial-depth concrete removal

In this experiment, a gas-powered concrete saw and a 27.6-pound electric jackhammer were used to remove the concrete patches. The saw model used was a gas-powered MAKITA EK7651H 14" and the jackhammer model was HILTI-TE 1000-AVR, as shown in Figures 4.3 and 4.4, respectively. This jackhammer is a concrete breaker, and it has chiseling performance up to 476 inch^3/minute and hammering frequency up to 1,950 impacts/minute. A single licensed operator was chosen to operate the jackhammer and the concrete saw.

Figure 4.3 MAKITA EK7651H 14" concrete saw

Figure 4.4 HILTI-TE 1000-AVR concrete jackhammer

In addition to examining the effectiveness of the different patch removal methods, any detrimental effect of these removal methods on the surrounding concrete is also of interest. Destructive and non-destructive testing of the surrounding concrete was performed to determine any negative effects on the surrounding concrete. The non-destructive testing method utilized in this experiment was the rebound hammer test, performed according to ASTM C805, Standard Test Method for Rebound Number of Hardened Concrete (ASTM 2013). The test is based on the principle that the rebound of an elastic mass depends on the hardness of the concrete surface against which the mass strikes. In other words, the rebound number recorded using the hammer depends on the hardness of the concrete surface. The device manufacturer provides a correlation curve that shows the relationship between the rebound number and the compressive strength of the concrete. Referring to that curve, the compressive strength can be calculated after the rebound number is read. This experiment used a Gilson HM-705 concrete test hammer, as shown in Figure 4.5.

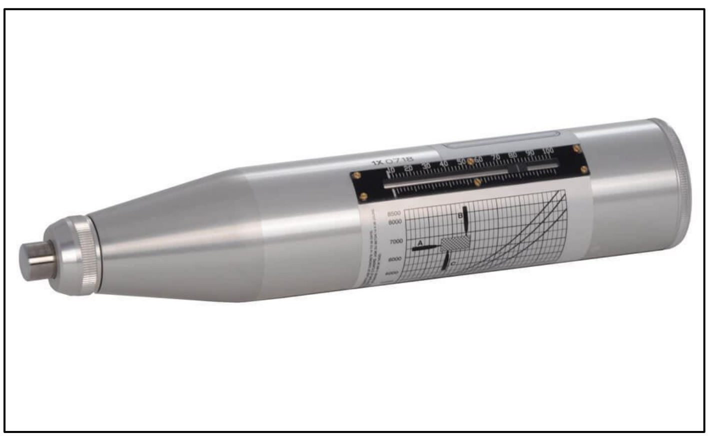


Figure 4.5 Gilson HM-705 Rebound hammer

The rebound test is taken three times: before starting the removal experiment, after the saw cutting, and after the completion of the patch removal by jackhammering. Three circles are marked on each side of the concrete slab, as shown in Figure 5.6, and the test is performed 20 to 40 times due to the smoothness of the slab side, and an average of those readings is taken.

Figure 4.6 Circles located on the concrete side where the rebound hammer test is taken

The destructive test used in this experiment was the concrete compressive strength of cores taken from the surrounding concrete after removal of the patches. The compressive strength test was carried out following ASTM C42, Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete (ASTM, 2016). Three, 3-in. diameter by 6-in.-tall cores were drilled from each concrete slab to measure the compressive strength of the concrete following the removal experiments. Figure 4.7 shows the core test equipment used in this experiment. Note that the cores are taken from the top of the slabs and after approximately one year of the original casting day.


Figure 4.7 Concrete core test equipment

4.3.2 Experiment Procedure

The experimental procedure steps are outlined as follows:

1. Prepare the concrete slab by marking the saw cutting lines and rebound test areas, then test the surrounding concrete using the rebound hammer (Figure 4.8).

Figure 4.8 Preparation of the concrete slab before saw-cutting

2. Use the saw to cut the concrete patch following Methods I, II, III, or IV. Measure the direct cutting time for each method (Figures 4.9 and 4.10).

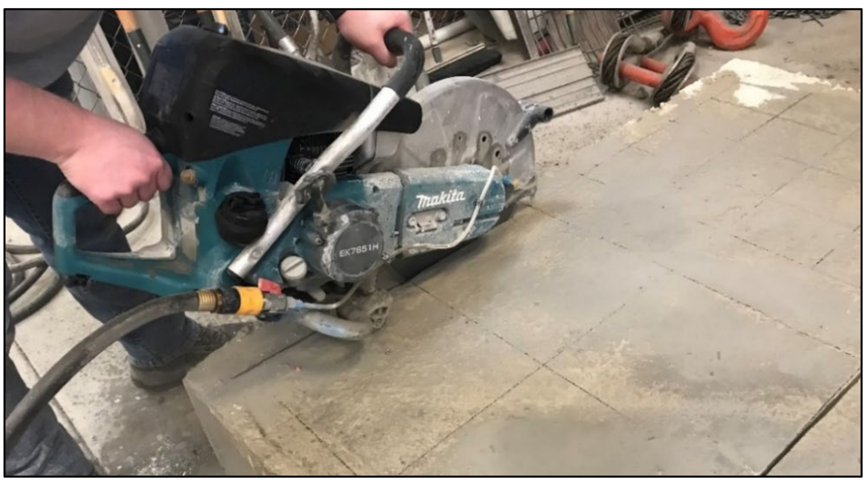


Figure 4.9 Sawing the concrete along the discretization lines

Figure 4.10 The concrete slab after saw cutting

3. Jackhammer the patches to a removal depth of 3 inches. Measure the time required for each method. Upon completion, retest the strength of the surrounding concrete using the rebound hammer (Figures 4.11 and 4.12).

Figure 4.11 Jackhammer removal of the concrete

Figure 4.12 The concrete slab after jackhammer removal

4. Measure the removal depth after jackhammering to ensure a 3-inch removal depth (Figure 4.13).
5. Test the compressive strength of the surrounding concrete using the rebound hammer.
6. Repeat Steps 1 through 5 for each slab.

Figure 4.13 Verifying the removal depth

4.4 Results and Discussion

4.4.1 Concrete Compressive Strength

The compressive strength testing results of 4-in. diameter by 8-in.-tall cylinders, taken when the slabs were poured and tested after 28 days according to ASTM C39 (ASTM 2018), are shown in Table 1. After removing a 3-inch depth of concrete from each slab using four different sawing and jackhammering methods, three cores are extracted from each concrete slab according to ASTM C42 (ASTM 2016) to measure the compressive strength of the concrete and evaluate the effects of sawing and jackhammering on the concrete strength. The average compressive strengths of the cylinders and cores are shown in Table 4.1.

Table 4.1 Average compressive strengths of concrete

Slab #	Average compressive strength 28 days (psi)	Standard deviation (psi)	Average compressive strength of cores (psi)	Standard deviation (psi)
Slab 1	5,688	415	7,535	2,035
Slab 2	5,781	489	6,303	334
Slab 3	6,145	567	7,176	1,447
Slab 4	6,205	1,029	8,743	1,681

Table 4.1 presents a comparison between the compressive strength of the concrete before and after the concrete removal. The results show that the strength of concrete at age one year is higher than the strength of cylinders at age 28 days. This is expected as concrete continues to increase in strength with time. The results indicate that in the case of small healthy concrete slabs, the core test indicates that the impacts of sawing and jackhammering does not have an adverse effect on concrete strength.

Table 4.2 shows the average measured rebound values, the converted compressive strength f'c, and the standard deviation of the rebound hammer tests. The rebound values are measured by the rebound hammer before the sawing, after the sawing, and after the jackhammering. The results of the four slabs indicate that concrete strength decreases after jackhammering, which means that the sawing and jackhammering have a negative impact on concrete strength.

Table 4.2 Rebound tests' results

Slab #	Before sawing			After sawing			After jackhammering		
	Rebound number	Mean. fc' (psi)	S.D. (psi)	Rebound number	Mean fc' (psi)	S.D. (psi)	Rebound number	Mean fc' (psi)	S.D. (psi)
Slab 1	38.3	4,558	180	35.7	4,048	286	37.7	4,443	232
Slab 2	40.6	5,110	227	40.8	5,110	212	40.4	5,080	164
Slab 3	41.3	5,240	211	41.1	5,190	180	39.4	4,840	457
Slab 4	38.5	4,613	227	38.5	4,630	288	37.2	4,350	248

4.4.2 Saw Removal Time

The four different discretized sawing-jackhammering methods have 4, 6, 8, and 10 saw cutting lines, respectively. The saw cutting time is calculated for each saw cutting line per minute, as shown in Table 4.3.

Table 4.3 Time of saw line cutting (minutes: seconds)

	Time of saw line cutting (minute)							
	Green				Orange			
	Method (1)	Method (2)	Method (3)	Method (4)	Method (1)	Method (2)	Method (3)	Method (4)
Line # 1	01:54.6	01:55.5	02:09.4	02:12.6	02:16.1	02:04.0	02:36.4	02:07.8
Line # 2	02:25.3	02:11.1	01:56.9	02:07.8	02:31.9	01:58.2	02:08.3	02:12.8
Line # 3	02:15.7	02:18.0	01:58.5	02:02.2	01:58.2	01:55.1	02:08.9	01:54.9
Line # 4	02:35.3	02:08.1	01:52.6	02:09.5	02:01.5	02:01.2	02:24.1	02:44.0
Line # 5		01:47.2	01:58.2	02:45.1		01:54.2	02:19.6	03:33.0
Line # 6		02:00.6	01:40.5	01:52.6		01:50.2	02:44.9	03:30.9
Line # 7			01:56.0	02:02.0			02:18.5	01:48.9
Line # 8			02:05.2	02:00.0			02:56.2	02:06.3
Line # 9				01:58.9				02:24.6
Line # 10				02:23.1				02:48.5
Total =	09:10.9	12:20.4	15:37.2	21:34.0	08:47.7	11:43.0	19:36.9	25:11.6
	Yellow				Blue			
	Method (1)	Method (2)	Method (3)	Method (4)	Method (1)	Method (2)	Method (3)	Method (4)
Line # 1	02:11.6	02:18.1	02:17.7	01:52.5	01:49.3	01:57.4	01:42.4	02:03.2
Line # 2	02:03.1	01:56.4	02:08.8	02:58.1	01:41.2	01:56.0	01:46.1	01:56.6
Line # 3	01:59.5	02:24.2	02:03.4	02:19.3	01:44.3	01:52.6	01:57.7	01:50.8
Line # 4	02:15.9	02:10.8	02:00.5	02:03.0	01:42.2	01:49.9	01:42.6	01:43.9
Line # 5		02:05.0	01:45.8	01:46.4		01:46.7	01:51.8	01:37.5
Line # 6		02:05.0	02:10.3	01:52.5		01:47.8	01:49.1	01:54.1
Line # 7			01:57.7	01:58.3			01:58.6	01:58.9
Line # 8			01:55.4	01:45.9			01:49.8	01:51.8
Line # 9				01:57.7				01:52.3
Line # 10				01:45.1				01:47.2
Total =	08:30.1	12:59.5	16:19.6	20:18.8	06:57.1	11:10.5	14:38.0	18:36.3

Figure 4.14 demonstrates the measured time to cut a line without considering either the concrete strength or the cutting method. The average time required to cut a 2-foot line using a saw is 124.6 seconds with a standard deviation of 21.27 seconds.

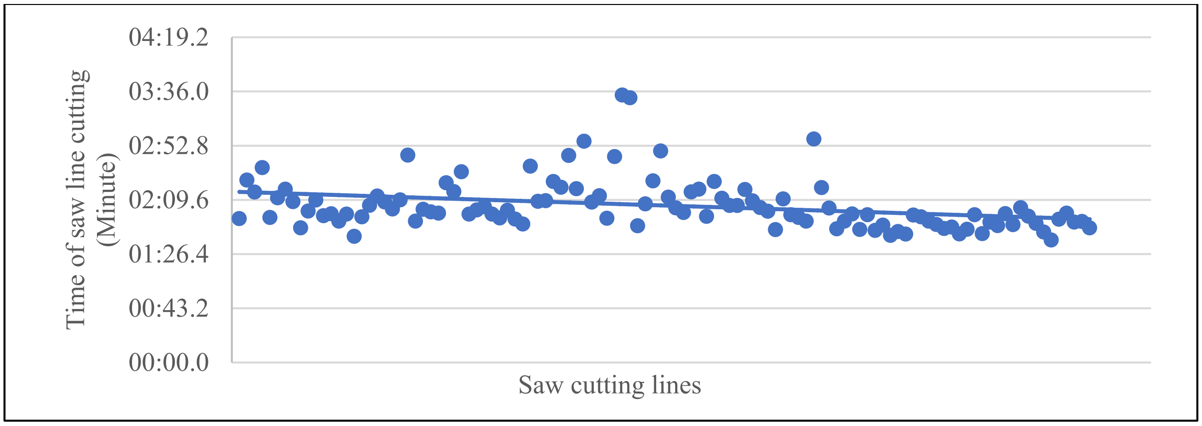


Figure 4.14 The required time of saw cutting line

The boxplots in Figure 4.15 represent the maximum and minimum time of each cutting line for the four different concrete strengths. The minimum saw cutting for a line is 01:37.5 minutes and the maximum is 3:33.0 minutes. The results do not indicate a distinct relationship between the saw cutting time and the concrete strength. This means that the concrete strength is not an influencing factor on the saw cutting time.

