# Using analytic hierarchy process for assessment of precast concrete inlay panel construction: A Canadian case study

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- Three support-condition options for asphalt pavement rehabilitation using precast concrete inlay panels were constructed and evaluated on Highway 400 in Ontario, Canada.
- The constructibility of the rehabilitation method with asphalt-supported, grade-supported, and grout-supported conditions was evaluated using the analytic hierarchy process.
- The analytic hierarchy process was conducted using input from the Ministry of Transportation of Ontario and the contractor that resulted in a ranking of the support conditions, with the grout-supported condition determined to be the best option.


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Rutted hot-mix asphalt (HMA) pavements in the province of Ontario, Canada, have been successfully rehabilitated using a mill-and-replace strategy. The pavement thickness and extent of deterioration govern how much of the surface HMA is removed, but the milling depth often extends into the granular base layers. Therefore, when pavement issues occur within the HMA or upper base layers, the mill-and-replace strategy is effective; however, for pavement issues occurring in the lower base, subbase, or subgrade layers, a more comprehensive reconstruction technique is often required. This may involve full removal of all pavement layers to address the deeper issues prior to reconstructing the entire pavement structure, which requires considerably more time than typical mill-and-replace rehabilitations.

The Ministry of Transportation of Ontario (MTO) often specifies mill-and-replace rehabilitations for its high-volume highways, including 400-series highways, which experience annual average daily traffic of more than 400,000 vehicles per day.[1] The strategy's fast replacements are ideally suited for these conditions. To minimize the impact on users, the MTO typically specifies that construction operations requiring lane closures on 400-series highways must occur between 10 p.m. and 6 a.m. and that all lanes must be reopened to full capacity by 6 a.m. Recently the MTO has observed pavement sections where the mill-and-replace rehabilitation has lasted only three to five years before failing due to rutting. This indicates a deep-seated issue that the mill-and-replace strategy does not address.

## Pavement rehabilitation

HMA and portland cement concrete (PCC) pavements both distribute loads across in-place subgrade materials while providing suitable riding surfaces for traffic, but the design philosophy for each is different. Due to the flexible behavior of HMA pavements, their design often includes thick layers of granular material to provide a stiff base for support. This stiffness limits the deflection-related tensile strains in the HMA layers and reduces the required thickness of HMA pavements. Limiting the deflection-related tensile strains improves the pavement's bottom-up fatigue performance, while limiting the HMA thickness reduces the potential for and severity of surface material rutting. These are two of the principal design criteria in HMA pavements.[2] Designing the HMA layer thickness to address each criterion individually results in conflicting effects, but increasing base layer thickness and stiffness addresses both design criteria effectively.

PCC is a much stiffer material that distributes traffic loads over a wider area of the lower pavement layers compared with HMA. Therefore, the stiffness of lower layers in PCC pavements is less critical because they are subjected to lower traffic-induced stresses.[3] A key function of a PCC pavement base is providing uniform and stable support.[4]

Therefore, if deep-seated rutting issues exist in an HMA pavement, the use of PCC can reduce the stresses acting on deeper pavement layers. The HMA pavement's base and subbase layers also provide a substantial and stable layer to support PCC and, if the HMA is only milled to a partial depth, the remaining HMA can provide a uniform and nonerodible base that is stiffer than typical granular subbase materials.

## Precast concrete pavement

Precast concrete pavement is often used to repair existing PCC pavements. For precast concrete pavement construction, concrete panels are fabricated under controlled conditions, transported to the site, and installed. The benefit of this method is that it removes the PCC casting and curing operations from the construction schedule's critical path. These operations are time-consuming and often preclude PCC pavements from use on high-volume roadways where agencies will not allow more than eight-hour lane closures. The controlled conditions of an off-site fabrication plant often produce higher-quality PCC in precast concrete units than can be achieved using cast-in-place concrete.[5,6]

Precast concrete pavement is used to repair existing PCC pavements as spot repairs by using single panels or as continuous repairs by placing several adjacent panels in a traffic lane. These repairs include removing deteriorated PCC, repairing any granular base material disturbed during the removal, and replacing the removed pavement with precast concrete pavement panels. The behavior of precast concrete pavement is similar to conventional PCC pavement, but it has some unique qualities. Cast-in-place concrete is placed on-site and can change shape to match the contours of the support layer. Because precast concrete pavement has cured before it is placed on the support layer, the support layer itself must be adjusted to provide a uniform bearing surface. In precast concrete pavement applications, the support conditions beneath the panels often govern their performance.[5,6] Nonuniform support can result in bridging, which produces significantly higher stresses in the panel than the stresses for the fully supported condition for which it was designed. This can severely reduce the time until fatigue cracking of the pavement by increasing the stress ratio between the applied stress and the pavement's flexural strength. According to Miner's fatigue hypothesis, a higher stress ratio requires fewer loading cycles to result in fatigue failure.[3] It should be noted that the high levels of reinforcement in precast concrete pavements generally arrest the propagation of these fatigue cracks, extending the pavement life far beyond the onset of fatigue cracking.