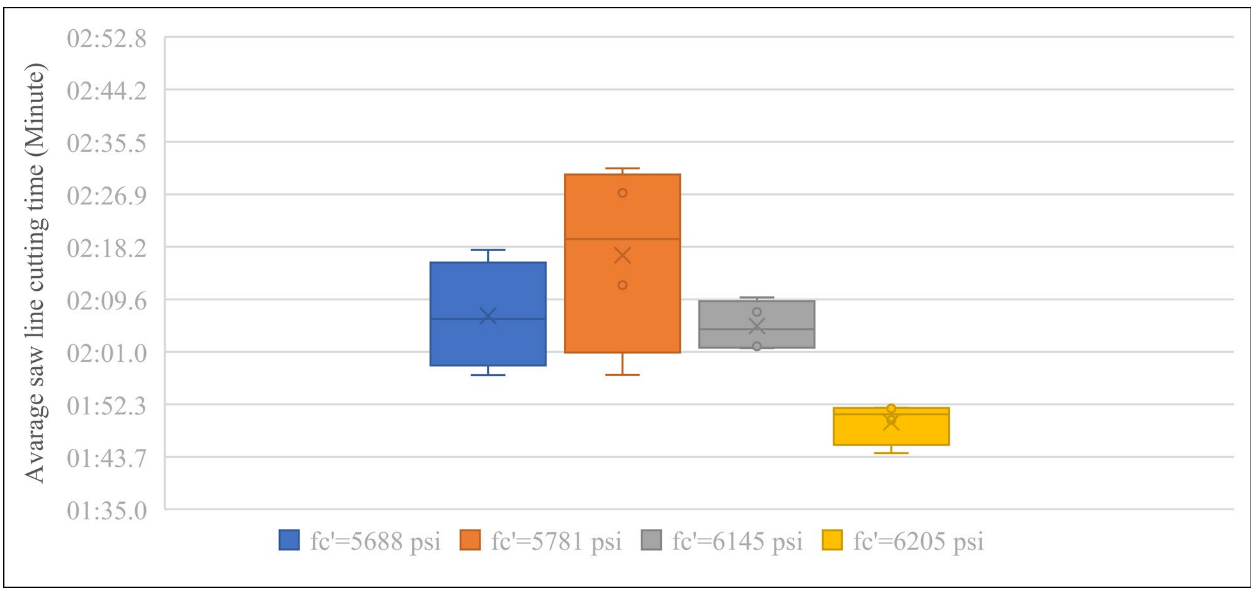


Figure 4.15 Boxplots of saw cutting time

From the field observation during the saw cutting process, it was noticed that other factors could have more effects on the saw cutting time, such as the sharpness of the saw blade and the productivity rate of the operator. Slab (1), with f'c=5,688 psi, was the first slab to be cut and the operator had little previous experience running the concrete saw, therefore it took more time to operate the saw and control the cutting process. For Slab (2), with f'c=5,781 psi, it was clear that the cutting time increased and the cutting rate decreased due to erosion of the saw blade and the operator's physical fatigue, as seen during concrete removal from Slab (1) and (2). The saw blade was degraded and needed to be changed, the working time was around 5 p.m., and the operator was tired after a long workday. Those two factors led to a lower productivity rate and more cutting time, as shown in Figure 4.15. Regarding the saw blade performance, another study stated that the saw blade wear rapidly decreases the cutting depth (Hu et al. 2006), which means that more time is required to complete the saw cutting. While the saw cutting of the third and fourth slabs gradually takes less time compared with the first and second slabs because the cutting is done in the morning, the saw has a new blade and the operator has become more skilled by repeating the same task four times.

4.4.3 Jackhammering Time

Figure 4.16 illustrates the relationship between the number of saw-cutting lines and the jackhammering time for the four concrete slabs. There is a strong correlation between the number of saw lines and the jackhammering time. The increased number of saw-cutting lines decreases the jackhammering time. For example, jackhammering the green slab that has four saw lines takes more than 25 minutes, but when the slab has 10 saw lines, the jackhammering time is reduced to 11:26.7 minutes: seconds, as shown in Figure 4.16a.

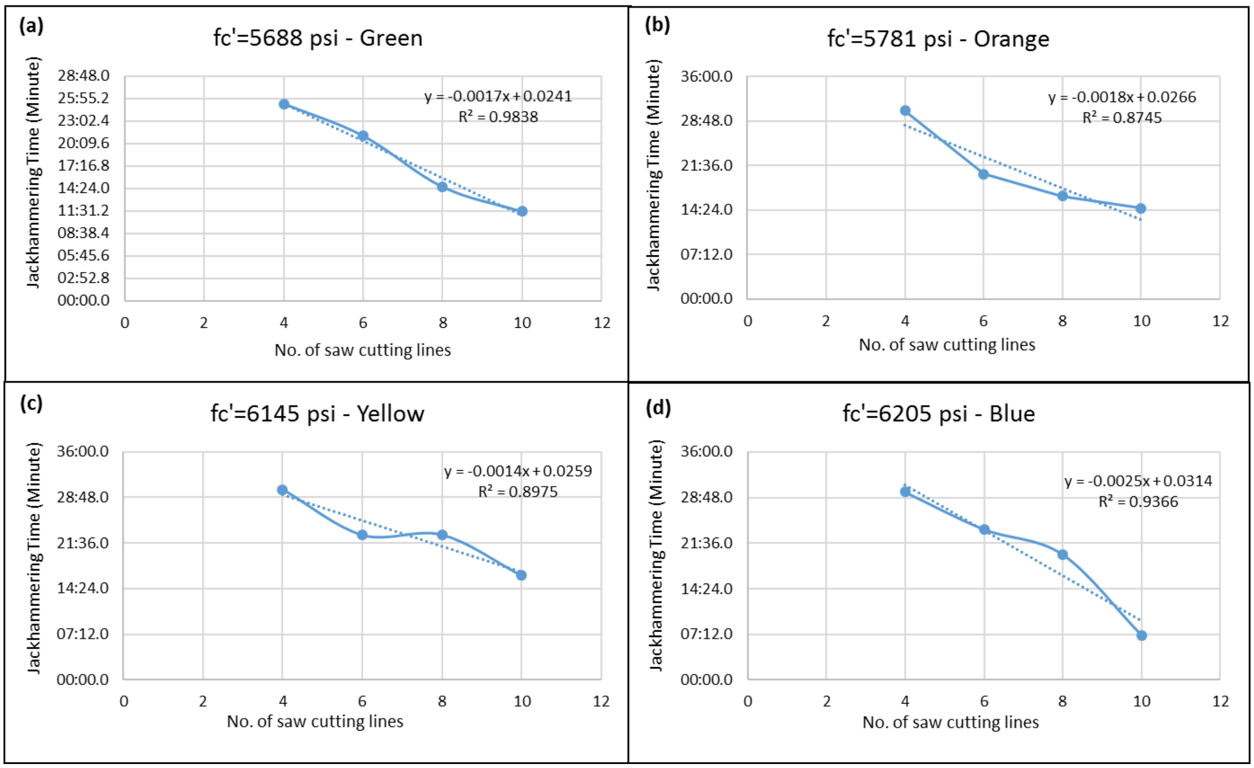


Figure 4.16 The number of the saw-cutting lines vs. jackhammering time

After removal of the concrete, an interview/discussion was held with the operator. Based on the operator's opinion, using the jackhammer requires a high muscular effort, and the operator is exposed to a high level of vibration. These can lead to some health issues such as overexertion, headache, reduced efficiency, and even possible injury (Johnson et al. 2017; Inyang et al. 2012). The jackhammer is considered a heavy construction tool and should be handled properly by a skilled operator to reduce the risk of accidents (Rodriguez 2019). However, the operator preferred using the saw rather than the jackhammer given the choice. In this regard, concrete removal Method IV with 10 saw lines has an advantage over the other methods. According to the field observation, the jackhammering time depends on certain factors, including the operator's skills, pull-off/impact angle, and the number of saw-cutting lines. The operator's skills are important in terms of the quantity of concrete removal and the quality of the cutting surface. Therefore, operators must try each cutting method on their own to become familiar with the jackhammer and the cutting process. In general, it has been noticed that jackhammering the first patches took more time and the operator faced some control difficulties while it was easier and more efficient for the last patches. In addition, the recommended right pull-off/impact angle is 45° (Vorster et al. 1992), but during jackhammering it was hard to consistently obtain this angle for many reasons, such as avoiding cutting the edges, limited maneuverability within the workspace, and using the operator's body force as shown in Figure 4.17. This has negative effects on the productivity rate and increases the jackhammering time.

Figure 4.17 Examples of pull-off/impact angles of the jackhammer

Additionally, increasing the saw-cutting lines has a positive impact on jackhammering. The saw lines divided the concrete area into smaller pieces, which decreased the mechanical bonds between those concrete pieces and made it easier for the operator to remove those small pieces with less muscular effort and less time as well.

4.4.4 Concrete Removal Volume

The target required removal volume of concrete is 2-ft x 2-ft x 3-in. (= 1.00 ft^3), but the saw blade dimension is 3.5 inches, which increases the cutting depth and removal volume to 1.167 ft3. After sawing and jackhammering, 20 depth measurements are taken from each removal area, and then the average of the 20 readings is used to calculate the actual concrete removal volume per ft3, as shown in Table 4.4.

Table 4.4 Concrete removal volume (ft^3)

	Method I 4 saw lines	Method II 6 saw lines	Method III 8 saw lines	Method IV 10 saw lines
Slab 1	0.902	1.023	1.007	1.023
Slab 2	0.988	1.040	1.092	1.135
Slab 3	0.985	0.985	1.073	1.038
Slab 4	0.923	1.078	1.095	1.205

The boxplots in Figure 4.18 show the concrete removal volume in terms of the number of saw lines. As can be seen in the figure, the increasing of the saw cutting lines increases the removal volume gradually regardless of the concrete strength. In Method I, the removal volume is less than the target, which requires additional chipping work to remove the remaining concrete. Method IV resulted in a volume closest to the target and there is no need for extra chipping.

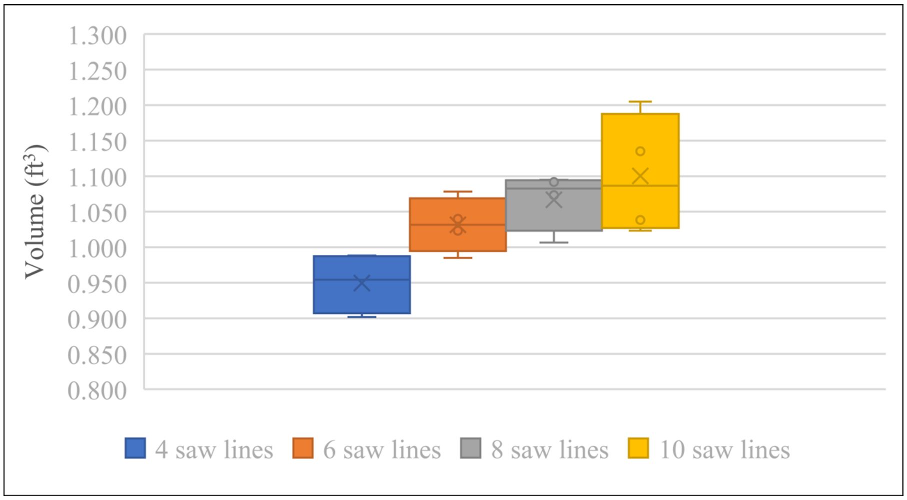


Figure 4.18 Boxplots of concrete removal volume (ft^3)

4.4.5 Optimal Removal Method

From the experimental data and field observation, using Method IV on Slab 4 is the optimal concrete removal method, as shown in Table 4.5. Method IV saws the concrete patch into 16 concrete pieces and then removes them using the jackhammer. The operator became an expert by that time and was familiar with the four cutting methods. The operator was able to use and control the cutting equipment professionally and was in a rested health condition. In addition, the saw blade was in good condition and the 45° jackhammering pull-off angle was obtained. As illustrated in Table 5, the total saw cutting time of Method IV for Slab 4 is the shortest time, 18:36.3 minutes. Also, the required jackhammering time on the same slab decreases dramatically to 07:04.6 minutes: seconds, which is 4:22.01 minutes: seconds less than the following time of Slab 1. Therefore, this concrete removal method is efficient and time-saving.

Table 4.5 The total sawing and jackhammering times of Method IV

#	Total saw cutting time (Minute)	Total jackhammering time (Minute)
Concrete Slab # 1	21:34.0	11:26.7
Concrete Slab # 2	25:11.6	14:42.4
Concrete Slab # 3	20:18.8	16:28.1
Concrete Slab # 4	18:36.3	07:04.6

Furthermore, in this slab, the operator jackhammered the first two concrete pieces then had enough space to go underneath each piece and pop it out, as shown in Figure 4.19. This also resulted in larger debris pieces that are easier to remove. The larger pieces also resulted in fewer smaller degree particles and dust, which also improves the sustainability of the removal method (Zhu et al. 2019). Based on these results, it appears that Method IV could potentially be automated in the future, as the saw cutting can easily be automated and removing the concrete pieces was more uniform, requiring less operator evaluation on removal depth.

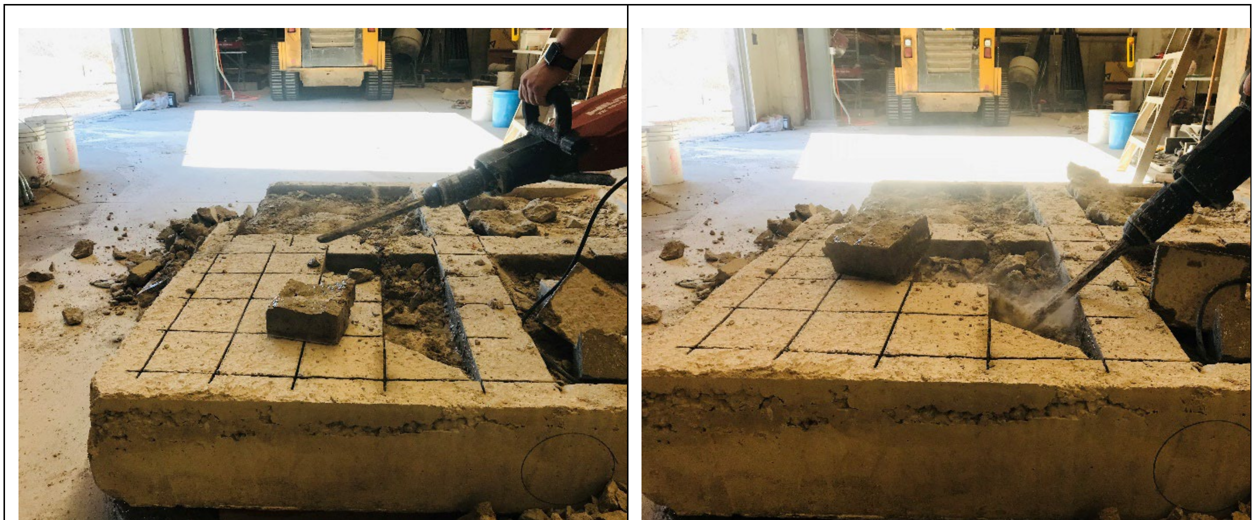


Figure 4.19 Removal of the discretized concrete pieces

4.4.6 Applied Example

In this section, the four sawing and jackhammering techniques presented in this study have been applied to a real partial-depth bridge deck repair project: the Utah SR-193 bridge over US-89 (Structure Number 0F 575) located in Layton, Utah. The SR-193 concrete bridge was built in 1995 with a 178.5-ft length and a 65.3-ft width (https://bridgereports.com/1570708). The total repair patch removal volume was 1,086.57 ft3; the details of the project and the repairing patches are given in Appendix A (Maguire et al. 2021). It is assumed that the project's repair patches are squares and the concrete compressive strength of the bridge is similar to the blue test concrete slab (6,205 psi). The four different methods are applied for the entire project, and the detailed results are seen in Appendix B while a summary of the results is shown in Table 4.6. The results indicate that using Method IV, the previously identified optimal case, is the fastest method to remove concrete from the bridge, and Method I, the current practice method, is the slowest. This means applying the optimal method that is carried out by this research can save approximately 35% of the required time to remove concrete from this project.

Table 4.6 The required time of concrete removal using the four methods

Method	Total time (hour)
Method I (4 saw cutting lines)	656.71
Method II (6 saw cutting lines)	610.07
Method III (8 saw cutting lines)	598.02
Method IV (10 saw cutting lines)	426.05

4.5 Conclusion

This chapter concludes that the saw and patch method is the most commonly used bridge deck concrete removal method despite it being the slowest and most labor-intensive. Increasing the saw cutting lines decreases the jackhammering time for the different concrete strengths and increases the concrete removal volume. The saw and patch method can be influenced by many factors, such as the operator's skills and health/energy level, saw blade sharpness, and jackhammer pull-off angle. Lastly, Method IV, which has the largest number of saw-cut lines, is the optimal concrete removal method among the other proposed methods and saves approximately 35% of the required concrete removal time. Also, it has the potential to be automated in the future.

5. EXPERIMENTAL STUDY OF THE HIGH-PRESSURE WATER JET “HYDRO-DEMOLITION TECHNIQUE” IMPACTING CONCRETE FOR PARTIAL-DEPTH CONCRETE BRIDGE DECK REPAIR

5.1 Introduction

Hydro-demolition refers to the use of the high-pressure water-jet technique for concrete removal (Lewis 1990). This water jet technique includes two types: the pure water jet and the abrasive water jet (AWJ). The pure water jet is the earliest application; the AWJ has been used to increase the cutting capability by adding abrasive material to the water (Xue et al. 2018). The hydro-demolition technique is an innovative technology, which has been widely used in rehabilitation of highway infrastructures (Bazanov 2019), particularly in full bridge deck rehabilitation (Lewis 1990) where preservation of the reinforcement steel is required (Sitek et al. 2011). This technique is also becoming more common for partial-depth concrete removal of bridge deck repairs (Roper 2018). In fact, Silfwerbrand (2009) states that hydro-demolition is the best technique for concrete removal. Wenzlick (2002) argues that hydro-demolition does not cause damage to the unsounded concrete left in place compared with other conventional methods such as jackhammering and milling, which can generate micro-fracturing in the concrete surface and can lead to premature loss of bond in the concrete patching or overlay material (Wenzlick 2002). Furthermore, the hydro-demolition technique has competitive operational advantages, including a dust-free, vibration-free, and heat-free work zone (Momber 2003). McCabe (2014) highlights that hydro-demolition can be done in a directional manner, which means it has selective concrete removal capability. Conversely, using hydro-demolition for partial-depth bridge deck repair has some challenges. One of these practical difficulties is called “ punch-through” or “blow-through,” which occurs when the high-pressure water causes a hole through the entire depth of the bridge deck (Hopwood et al. 2015). Figure 5.1 shows examples of significant and insignificant types of punch-through, which is considered a structural failure that occurs when the concrete bridge deck section capacity is less than the applied forces from the high-water pressure. The concrete failure could be in bending, one-way shear, or two-way shear failure models. According to a recent study, the governing failure model of punch-through is the bending moment in the orientation where the length of the concrete section is greater than the width (Roper 2018).

(a)

(b)

Figure 5.1 Examples of bridge deck punch-through, (a) insignificant punch-through and (b) significant punch-through (Roper 2018)

Punch-through has human safety and environmental concerns, including falling concrete debris under the bridge might injure some people and/or damage their properties. The resulting deck holes are also construction hazards to the health and safety of the workers, and the hydro-demolition water can run through the open holes before it is treated, which can be harmful to the environment. This is in addition to the significant increase in the deck repair cost due to the extra work hours and material (Roper 2018). However, the occurrence of punch-through is not clearly identified due to limited information and studies (ICRI 2014). This is especially true for partial deck concrete removal because, to date, no study can be found that correlates the necessary water pressure for removal to the strength or material properties of the concrete. Therefore, it is necessary to focus on the partial-depth concrete removal process impacted by high-pressure water and the influential parameters of using this technique while considering the required water cutting time for different types of concrete strengths.

5.2 Methodology

This study aims to investigate the partial-depth concrete removal process for bridge deck repair using the hydro-demolition technique by analyzing the impacts of different water jet pressures on different concrete strengths as well as concrete behavior under those pressure jets. Specifically, the study seeks to: identify the influential parameters that affect the entire partial-depth removal process when using hydro-demolition to, minimize the occurrence of the punch-through problem, and reduce the traffic closure time due to the bridge deck repairing. In this chapter, an experimental study was conducted to analyze the impacts of high-pressure water on concrete as part of the PDR of the concrete bridge deck. Small-scale trials of 15 concrete specimens with varying compressive strengths were tested. A statistical analysis for the experimental data of AWJ on concrete with different compressive strengths was then carried out in order to develop a predictive model for determining the input parameters to accurately predict concrete removal to a specified depth. The results of this study can provide a better understating of the controllability and efficiency of using the hydro-demolition technique for partial-depth concrete bridge deck removal.

5.3 Experimental Setup, Procedure & Results

5.3.1 Equipment

A high-pressure water jet machine, the Integrated Flying Bridge Water Jet Machine manufactured by FLOW company (as shown in Figure 5.2), was used to carry out the physical experiments. This machine has a computer control system that controls the input parameters of the water jet, including the nozzle stand-off distance, the nozzle angle, the abrasive flow rate, and the water pressure. The machine work plate dimensions were 6 ft by 10 ft, the maximum pressure of the water jet was 45 ksi, and the pump is 30 hp. The water cutting tolerance of the machine is ± 0.001 inch. In addition to the water jet, other tools are used for testing concrete properties such as compressive strength machine, air meter test, and slump cone test. Subsequent sections of this chapter discuss this in further detail.

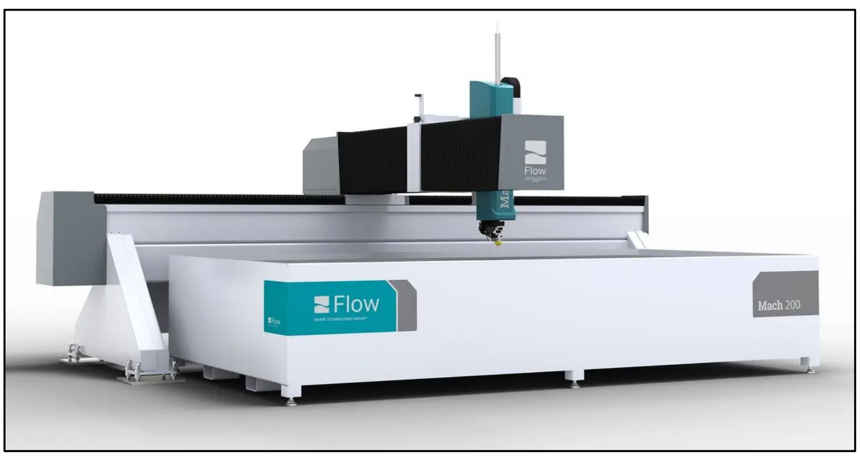


Figure 5.2 FLOW abrasive water jet machine

5.3.2 Sample Specimens

Five unreinforced concrete mixtures were designed for this study. In the concrete mixtures, the water to cement ratio has been changed while the aggregate amount and grading were kept the same. Fifteen slabs/specimens, 24-ins. long by 8-ins. wide by 5-ins. deep, were cast in the Concrete Technology Lab at Utah State University. The dimensions and average compressive strengths of the specimens are shown in Figure 5.3.

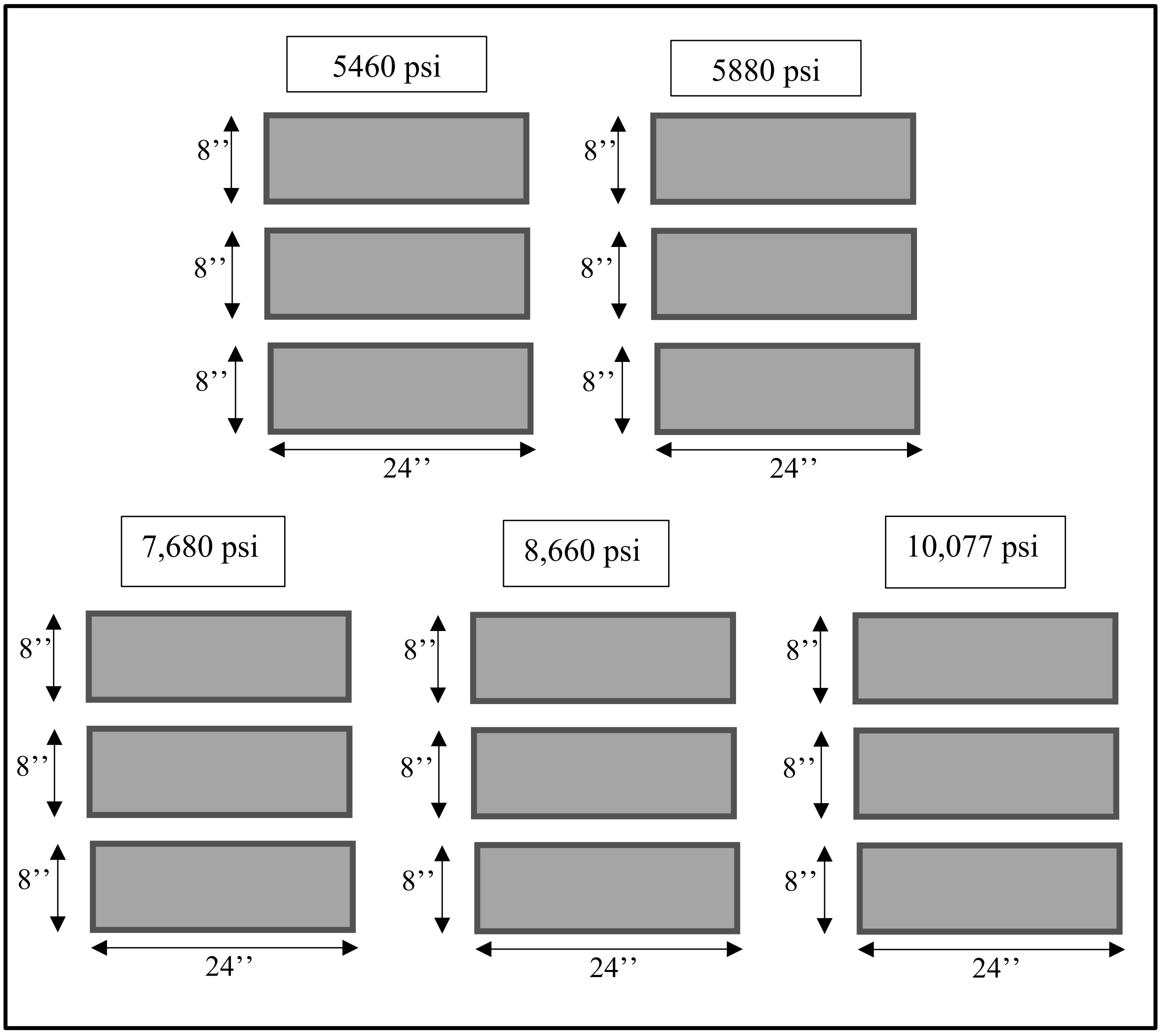


Figure 5.3 Concrete specimens for water jet cutting

The following properties of fresh and hardened concrete were examined: 1) the consistency of fresh concrete by slump test according to ASTM C143, Standard Test Method for Slump Of Portland Cement Concrete (ASTM 2012), as shown in Figure 5.4; 2) the air content of fresh concrete by pressure test according to ASTM C231, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method (ASTM 2013), as shown in Figure 5.5; and 3) the compressive strength of hardened concrete by testing 4-in. diameter by 8-in. high cylinders according to ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM 2018), as shown in Figures 5.6 and 5.7.

Figure 5.4 Slump test

Figure 5.5 Air content test

Figure 5.6 Cylinders for compressive strength

Figure 5.7 Compressive strength test, (a) before applying the loads, (b) after applying the loads

The results of these tests are presented in Table 5.1.

Table 5.1 The properties of concrete specimens

#	Color Code	Average compressive strength (psi)	Compressive strength standard deviation (psi)	Air content %	Slump (inch)
1	Yellow	5,460	645	1.8%	0
2	Pink	5,880	782	1.5%	5.5
3	Orange	7,683	953	2.4%	2.5
4	Green	8,660	613	1.6%	6.5
5	Blue	10,077	1,027	3.6%	4.2

5.3.3 Experimental Procedure

In this study, 125 water jet cutting operations were done (24 penetration points x 5 specimens + 5 lines =125 operations), as shown in Figure 5.8.

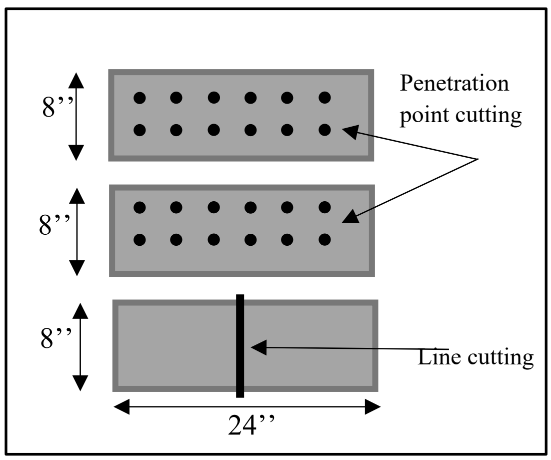


Figure 5.8 The cutting operations of concrete

The AWJ machine parameters such as nozzle diameter, nozzle angle, stand-off distance, abrasive grain size, and abrasive flow rate were maintained to a constant value of 0.04 inches, 0°, 0.125 inches, Garnett 80 mesh, and 1.1 pounds per minute, respectively. In addition, three parameters (water pressure, concrete strength, and cutting time) were varied, as shown in Table 5.2.

Table 5.2 AWJ input paraments

Constants		Variables	
Nozzle diameter	0.04 inch	Compressive strength of concrete f'c	5,460, 5,880, 7,683, 8,660, 10,077 psi
Nozzle angle	0°		
Stand-off distance	0.125 inch	Water Pressure P	10, 12.5, 15, 17.5 ksi
Abrasive grain size	Garnett 80 mesh		
Abrasive flow rate	1.1 lb/min	Cutting Time T	1, 1.5, 2 min.

The water jet cutting for the concrete specimens included 24 penetration points and one line for each compressive strength batch. Each penetration point was tested twice under a different pressure, 10, 12.5, 15, and 17.5 ksi, for a preset amount of time. The penetration depth was then measured at the end of the preset time. After that, one specified pressure was used to cut a line, for which the cutting time, cutting depth, and cutting width of the line were measured. The experiment procedure steps of the water jet cutting are as follows:

1. Set up the water jet machine, including the nozzle diameter, nozzle angle, stand-off distance, abrasive type, and abrasive flow rate.
2. Submerge the concrete specimens in the water tank at depth of 4 inches below the water line. The specimens were pre-soaked prior to immersion to inhibit absorption of the water from the tank (See Figure 5.9).

Figure 5.9 Submerging the concrete slabs

3. Prepare the timer and the datasheet to take the results.
4. Set the water pressure at 10 ksi.
5. Point the jet nozzle above the first marked penetration point for specified time (e.g., 1 minute) then measure the penetration depth (see Figures 5.10 and 5.11).

Figure 5.10 Penetration point cutting

Figure 5.11 Measuring the penetration cutting depth

6. Repeat step (5) for second marked penetration point.
7. Repeat steps (5 & 6) for 1.5 minutes and 2 minutes, sequentially.
8. Reset water pressure to 12.5 ksi, 15 ksi, and 17.5 ksi. Repeat steps from 5 to 7.
9. Reset the water jet machine based on pressure (17.5 ksi) and cut a line. Then measure the width and depth of cutting (see Figure 5.12).

Figure 5.12 Measuring the line's cutting depth

10. Remove the concrete specimen and clean the machine.
11. Repeat Steps from (1) to (10) for the other concrete specimen strengths.

5.3.4 Experimental Results

For the AWJ cutting, Table 5.3 shows the experimental results of cutting lines; Table 5.4 shows a sample of the experimental results of the penetration points for the concrete strength 5,460 psi. The complete tabulated results are presented in Appendix C.

Table 5.3 Line cutting experimental results

Compressive Strength (164) days (psi)	Water pressure (ksi)	Time (minute)	Line Width (inch)	Line length (inch)	Cutting depth (inch)		
					point (1)	Point (2)	point (3)
5,460	17.5	17	0.058	8	3.549	2.95	3.402
5,880	17.5	16.75	0.058	8	3.953	3.648	4.314
7,683	17.5	19.4	0.058	8	3.268	2.155	3.004
8,660	17.5	17.43	0.058	8	3.699	3.189	3.769
10,077	17.5	18.08	0.058	8	2.722	2.266	2.595

Table 5.4 Sample experimental results of penetration point testing for concrete strength 5,460 psi

Exp. #	Compressive strength (psi)	Water pressure (ksi)	Cutting time (minutes)	Cutting depth (inch)
1	5,460	10	1	2.084
2	5,460	10	1	1.978
3	5,460	10	1.5	1.621
4	5,460	10	1.5	1.753
5	5,460	10	2	2.731
6	5,460	10	2	2.506
7	5,460	12.5	1	1.147
8	5,460	12.5	1	2.366
9	5,460	12.5	1.5	2.888
10	5,460	12.5	1.5	2.976
11	5,460	12.5	2	3.104
12	5,460	12.5	2	3.184
13	5,460	15	1	2.184
14	5,460	15	1	1.338
15	5,460	15	1.5	3.518
16	5,460	15	1.5	3.621
17	5,460	15	2	2.361
18	5,460	15	2	3.909
19	5,460	17.5	1	3.872
20	5,460	17.5	1	3.1495
21	5,460	17.5	1.5	3.4605
22	5,460	17.5	1.5	4.1295
23	5,460	17.5	2	3.8965
24	5,460	17.5	2	4.5815

5.4 Experimental Setup, Procedure & Results

This section presents the statistical methods used for this study, including the parametric analysis, ANOVA analysis, and regression model. Five constant input parameters are analyzed: nozzle diameter, nozzle angle, stand-off distance, abrasive grain size, and abrasive flow rate. Additionally, three input variables, water pressure, concrete strength, and cutting time, are measured with the corresponding cutting depth. Furthermore, the effect of each input variable of AWJ is analyzed using parametric analysis, ANOVA, regression analysis, and empirical predictive models are done to show the AWJ's statistical significance for the optimum prediction of the cutting process. Finally, a model validation process is developed to verify the predictive models' results with experimental data.

5.4.1 Statistical Analysis of the Line Cutting

Five 8-inch lines are cut to a target 3-inch depth using 17.5 ksi water pressure. One line cutting was done for each concrete strength. The measured results from the experiments are the cutting depth, cutting width, and time to cut across the specimen. The resulting cut is deeper at the edges and shallower in the middle of the slab resulting in a cutting line cutting that has a curved shape. Therefore, the average depth was obtained by taking three measurement points at the right edge, middle, and left edge of the slab. The results of those measurements are shown in Table 5.3. These experimental measurements were used to determine the removal material volume per cubic inch. The values were divided by the cutting time to get the material removal rate as a volume per time, as shown in Table 5.5.

Table 5.5 Material removal rates

#	Average compressive strength (psi)	Cutting time (minute)	Material removal volume ($inch^3$)	Material removal rate ($inch^3$/minute)
1	5,460	17	1.450	0.085
2	5,880	16.75	1.792	0.107
3	7,683	19.4	1.152	0.059
4	8660	17.43	1.564	0.090
5	10,077	18.08	1.112	0.061

In general, there is a decreasing trend in the removal material rate with the increase of the concrete strength. Concrete slabs 2, 4, and 5 show that the material removal rate has a negative relationship to the concrete strength, which means that with higher concrete strength the removal rate is less. For example, the removal rate of concrete strength 5,141 psi is 0.107 $inch^3$/minute while it equals 0.061 in concrete strength 8,811 psi. However, slabs 1 and 3 are not aligned with the general trend due to the heterogeneity of the concrete mixing (compressive strength variability) as well as the limited number of specimens that were tested due to financial restraints. These results are as expected and align with previous studies that show that as material strength increases, the cutting time increases (Karakurt et al. 2012; Liu et al. 2019; Momber 2011). The material removal rate is normalized to the compressive strength of concrete and the results are shown in Figure 5.13. Using the equation of the line from Figure 5.13 and a known concrete compressive strength, the removal time of concrete can be predicted.

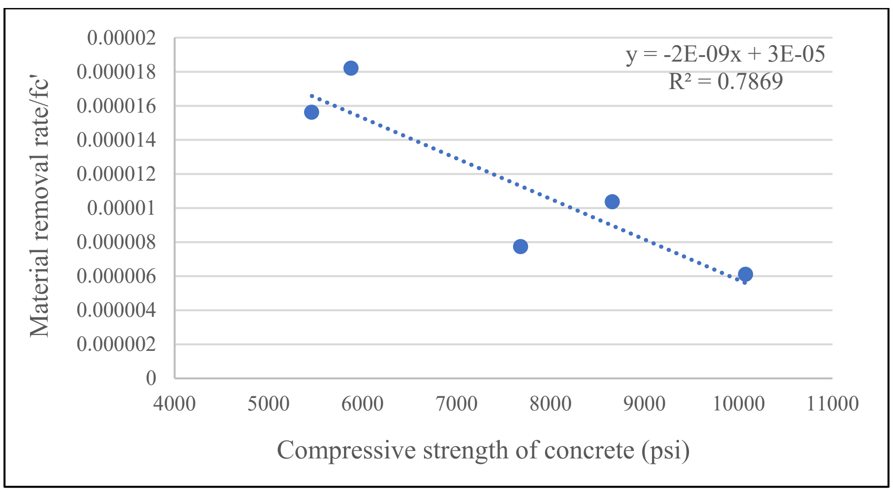


Figure 5.13 Normalization of the material removal rate

The uncertainty associated with the compressive strength of concrete was quantified by calculating the upper and lower limits at a 95% confidence interval, as shown in Table 5.6. Then, the percentage of the uncertainty was considered for the material removal rate of concrete, as shown in Table 5.7.

Table 5.6 The uncertainty of the compressive strength of concrete

Average compressive strength (psi)	Standard deviation	Confidence level	Z	Upper limit	Lower limit
5,460	645	95%	1.96	6025	5282
5,880	782	95%	1.96	6565	5754
7,683	953	95%	1.96	8519	7467
8,660	613	95%	1.96	9197	8062
10,077	1027	95%	1.96	10977	9622

Table 5.7 Material removal of AWJ cutting

Material removal rate (inch^3/minute)	Upper limit	Lower limit
0.085	0.094	0.082
0.107	0.119	0.105
0.059	0.066	0.058
0.090	0.095	0.084
0.061	0.067	0.059

5.4.2 Statistical analysis of the penetration points

5.4.2.1 Parametric analysis

All penetration point experiments are performed twice under the same conditions in terms of compressive strength, cutting time, and cutting pressure. The average cutting depth of the two experiments is taken and compared with the AWJ input variables such as water jet pressure, cutting time, and penetration depth for the five different concrete strengths. For each concrete strength, the relationship between the average penetration depth and water pressure is illustrated for the three different penetration times (1, 1.5, and 2 minutes). These results are shown in Figure 5.14.

In general, the experimental results show that the increase in the water pressure is associated with an increase in the cutting depth for any concrete strength and for any penetration time. For example, when AWJ is run for 1 minute on a concrete strength of 4,774 psi at a pressure of 10 ksi, the resulting cutting depth is 2.03 inches. It increases to 4.24 inches at a pressure of 17.5 ksi. Another example, concrete strength of 5,141 psi, at 2 minutes the depth is gradually increasing with the increase of the water pressure, as shown in Figure 5.14. Furthermore, Figure 5.14 describes the relationship between the cutting time and depth at the same water pressure. The cutting depth showed an increasing trend with the increasing of time. For example, cutting concrete strength 7,572 psi, using a pressure of 10 ksi gave a cutting depth of 1.64 inches at 1 minute, 1.86 inches at 1.5 minutes, and 2.01 inches at 2 minutes. Similarly, the cutting depth of concrete strength 8,811 psi impacted by a water pressure of 15 ksi measured 1.94, 2.82, and 3.33 inches at 1, 1.5, and 2 minutes, respectively. Overall, it was determined that both the water pressure and the cutting time have significant effects on increasing the rate of the cutting depth of the concrete for any compressive strength. This is aligned with previous research studies, such as Ojmertz's study, which stated that the tolerance of the cutting depth increases linearly with the increase of water pressure (Ojmertz 1993).

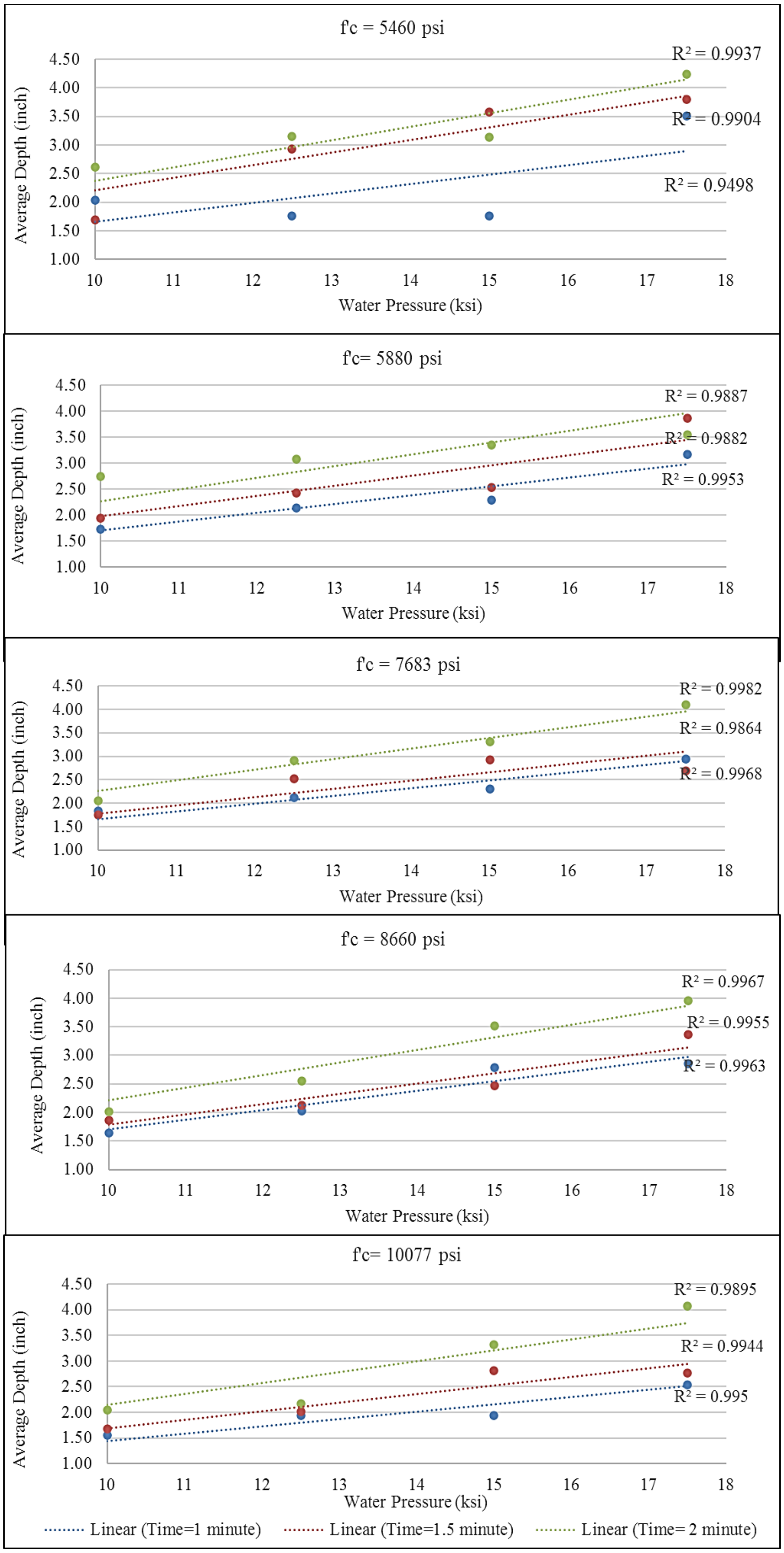


Figure 5.14 The input effect of the input parameters on the cutting depth of concrete

5.4.2.2 Regression analysis

This research also carried out regression analysis on the results of the penetration experiments. Regression analysis is a statistical analysis consisting of the determination of the inter-relationships between the variables. Regression analysis is one of the most widely employed methods to fit a line or a curve to datasets that belong to variables that are in statistically significant linear and non-linear correlations. The value of a dependent variable can be predicted for any value of an independent variable by using the regression model fitted (Atici and Ersoy 2009). In this study, the effect of the different variables compressive strength of the concrete, water pressure, and cutting time on the cutting depth of the concrete was determined by developing empirical models to predict the concrete cutting depth. The models include linear and non-linear empirical equations where the cutting depth D is considered as the dependent variable and the compressive strength of concrete f'c, the cutting time T, and water pressure P are the independent variables. The square root of the compressive strength was also considered, as many of the inter-relationships of the mechanical properties of concrete (e.g., modulus of elasticity) have been shown to be related by the square root of the compressive strength. The developed empirical equations are listed in Equations 5.1 to Equations 5.4.

$$D_1\ (inch) = a_1 * f'c\ (psi) + a_2 * P(ksi) + a_3 * T(min.) \qquad Eq. 5.1$$

$$D_2\ (inch) = a_1 * \sqrt{f'c}\,(psi) + a_2 * P(ksi) + a_3 * T(min.) \qquad Eq. 5.2$$

$$D_3\ (inch) = a_1 * f'c\ (psi) + a_2 * P^2(ksi) + a_3 * T(min.) \qquad Eq. 5.3$$

$$D_4\ (inch) = a_1 * \sqrt{f'c}\,(psi) + a_2 * P^2(ksi) + a_3 * T(min.) \qquad Eq. 5.4$$

Where: D is the removal depth, f'c is the compressive strength of concrete, P is water pressure, and T is time.

However, before using any of those models, the constants (a1, a2, and a3) in the models need to be determined. For this purpose, the multiple regression analysis was performed using the R software version 4.2.1 and the experimental results from Table 5.4. Substituting these constants into the equations results in Equations 5.5 through 5.8.

$$D_1 = -1.13 * 10^{-4} f'c + 0.174\,P + 0.744\,T \qquad Eq. (5.5)$$

$$D_2 = -0.0149\sqrt{fc} + 0.193\,P + 0.844\,T \qquad Eq. (5.6)$$

$$D_3 = -0.00335\sqrt{fc} + 0.075 * P^2 + 0.965\,T \qquad Eq. (5.7)$$

$$D_4 = -0.016\,\sqrt{f'c} + 0.007\,P^2 + 0.849\,T \qquad Eq. (5.8)$$

Equations 5.5 to 5.8 for cutting depth show that the parameter of the compressive strength of concrete (f'c) poses positive effects while the other two parameters, the water pressure P and the cutting time T, both pose negative effects.

5.4.2.3 ANOVA analysis

The statistical method of analysis of variance (ANOVA) is used to study the influence of each input variable on the cutting depth of the concrete. The factors that influence statistical significance and model adequacies developed are tested for the preset 95% confidence level. In ANOVA, Fisher's statistical test

(F ratio) and statistical probability (P-value) are used to determine the most influencing parameters and the statistical significance toward response variables, respectively (Gupta 2020). A larger F-statistic value of a parameter dictates the most significant parameter, while the P value ($P < 0.5$) determines the parameter that is statistically significant (Azmir et al. 2009). Three parameters were investigated—concrete compressive strength, AWJ water pressure, and cutting time—to see their impact on the cutting depth. The F value was calculated for each parameter. The ANOVA analysis was carried out using R software version 4.2.1 and the ANOVA results are presented in Table 5.8.

Table 5.8 ANOVA results for the cutting depth model

	Df	Sum Sq	Mean Sq	F-value	P-value
Model 1					
Strength of concrete f'c	1	2.48	2.48	13.89	0.0003
Water Pressure P	1	35.38	35.38	198.29	< 2e-16
Time	1	14.42	14.42	80.84	5.46E-15
Residuals	116	20.7	0.18		
Model 2					
Sqr. Strength of concrete $f'c^{0.5}$	1	2.47	2.47	13.81	0.00031
Water Pressure P	1	35.38	35.38	198.18	< 2e-16
Time	1	14.42	14.42	80.79	5.53E-15
Residuals	116	20.71	0.18		
Model 3					
Strength of concrete f'c	1	2.48	2.48	14.05	0.00028
Sq. Water Pressure P^2	1	35.62	35.62	201.99	2.00E-16
Time	1	14.42	14.42	81.79	4.11E-15
Residuals	116	20.46	0.18		
Model 4					
Sqr. Strength of concrete $f'c^{0.5}$	1	2.47	2.47	13.97	0.00029
Sq. Water Pressure P^2	1	35.62	35.62	201.87	< 2e-16
Time	1	14.42	14.42	81.87	4.17E-15
Residuals	116	20.47	0.18		

The ANOVA results show that the four models are statistically significant at the 95% confidence level and the effects of the parameters for all models demonstrate a similar trend. According to F-value and P-value, the water pressure emerges as the most influencing input parameter, followed by cutting time and strength of concrete. For example, in Model 1, the F-value of water pressure is 198.29, cutting time is 80.84, and compressive strength of concrete is 13.89. Also, the P-value is less than 0.001 for the three parameters, as shown in Table 5.8. This agrees with previous studies that show water pressure has a very high impact on the AWJ cutting process compared with other parameters (Llanto et al. 2021). Therefore, changing the water pressure will have the greatest effect on the concrete's removal rate.

5.4.2.4 Validation of the Models

A quantitative assessment to validate the predictive models was carried out by direct comparison between the models' cutting depth results to experimental results. The validation process was conducted using two main criteria: the coefficient of the models' R^2 value and the residuals. Figure 5.15 presents the predicted cutting depth of the concrete derived from the models versus the experimental values of cutting depth. The R^2 values for the four models are equal to 97%, which indicates that the presented models fit the data and can give an adequate prediction of the cutting depth of concrete within the conditions tested in this study.

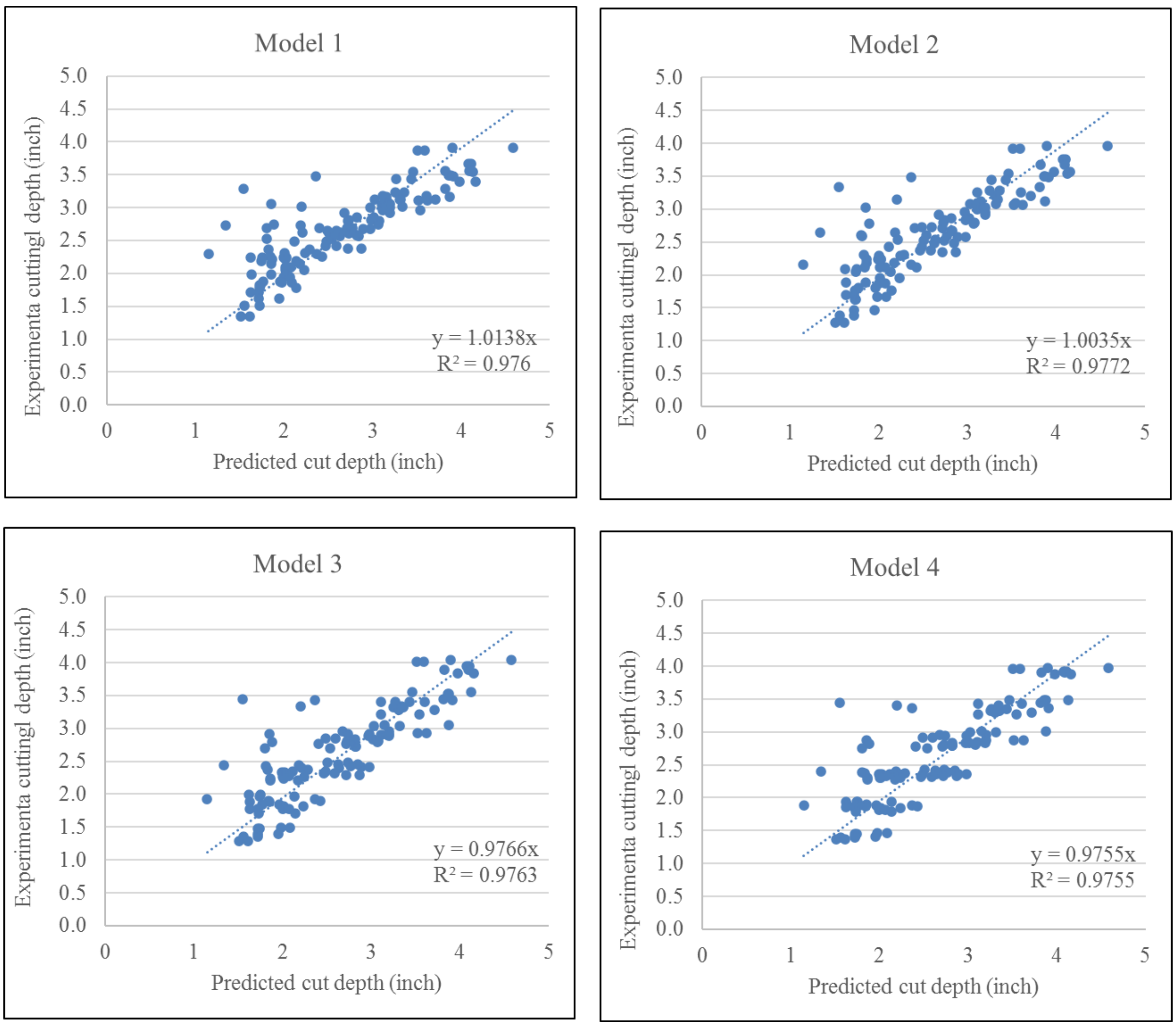


Figure 5.15 Predicted cutting depth versus the experimental cutting depth

Another validation method used for checking the models was the residual, which is the difference between an observed value and the predicted value. This technique presents a better test, providing a very effective means of detecting abnormal behavior in the residuals. Figure 5.16 shows that the residuals are randomly scattered around the line, which means that the residuals do not have a bias with constant variance.

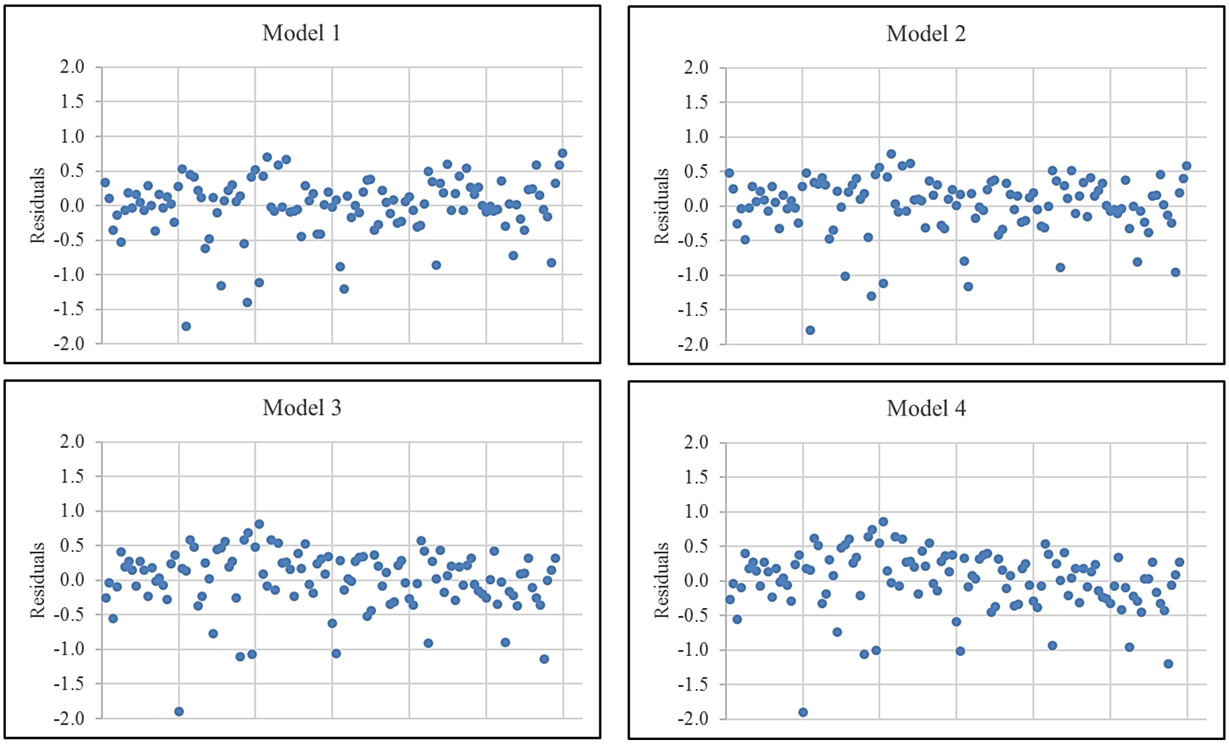


Figure 5.16 Residuals of the models

5.5 Conclusion

In this chapter, the hydro-demolition technique used for partial-depth bridge deck repair is investigated to eliminate the occurrence of the punch-through problem and identify its influence parameters. The investigation is carried out by lab experiments and statistical analysis. The experimental study finds that water pressure, cutting time, and compressive strength of concrete influence the cutting depth of the water jet. The statistical analysis provides a multi-regression model that can be employed for the prediction and optimization of response parameters of the hydro-demolition technique. Finally, it is concluded that the punch-through problem can be eliminated and the water jet cutting depth can be controlled by knowing and controlling the process parameters, such as the given water pressure, cutting time, and compressive strength of the deteriorated concrete.

6. SUMMARY, CONCLUSIONS, AND FUTURE WORKS

6.1 Summary & Conclusions

This study investigates different concrete removal methods used for partial-depth bridge deck repair to decrease traffic closure time due to the preparation process for partial-depth replacement, improve the efficiency of the concrete removal methods, and evaluate the life cycle sustainability of those techniques. The study evaluates the techniques that are currently used and identifies the saw and patch method, chip and patch method, mill and patch, and water-blast and patch method (hydro-demolition) as some commonly utilized methods for concrete removal; as well as the advantages and disadvantages of using each technique. The initial interest of this research starts with focusing on the environmental impacts of the different concrete removal techniques used for partial-depth repair (PDR) of bridge decks. The environmental study identifies a significant factor, the required time to remove the concrete using each method, which needs to be considered. The study noted that the most used method, saw and patch, is the slowest while the newest used method, hydro-demolition, is the fastest. In light of this result, this research further investigated those two methods. This leads to three main points that warrant consideration: 1) The saw and patch is the most commonly used method due to its advantages compared with other methods; however, this method is very time-consuming and labor-intensive compared with the other methods. 2) The hydro-demolition technique has competitive operational advantages over the other methods; however, using hydro-demolition for partial-depth bridge deck repair can result in a " punch-through" problem, which occurs when the high-pressure water causes a hole through the entire depth of the bridge deck. 3) The environmental impact of using these methods has not been studied yet.

To investigate the environmental impact of each removal method, a comparative study of the different concrete removal methods is conducted to identify the least environmentally impactful removal technique for partial-depth bridge deck repair. The methods are evaluated from an environmental perspective by estimating the air pollutant emission emitted by each method. Five-air pollutant emissions, CO_2, CO, NOx, SO_2, and PM10, are estimated utilizing the MOVES2014b and GREET models. The results showed that the milling technique produced the largest amount of emissions. The chipping method generated the lowest amount of emissions. CO_2 is produced in large quantities among all techniques while SO_2 is the smallest compared with other emissions. Additionally, the results indicate that the amount of air emissions increase relative to the utilization time of the removal technique. The values for emissions per cubic foot can also be used to estimate emissions for larger projects for which environmental offsets can be made. Also note that the estimated removal times can help transportation officials determine the best methods, as the goal in partial-depth replacement is typically to re-open the travel lanes to traffic as soon as possible. The results of the study are significant in that they can be used to help state and local transportation officials develop removal standards that include sustainable practices.

To expedite the concrete removal time and decrease traffic closure time due to the preparation process when the saw and patch method is used, an experimental study was carried out. This study evaluated four different discretized sawing and jackhammering methods in terms of removal time, equipment usage, and damage to the surrounding concrete area. The impacts of utilizing this removal equipment on the soundness of the concrete surrounding the patch area are also evaluated. The performance of the removal methods is evaluated in terms of the patch preparation time, which directly correlates to the bridge traffic closure time. This study concludes that increasing the saw cutting lines decrease the jackhammering time for the different concrete strengths and increases the concrete removal volume. The saw and patch method can be influenced by many factors, such as the operator's skills and health/energy level, saw blade sharpness, and jackhammer pull-off angle. Method IV, which has the largest number of saw-cut lines, is the optimal concrete removal method among the other proposed methods and saves approximately 35% of the required concrete removal time. It also has the potential to be automated in the future.

Finally, the hydro-demolition technique, used for the partial-depth bridge deck repair. is investigated with the objective to eliminate the occurrence of the punch-through problem. Experimental and statistical analyses are performed to analyze the impacts of high-pressure water on concrete as part of the PDR of a concrete bridge deck. Small-scale trials of 15 concrete specimens with varying compressive strengths are tested. Statistical analysis for the experimental data of abrasive water jet on concrete with different compressive strengths is then carried out to develop a predictive model for determining the input parameters to accurately predict concrete removal to a specified depth. The experimental study finds that the water pressure, cutting time, and compressive strength of concrete influence the water jet cutting depth. The statistical analysis provides a multi-regression model that can be employed for the prediction and optimization of response parameters of the hydro-demolition technique. The results of this study can provide a better understating of the controllability and efficiency of using the hydro-demolition technique for partial-depth concrete bridge deck removal.

6.2 Recommendation for Future Works

Based on the findings of this research, several future research projects can be conducted. In this research, the environmental impacts of using the PDR method are considered for one project and one-time bridge deck repair. Furthermore, the study covers only the environmental impacts on air quality by estimating emissions of five air pollutants. This can be extended to include all repair times during the entire life cycle of the bridge deck, and the environmental impacts on water quality as well.

The experimental study of the different discretized sawing and jackhammering methods is only carried out for four small-scale concrete slabs, and one operator did all the removal work. The study's research results could be expanded for large-scale concrete slabs and using the average values of multiple operators. Additionally, the optimal sawing and jackhammering method has also shown the potential to be automated. Automating this method will be a remarkable forward step in the PDR procedure and will save a lot of labor efforts and traffic closure time.

Regarding hydro-demolition, several influence parameters have effects on the occurrence of the punch-through problem. This study observes the impacts of three of those parameters: water jet pressure, cutting time, and the compressive strength of nonreinforced concrete. Considering other input variables such as nozzle diameter and stand-off distance will provide a better understanding of the effects of the entire hydro-demolition process and its influence parameters. In addition, using some advanced non-destructive concrete testing techniques will help track the concrete behavior and analyze the concrete failure that causes the punch-through.

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APPENDIX A

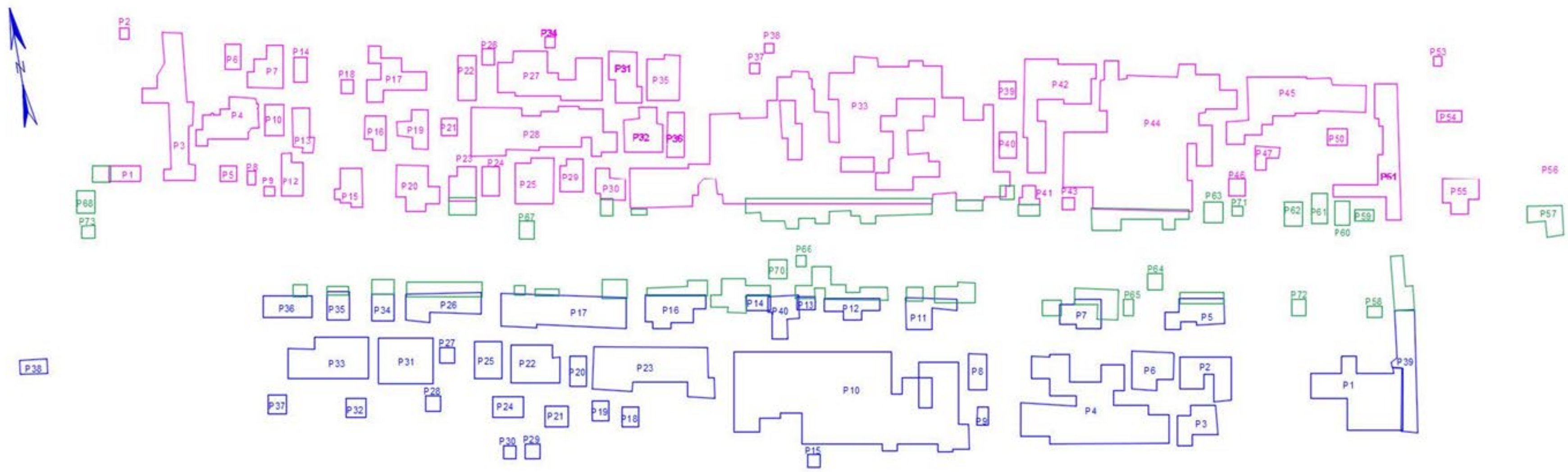

Figure A.1: Map of the Repair patches (Phase 1: Blue, Phase 2: Green, Phase 3: Magenta)

Table A.1: Summery of the repair patches.

Phase 1				Phase 2				Phase 3			
Repair	Area (ft^2)	Average Depth (in)	Volume (ft^3)	Repair	Area (ft^2)	Average Depth (in)	Volume (ft^3)	Repair	Area (ft^2)	Average Depth (in)	Volume (ft^3)
1	16.33	3.5	4.76	57	16.52	3.5	4.82	1	91.93	3	22.98
2	2.11	2	0.35	58	3.43	2.5	0.71	2	36.22	3	9.06
3	75.98	3.5	22.16	59	4.38	3	1.10	3	23.85	2.5	4.97
4	34.14	3.75	10.67	60	9.75	3	2.44	4	163.75	3.5	47.76
5	5.63	4	1.88	61	9.88	3	2.47	5	28.72	3.5	8.38
6	7.88	3.5	2.30	62	9.11	3	2.28	6	29.17	3	7.29
7	24.14	4	8.05	63	7.8	2.5	1.63	7	22.57	3.5	6.58
8	2.6	4	0.87	64	5.06	3	1.27	8	13.67	3	3.42
9	2.11	3	0.53	65	4.38	2.5	0.91	9	4.06	3.75	1.27
10	12.51	3.5	3.65	66	2.24	2.5	0.47	10	380.76	3.25	103.12
11	0	0	0.00	67	5.42	3	1.36	11	22.73	3	5.68
12	18.81	4	6.27	68	8.67	3	2.17	12	18.6	3	4.65
13	15.14	3.5	4.42	70	7.33	2.5	1.53	13	5.04	3	1.26
14	6.71	3	1.68	71	2.24	2	0.37	14	7.76	3	1.94
15	18.06	3.5	5.27	72	5.04	2.5	1.05	15	3.67	2.5	0.76
16	12.65	3.5	3.69	P1-1	6.45	2.5	1.34	16	33.06	4	11.02
17	35.32	3.5	10.30	P1-23	9.87	3.25	2.67	17	79.53	4	26.51
18	3.5	3	0.88	P1-30	4.4	2.5	0.92	18	7.2	4	2.40
19	18.59	4	6.20	P1-33a	2.22	3	0.56	19	6.85	4	2.28
20	32.05	3.75	10.02	P1-33b	63.03	3.5	18.38	20	10.42	3.5	3.04
21	5.44	3.5	1.59	P1-33c	3.99	3.5	1.16	21	10.21	3.25	2.77
22	17.65	3.5	5.15	P1-33d	4	3	1.00	22	36.73	3.25	9.95
23	18.58	4	6.19	P1-41	5.02	3	1.26	23	100.38	3.25	27.19
24	10.63	4	3.54	P1-44	29.16	3	7.29	24	13.5	3.5	3.94
25	36.02	3.5	10.51	P3-11a	15.4	3	3.85	25	21.27	2.5	4.43
26	4.08	3.5	1.19	P3-11b	4.81	3	1.20	26	34.63	4	11.54
27	76.68	2.75	17.57	P2-12	27.53	3	6.88	27	4.69	3.5	1.37
28	118.92	4	39.64	P2-14	23.1	3	5.78	28	4.78	4	1.59
29	14.72	3.5	4.29	P3-16	13.98	3	3.50	29	4.51	2	0.75
30	16.49	4	5.50	P3-17a	8.86	2.5	1.85	30	3.51	2	0.59
31	27.93	3.5	8.15	P3-17b	3.5	3	0.88	31	54	3	13.50
32	30.47	3.5	8.89	P3-17c	2.25	3.25	0.61	32	7.44	3	1.86
33	613.75	3	153.44	P3-26	22.17	3	5.54	33	62.49	3.75	19.53
34	2.5	2	0.42	P3-34	6.5	3	1.63	34	12.46	4.25	4.41
35	29.54	3	7.39	P3-35	3.79	3	0.95	35	13.44	4	4.48
36	15.57	3.75	4.87	P3-36	3.8	2.5	0.79	36	22.43	4	7.48
37	0	0	0.00	P3-39	16.69	4	5.56	37	7.79	3.75	2.43
38	0	0	0.00	P3-5	9.75	2.5	2.03	38	9.28	4	3.09
39	6.04	3	1.51	P3-7a	20.68	3	5.17	39	38.97	5.25	17.05
40	9.68	3	2.42	P3-7b	5.96	2.5	1.24	40	20.82	3.5	6.07
41	6.37	2.5	1.33	73	3.56	2.5	0.74				
42	81.1	3	20.28								
43	3.2	2.5	0.67								
44	335.35	3	83.84								
45	92.4	3	23.10								
46	6.05	3	1.51								
47	8.45	3	2.11								
48	0	0	0.00								
49	0	0	0.00								
50	7.2	3	1.80								
51	70.47	5	29.36								
52	0	0	0.00								
53	1.56	2	0.26								
54	6.25	2.5	1.30								
55	21.99	3	5.50								
56	12.5	3.5	3.65								

APPENDIX B

Repair patech				Method I (4 saw cutting)			Method II (6 saw cutting)			Method III (8 saw cutting)			Method IV (10 saw cutting)		
Repair Patch #	Area (ft2)	L (ft)	Volume (ft3)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)
1	16.33	8.17	4.76	29.72	141.13	170.85	44.58	113.15	157.73	59.44	94.25	153.69	74.30	33.32	107.62
2	2.11	1.06	0.35	3.84	10.38	14.22	5.76	8.32	14.08	7.68	6.93	14.61	9.60	2.45	12.05
3	75.98	37.99	22.16	138.28	657.04	795.33	207.43	526.74	734.17	276.57	438.77	715.34	345.71	155.12	500.83
4	34.14	17.07	10.67	62.13	316.37	378.50	93.20	253.63	346.83	124.27	211.27	335.54	155.34	74.69	230.03
5	5.63	2.82	1.88	10.25	55.74	65.99	15.37	44.69	60.06	20.49	37.22	57.72	25.62	13.16	38.78
6	7.88	3.94	2.30	14.34	68.20	82.54	21.51	54.67	76.18	28.68	45.54	74.22	35.85	16.10	51.95
7	24.14	12.07	8.05	43.93	238.68	282.62	65.90	191.35	257.25	87.87	159.39	247.26	109.84	56.35	166.19
8	2.60	1.30	0.87	4.73	25.80	30.53	7.10	20.68	27.78	9.46	17.23	26.69	11.83	6.09	17.92
9	2.11	1.06	0.53	3.84	15.71	19.55	5.76	12.60	18.36	7.68	10.49	18.17	9.60	3.71	13.31
10	12.51	6.26	3.65	22.77	108.22	130.99	34.15	86.76	120.91	45.54	72.27	117.81	56.92	25.55	82.47
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	18.81	9.41	6.27	34.23	185.91	220.14	51.35	149.04	200.39	68.47	124.15	192.61	85.59	43.89	129.48
13	15.14	7.57	4.42	27.55	131.05	158.61	41.33	105.06	146.40	55.11	87.52	142.63	68.89	30.94	99.83
14	6.71	3.36	1.68	12.21	49.81	62.02	18.32	39.93	58.25	24.42	33.26	57.69	30.53	11.76	42.29
15	18.06	9.03	5.27	32.87	156.26	189.12	49.30	125.27	174.57	65.74	104.35	170.08	82.17	36.89	119.06
16	12.65	6.33	3.69	23.02	109.41	132.43	34.53	87.71	122.25	46.05	73.06	119.11	57.56	25.83	83.39
17	35.32	17.66	10.30	64.28	305.40	369.68	96.42	244.83	341.25	128.56	203.94	332.50	160.71	72.10	232.81
18	3.50	1.75	0.88	6.37	26.09	32.46	9.56	20.92	30.47	12.74	17.42	30.16	15.93	6.16	22.09
19	18.59	9.30	6.20	33.83	183.83	217.66	50.75	147.37	198.12	67.67	122.76	190.43	84.58	43.40	127.98
20	32.05	16.03	10.02	58.33	297.09	355.42	87.50	238.18	325.67	116.66	198.40	315.06	145.83	70.14	215.97
21	5.44	2.72	1.59	9.90	47.14	57.04	14.85	37.79	52.65	19.80	31.48	51.28	24.75	11.13	35.88
22	17.65	8.83	5.15	32.12	152.70	184.82	48.18	122.42	170.60	64.25	101.97	166.22	80.31	36.05	116.36
23	18.58	9.29	6.19	33.82	183.53	217.35	50.72	147.14	197.86	67.63	122.56	190.19	84.54	43.33	127.87
24	10.63	5.32	3.54	19.35	104.96	124.31	29.02	84.15	113.17	38.69	70.09	108.79	48.37	24.78	73.15
25	36.02	18.01	10.51	65.56	311.62	377.18	98.33	249.82	348.16	131.11	208.10	339.21	163.89	73.57	237.46
26	4.08	2.04	1.19	7.43	35.28	42.71	11.14	28.29	39.42	14.85	23.56	38.41	18.56	8.33	26.89
27	76.68	38.34	17.57	139.56	520.95	660.51	209.34	417.64	626.98	279.12	347.89	627.00	348.89	122.99	471.88
28	118.92	59.46	39.64	216.43	1175.33	1391.76	324.65	942.24	1266.89	432.87	784.87	1217.74	541.09	277.48	818.57
29	14.72	7.36	4.29	26.79	127.20	153.99	40.19	101.97	142.16	53.58	84.94	138.52	66.98	30.03	97.01
30	16.49	8.25	5.50	30.01	163.08	193.09	45.02	130.74	175.75	60.02	108.90	168.92	75.03	38.50	113.53
31	27.93	13.97	8.15	50.83	241.65	292.48	76.25	193.73	269.97	101.67	161.37	263.04	127.08	57.05	184.13
32	30.47	15.24	8.89	55.46	263.59	319.04	83.18	211.32	294.50	110.91	176.02	286.93	138.64	62.23	200.87
33	613.75	306.88	153.44	1117.03	4549.50	5666.52	1675.54	3647.27	5322.81	2234.05	3038.11	5272.16	2792.56	1074.08	3866.64
34	2.50	1.25	0.42	4.55	12.45	17.00	6.83	9.98	16.81	9.10	8.32	17.42	11.38	2.94	14.32
35	29.54	14.77	7.39	53.76	219.11	272.88	80.64	175.66	256.30	107.53	146.32	253.85	134.41	51.73	186.14
36	15.57	7.79	4.87	28.34	144.40	172.73	42.51	115.76	158.27	56.67	96.43	153.10	70.84	34.09	104.93
37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	6.04	3.02	1.51	10.99	44.77	55.76	16.49	35.89	52.38	21.99	29.90	51.88	27.48	10.57	38.05
40	9.68	4.84	2.42	17.62	71.75	89.37	26.43	57.52	83.95	35.24	47.92	83.15	44.04	16.94	60.98
41	6.37	3.19	1.33	11.59	39.43	51.03	17.39	31.61	49.00	23.19	26.33	49.52	28.98	9.31	38.29
42	81.10	40.55	20.28	147.60	601.30	748.90	221.40	482.06	703.46	295.20	401.54	696.75	369.01	141.96	510.97
43	3.20	1.60	0.67	5.82	19.87	25.69	8.74	15.93	24.66	11.65	13.27	24.91	14.56	4.69	19.25
44	335.35	167.68	83.84	610.34	2485.86	3096.19	915.51	1992.88	2908.38	1220.67	1660.03	2880.71	1525.84	586.88	2112.72
45	92.40	46.20	23.10	168.17	684.92	853.08	252.25	549.09	801.34	336.34	457.38	793.72	420.42	161.70	582.12
46	6.05	3.03	1.51	11.01	44.77	55.78	16.52	35.89	52.41	22.02	29.90	51.92	27.53	10.57	38.10
47	8.45	4.23	2.11	15.38	62.56	77.94	23.07	50.15	73.22	30.76	41.78	72.54	38.45	14.77	53.22
48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	7.20	3.60	1.80	13.10	53.37	66.47	19.66	42.79	62.44	26.21	35.64	61.85	32.76	12.60	45.36
51	70.47	35.24	29.36	128.26	870.52	998.78	192.38	697.89	890.27	256.51	581.33	837.84	320.64	205.52	526.16
52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
53	1.56	0.78	0.26	2.84	7.71	10.55	4.26	6.18	10.44	5.68	5.15	10.83	7.10	1.82	8.92
54	6.25	3.13	1.30	11.38	38.55	49.92	17.06	30.90	47.96	22.75	25.74	48.49	28.44	9.10	37.54
55	21.99	11.00	5.50	40.02	163.08	203.10	60.03	130.74	190.77	80.04	108.90	188.94	100.05	38.50	138.55
56	12.50	6.25	3.65	22.75	108.22	130.97	34.13	86.76	120.89	45.50	72.27	117.77	56.88	25.55	82.43
57	16.52	8.26	4.82	30.07	142.91	172.98	45.10	114.57	159.67	60.13	95.44	155.57	75.17	33.74	108.91
58	3.43	1.72	0.71	6.24	21.05	27.29	9.36	16.88	26.24	12.49	14.06	26.54	15.61	4.97	20.58
59	4.38	2.19	1.10	7.97	32.62	40.59	11.96	26.15	38.10	15.94	21.78	37.72	19.93	7.70	27.63
60	9.75	4.88	2.44	17.75	72.35	90.09	26.62	58.00	84.62	35.49	48.31	83.80	44.36	17.08	61.44
61	9.88	4.94	2.47	17.98	73.24	91.22	26.97	58.71	85.68	35.96	48.91	84.87	44.95	17.29	62.24
62	9.11	4.56	2.28	16.58	67.60	84.18	24.87	54.20	79.07	33.16	45.14	78.30	41.45	15.96	57.41
63	7.80	3.90	1.63	14.20	48.33	62.53	21.29	38.75	60.04	28.39	32.27	60.67	35.49	11.41	46.90
64	5.06	2.53	1.27	9.21	37.66	46.86	13.81	30.19	44.00	18.42	25.15	43.56	23.02	8.89	31.91
65	4.38	2.19	0.91	7.97	26.98	34.95	11.96	21.63	33.59	15.94	18.02	33.96	19.93	6.37	26.30
66	2.24	1.12	0.47	4.08	13.94	18.01	6.12	11.17	17.29	8.15	9.31	17.46	10.19	3.29	13.48
67	5.42	2.71	1.36	9.86	40.32	50.19	14.80	32.33	47.12	19.73	26.93	46.66	24.66	9.52	34.18

Repairpatech				Method I (4 saw cutting)			Method II (6 saw cutting)			Method III (8 saw cutting)			Method IV (10 saw cutting)		
Repair Patch #	Area (ft2)	L (ft)	Volume (ft3)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)	Saw cutting time (minute)	Jackhammering time (minute)	Total time (minute)
68	8.67	4.34	2.17	15.78	64.34	80.12	23.67	51.58	75.25	31.56	42.97	74.52	39.45	15.19	54.64
69	7.33	3.67	1.53	13.34	45.36	58.71	20.01	36.37	56.38	26.68	30.29	56.98	33.35	10.71	44.06
70	2.24	1.12	0.37	4.08	10.97	15.05	6.12	8.79	14.91	8.15	7.33	15.48	10.19	2.59	12.78
71	5.04	2.52	1.05	9.17	31.13	40.31	13.76	24.96	38.72	18.35	20.79	39.14	22.93	7.35	30.28
72	6.45	3.23	1.34	11.74	39.73	51.47	17.61	31.85	49.46	23.48	26.53	50.01	29.35	9.38	38.73
73	9.87	4.94	2.67	17.96	79.17	97.13	26.95	63.47	90.41	35.93	52.87	88.79	44.91	18.69	63.60
74	4.40	2.20	0.92	8.01	27.28	35.29	12.01	21.87	33.88	16.02	18.22	34.23	20.02	6.44	26.46
75	2.22	1.11	0.56	4.04	16.60	20.64	6.06	13.31	19.37	8.08	11.09	19.17	10.10	3.92	14.02
76	63.03	31.52	18.38	114.71	544.97	659.68	172.07	436.89	608.96	229.43	363.92	593.35	286.79	128.66	415.45
77	3.99	2.00	1.16	7.26	34.39	41.66	10.89	27.57	38.47	14.52	22.97	37.49	18.15	8.12	26.27
78	4.00	2.00	1.00	7.28	29.65	36.93	10.92	23.77	34.69	14.56	19.80	34.36	18.20	7.00	25.20
79	5.02	2.51	1.26	9.14	37.36	46.50	13.70	29.95	43.65	18.27	24.95	43.22	22.84	8.82	31.66
80	29.16	14.58	7.29	53.07	216.15	269.22	79.61	173.28	252.89	106.14	144.34	250.48	132.68	51.03	183.71
81	15.40	7.70	3.85	28.03	114.15	142.18	42.04	91.51	133.56	56.06	76.23	132.29	70.07	26.95	97.02
82	4.81	2.41	1.20	8.75	35.58	44.33	13.13	28.52	41.66	17.51	23.76	41.27	21.89	8.40	30.29
83	27.53	13.77	6.88	50.10	203.99	254.10	75.16	163.54	238.69	100.21	136.22	236.43	125.26	48.16	173.42
84	23.10	11.55	5.78	42.04	171.38	213.42	63.06	137.39	200.45	84.08	114.44	198.53	105.11	40.46	145.57
85	13.98	6.99	3.50	25.44	103.78	129.22	38.17	83.20	121.36	50.89	69.30	120.19	63.61	24.50	88.11
86	8.86	4.43	1.85	16.13	54.85	70.98	24.19	43.97	68.16	32.25	36.63	68.88	40.31	12.95	53.26
87	3.50	1.75	0.88	6.37	26.09	32.46	9.56	20.92	30.47	12.74	17.42	30.16	15.93	6.16	22.09
88	2.25	1.13	0.61	4.10	18.09	22.18	6.14	14.50	20.64	8.19	12.08	20.27	10.24	4.27	14.51
89	22.17	11.09	5.54	40.35	164.26	204.61	60.52	131.69	192.21	80.70	109.69	190.39	100.87	38.78	139.65
90	6.50	3.25	1.63	11.83	48.33	60.16	17.75	38.75	56.49	23.66	32.27	55.93	29.58	11.41	40.99
91	3.79	1.90	0.95	6.90	28.17	35.07	10.35	22.58	32.93	13.80	18.81	32.61	17.24	6.65	23.89
92	3.80	1.90	0.79	6.92	23.42	30.34	10.37	18.78	29.15	13.83	15.64	29.47	17.29	5.53	22.82
93	16.69	8.35	5.56	30.38	164.85	195.23	45.56	132.16	177.72	60.75	110.09	170.84	75.94	38.92	114.86
94	9.75	4.88	2.03	17.75	60.19	77.93	26.62	48.25	74.87	35.49	40.19	75.68	44.36	14.21	58.57
95	20.68	10.34	5.17	37.64	153.29	190.93	56.46	122.89	179.35	75.28	102.37	177.64	94.09	36.19	130.28
96	5.96	2.98	1.24	10.85	36.77	47.61	16.27	29.47	45.75	21.69	24.55	46.25	27.12	8.68	35.80
97	3.56	1.78	0.74	6.48	21.94	28.42	9.72	17.59	27.31	12.96	14.65	27.61	16.20	5.18	21.38
98	91.93	45.97	22.98	167.31	681.36	848.67	250.97	546.23	797.20	334.63	455.00	789.63	418.28	160.86	579.14
99	36.22	18.11	9.06	65.92	268.63	334.55	98.88	215.36	314.24	131.84	179.39	311.23	164.80	63.42	228.22
100	23.85	11.93	4.97	43.41	147.36	190.77	65.11	118.14	183.25	86.81	98.41	185.22	108.52	34.79	143.31
101	163.75	81.88	47.76	298.03	1416.08	1714.11	447.04	1135.26	1582.29	596.05	945.65	1541.70	745.06	334.32	1079.38
102	28.72	14.36	8.38	52.27	248.47	300.74	78.41	199.19	277.60	104.54	165.92	270.46	130.68	58.66	189.34
103	29.17	14.59	7.29	53.09	216.15	269.24	79.63	173.28	252.92	106.18	144.34	250.52	132.72	51.03	183.75
104	22.57	11.29	6.58	41.08	195.10	236.17	61.62	156.41	218.02	82.15	130.28	212.44	102.69	46.06	148.75
105	13.67	6.84	3.42	24.88	101.40	126.28	37.32	81.29	118.61	49.76	67.72	117.47	62.20	23.94	86.14
106	4.06	2.03	1.27	7.39	37.66	45.04	11.08	30.19	41.27	14.78	25.15	39.92	18.47	8.89	27.36
107	380.76	190.38	103.12	692.98	3057.51	3750.49	1039.47	2451.16	3490.64	1385.97	2041.78	3427.74	1732.46	721.84	2454.30
108	22.73	11.37	5.68	41.37	168.41	209.78	62.05	135.01	197.07	82.74	112.46	195.20	103.42	39.76	143.18
109	18.60	9.30	4.65	33.85	137.87	171.72	50.78	110.53	161.31	67.70	92.07	159.77	84.63	32.55	117.18
110	5.04	2.52	1.26	9.17	37.36	46.53	13.76	29.95	43.71	18.35	24.95	43.29	22.93	8.82	31.75
111	7.76	3.88	1.94	14.12	57.52	71.64	21.18	46.11	67.30	28.25	38.41	66.66	35.31	13.58	48.89
112	3.67	1.84	0.76	6.68	22.53	29.21	10.02	18.07	28.08	13.36	15.05	28.41	16.70	5.32	22.02
113	33.06	16.53	11.02	60.17	326.74	386.91	90.25	261.95	352.20	120.34	218.20	338.53	150.42	77.14	227.56
114	79.53	39.77	26.51	144.74	786.02	930.77	217.12	630.14	847.26	289.49	524.90	814.39	361.86	185.57	547.43
115	7.20	3.60	2.40	13.10	71.16	84.26	19.66	57.05	76.70	26.21	47.52	73.73	32.76	16.80	49.56
116	6.85	3.43	2.28	12.47	67.60	80.07	18.70	54.20	72.90	24.93	45.14	70.08	31.17	15.96	47.13
117	10.42	5.21	3.04	18.96	90.14	109.10	28.45	72.26	100.71	37.93	60.19	98.12	47.41	21.28	68.69
118	10.21	5.11	2.77	18.58	82.13	100.71	27.87	65.84	93.72	37.16	54.85	92.01	46.46	19.39	65.85
119	36.73	18.37	9.95	66.85	295.02	361.87	100.27	236.51	336.78	133.70	197.01	330.71	167.12	69.65	236.77
120	100.38	50.19	27.19	182.69	806.18	988.88	274.04	646.31	920.34	365.38	538.36	903.75	456.73	190.33	647.06
121	13.50	6.75	3.94	24.57	116.82	141.39	36.86	93.65	130.51	49.14	78.01	127.15	61.43	27.58	89.01
122	21.27	10.64	4.43	38.71	131.35	170.06	58.07	105.30	163.37	77.42	87.71	165.14	96.78	31.01	127.79
123	34.63	17.32	11.54	63.03	342.16	405.19	94.54	274.31	368.85	126.05	228.49	354.55	157.57	80.78	238.35
124	4.69	2.35	1.37	8.54	40.62	49.16	12.80	32.56	45.37	17.07	27.13	44.20	21.34	9.59	30.93
125	4.78	2.39	1.59	8.70	47.14	55.84	13.05	37.79	50.84	17.40	31.48	48.88	21.75	11.13	32.88
126	4.51	2.26	0.75	8.21	22.24	30.45	12.31	17.83	30.14	16.42	14.85	31.27	20.52	5.25	25.77
127	3.51	1.76	0.59	6.39	17.49	23.88	9.58	14.02	23.61	12.78	11.68	24.46	15.97	4.13	20.10
128	54.00	27.00	13.50	98.28	400.28	498.56	147.42	320.90	468.32	196.56	267.30	463.86	245.70	94.50	340.20
129	7.44	3.72	1.86	13.54	55.15	68.69	20.31	44.21	64.52	27.08	36.83	63.91	33.85	13.02	46.87
130	62.49	31.25	19.53	113.73	579.06	692.80	170.60	464.23	634.83	227.46	386.69	614.16	284.33	136.71	421.04
131	12.46	6.23	4.41	22.68	130.76	153.43	34.02	104.83	138.84	45.35	87.32	132.67	56.69	30.87	87.56
132	13.44	6.72	4.48	24.46	132.83	157.29	36.69	106.49	143.18	48.92	88.70	137.63	61.15	31.36	92.51
133	22.43	11.22	7.48	40.82	221.78	262.60	61.23	177.80	239.03	81.65	148.10	229.75	102.06	52.36	154.42
134	7.79	3.90	2.43	14.18	72.05	86.23	21.27	57.76	79.03	28.36	48.11	76.47	35.44	17.01	52.45
135	9.28	4.64	3.09	16.89	91.62	108.51	25.33	73.45	98.78	33.78	61.18	94.96	42.22	21.63	63.85
136	38.97	19.49	17.05	70.93	505.53	576.46	106.39	405.28	511.67	141.85	337.59	479.44	177.31	119.35	296.66
137	20.82	10.41	6.07	37.89	179.98	217.87	56.84	144.28	201.12	75.78	120.19	195.97	94.73	42.49	137.22
Total time (minute) =						39402.30			36603.95			35881.14			25563.04
Total time (hour) =						656.71			610.07			598.02			426.05

APPENDIX C

#	Color	fc (psi)	Pressure (ksi)	Time (minute)	Cutting depth (inch)
1	Orange	7683	10	1	1.949
2	Orange	7683	10	1	1.718
3	Orange	7683	10	1.5	1.632
4	Orange	7683	10	1.5	1.854
5	Orange	7683	10	2	1.828
6	Orange	7683	10	2	2.287
7	Orange	7683	12.5	1	2.231
8	Orange	7683	12.5	1	2.013
9	Orange	7683	12.5	1.5	2.589
10	Orange	7683	12.5	1.5	2.465
11	Orange	7683	12.5	2	2.725
12	Orange	7683	12.5	2	3.076
13	Orange	7683	15	1	2.484
14	Orange	7683	15	1	2.115
15	Orange	7683	15	1.5	3.015
16	Orange	7683	15	1.5	2.821
17	Orange	7683	15	2	3.357
18	Orange	7683	15	2	3.254
19	Orange	7683	17.5	1	2.677
20	Orange	7683	17.5	1	3.198
21	Orange	7683	17.5	1.5	3.818
22	Orange	7683	17.5	1.5	1.546
23	Orange	7683	17.5	2	4.107
24	Orange	7683	17.5	2	4.078
25	Yellow	5460	10	1	2.084
26	Yellow	5460	10	1	1.978
27	Yellow	5460	10	1.5	1.621
28	Yellow	5460	10	1.5	1.753
29	Yellow	5460	10	2	2.731
30	Yellow	5460	10	2	2.506
31	Yellow	5460	12.5	1	1.147
32	Yellow	5460	12.5	1	2.366
33	Yellow	5460	12.5	1.5	2.888
34	Yellow	5460	12.5	1.5	2.976
35	Yellow	5460	12.5	2	3.104
36	Yellow	5460	12.5	2	3.184
37	Yellow	5460	15	1	2.184
38	Yellow	5460	15	1	1.338
39	Yellow	5460	15	1.5	3.518
40	Yellow	5460	15	1.5	3.621
41	Yellow	5460	15	2	2.361
42	Yellow	5460	15	2	3.909
43	Yellow	5460	17.5	1	3.872
44	Yellow	5460	17.5	1	3.1495
45	Yellow	5460	17.5	1.5	3.4605

#	Color	fc (psi)	Pressure (ksi)	Time (minute)	Cutting depth (inch)
46	Yellow	5460	17.5	1.5	4.1295
47	Yellow	5460	17.5	2	3.8965
48	Yellow	5460	17.5	2	4.5815
49	Pink	5880	10	1	1.724
50	Pink	5880	10	1	1.738
51	Pink	5880	10	1.5	2.132
52	Pink	5880	10	1.5	1.742
53	Pink	5880	10	2	2.846
54	Pink	5880	10	2	2.63
55	Pink	5880	12.5	1	2.424
56	Pink	5880	12.5	1	1.841
57	Pink	5880	12.5	1.5	2.21
58	Pink	5880	12.5	1.5	2.639
59	Pink	5880	12.5	2	3.196
60	Pink	5880	12.5	2	2.971
61	Pink	5880	15	1	2.77
62	Pink	5880	15	1	1.805
63	Pink	5880	15	1.5	1.853
64	Pink	5880	15	1.5	3.198
65	Pink	5880	15	2	3.266
66	Pink	5880	15	2	3.433
67	Pink	5880	17.5	1	3.025
68	Pink	5880	17.5	1	3.315
69	Pink	5880	17.5	1.5	3.859
70	Pink	5880	17.5	1.5	3.878
71	Pink	5880	17.5	2	3.508
72	Pink	5880	17.5	2	3.588
73	Green	8660	10	1	1.719
74	Green	8660	10	1	1.556
75	Green	8660	10	1.5	1.767
76	Green	8660	10	1.5	1.959
77	Green	8660	10	2	1.995
78	Green	8660	10	2	2.023
79	Green	8660	12.5	1	1.996
80	Green	8660	12.5	1	2.068
81	Green	8660	12.5	1.5	2.239
82	Green	8660	12.5	1.5	2.005
83	Green	8660	12.5	2	2.402
84	Green	8660	12.5	2	2.712
85	Green	8660	15	1	2.867
86	Green	8660	15	1	2.718
87	Green	8660	15	1.5	1.885
88	Green	8660	15	1.5	3.066
89	Green	8660	15	2	3.307
90	Green	8660	15	2	3.712
91	Green	8660	17.5	1	2.735
92	Green	8660	17.5	1	2.981

#	Color	fc (psi)	Pressure (ksi)	Time (minute)	Cutting depth (inch)
93	Green	8660	17.5	1.5	3.605
94	Green	8660	17.5	1.5	3.111
95	Green	8660	17.5	2	4.091
96	Green	8660	17.5	2	3.823
97	Blue	10077	10	1	1.508
98	Blue	10077	10	1	1.612
99	Blue	10077	10	1.5	1.716
100	Blue	10077	10	1.5	1.625
101	Blue	10077	10	2	2.076
102	Blue	10077	10	2	2.014
103	Blue	10077	12.5	1	1.727
104	Blue	10077	12.5	1	2.138
105	Blue	10077	12.5	1.5	1.858
106	Blue	10077	12.5	1.5	2.176
107	Blue	10077	12.5	2	1.801
108	Blue	10077	12.5	2	2.536
109	Blue	10077	15	1	2.016
110	Blue	10077	15	1	1.862
111	Blue	10077	15	1.5	2.817
112	Blue	10077	15	1.5	2.823
113	Blue	10077	15	2	3.54
114	Blue	10077	15	2	3.112
115	Blue	10077	17.5	1	2.594
116	Blue	10077	17.5	1	2.487
117	Blue	10077	17.5	1.5	2.198
118	Blue	10077	17.5	1.5	3.338
119	Blue	10077	17.5	2	3.975
120	Blue	10077	17.5	2	4.157