In typical precast concrete pavement applications, uniform support is provided by placing fine granular material on the underlying granular material and precision grading it to match the flat bottom surface of the precast concrete pavement or by pumping a flowable material, such as structural grout or polyurethane foam, between the existing granular surface and the precast concrete pavement panel.[5] A flowable bedding grout is typically pumped beneath the panels even when using precision grading to fill small voids, but the graded material directly supports most of the panel. Structural grout and polyurethane foam flow and conform to the contours of the support surface and the precast concrete pavement panel. When flowable materials are used without precision grading, they require curing time to gain sufficient strength to fully support the panels and traffic loads. This is an important consideration because precast concrete pavement is often used where construction time windows are restricted.

## Precast concrete inlay panel trial

The MTO is interested in research on the use of precast concrete pavement to rehabilitate HMA pavement sections where mill-and-replace rehabilitation is insufficient.[7] Precast concrete pavement has been used to rehabilitate HMA pavement sections where the HMA pavement layers were fully removed and the precast concrete pavement was placed on the existing granular base material.[8] For this study, the precast concrete pavement was placed within the HMA pavement layers and was therefore considered to be precast concrete inlay panels (PCIPs). The PCIPs provide a stiffer pavement layer than HMA to distribute traffic loads over a larger subgrade area, making the pavement less susceptible to the effects of any deep-seated issue. Precast concrete panels allow the concrete to support traffic loads immediately after placement, unlike cast-in-place concrete. This allows concrete to be used for rehabilitation while still limiting lane closures for construction. PCIPs are expected to have a service life much longer than the observed three to five years of the mill-and-replace strategy, thus reducing user costs and worker safety issues associated with frequent construction operations.[9]

Based on the MTO's interest, a design for a PCIP trial section was developed. The design included partially milling the HMA pavement and replacing it with an equivalent depth of precast concrete panel and support material. The PCIP design is unique because it is the first time precast concrete pavement has been used to rehabilitate HMA pavements through partial-depth replacement using the existing HMA base.

## Scope and objectives

This paper describes a new method for rehabilitating high-volume HMA pavement highways using PCIP. The design was implemented in a trial section on a high-volume highway in Ontario, Canada, and the trial construction operation is described in detail. **Figure 1** shows the placement operation of a panel during the construction of the trial section. As part of the trial, three methods for providing subpanel support were designed and constructed, each with inherent advantages and disadvantages related to the constructibility of PCIP. The support methods were analyzed with respect to construction-related criteria using the analytic hierarchy process (AHP). The relative weighting of the criteria was determined based on input from MTO staff, while the relative performance with respect to the criteria was provided by the trial section's construction contractor. This analysis identifies the support method that provides the most advantages for rehabilitation using PCIP.

The in-place performance of each of the support conditions for PCIP will determine the viability of the rehabilitation technique, but feasible overnight construction of the support condition is essential to successful rehabilitation with PCIP. This paper using a defensible selection process to determine the best method of constructing the PCIP support condition based on its constructibility.

The data and analysis in this paper are based on a single trial application with a limited scope. Because this trial was a new application of precast concrete pavement, it represented the sole available source for relevant construction data. Although the findings of this study are meaningful, they should therefore be considered preliminary findings in the field of PCIP rehabilitation.

## Support conditions

The research focused on developing methods to provide uniform support to the PCIP because partial-depth milling of the HMA pavement was a new design consideration for rehabilitation using precast concrete pavement. The support must provide a uniform surface for the precast concrete panels and be easily constructed under high-volume highway conditions. Nonuniform support occurs in two main ways: either the support material beneath the panel settles or the support material beneath the panel was placed unevenly. For PCIP, the proper placement of the support material is the main challenge in preparing the support conditions because the HMA beneath the panel should not settle under traffic loads.

**Figure 1.** Installation of a precast concrete inlay panel during trial section construction.

Three methods for constructing the PCIP support condition were developed for this research. Each method was developed to address different aspects of the construction process that could create issues. The different support conditions considered were asphalt supported (AS), grade supported (GraS), and grout supported (GroS). Each support condition included bedding or structural grout beneath the precast concrete panels. The grout provided some bonding between the PCIP and HMA pavement layers, which increases the structural capacity of the section. However, the additional capacity was not accounted for in the PCIP design, which did not consider bonding and only accounted for the HMA layers as supporting layers.[10]

## Asphalt supported

The AS condition included the precision milling of the HMA pavement to a depth of 206 mm (8.1 in.) with a ±3 mm (1⁄8 in.) surface tolerance. The surface tolerance was based on the experience of the Fort Miller Co. of Schuylerville, N.Y., with conventional precast concrete pavement rehabilitations. The milled HMA surface was thoroughly cleaned with a power broom, and the PCIPs were placed directly on the milled surface. Structural grout was pumped into the transverse joints between PCIPs to provide load transfer through dowels and into the longitudinal joints to fill the gap between the PCIP and the adjacent lanes with HMA pavement. After the structural grout was placed, a thinner more flowable bedding grout was pumped beneath the PCIP to fill any small voids between the PCIP and the milled surface to ensure uniform panel support.

The PCIPs were exposed to traffic loads after they were placed but before the structural grout was placed and cured the following night. Without the structural grout no interpanel load transfer occurred, but the panels resisted the loads individually. The structural grout was placed at the beginning of the following night's construction closure, providing more time for the grout to reach its minimum required strength of 20 MPa (2.9 ksi) before being subjected to traffic loads, which improved construction staging.[7]

## Grade supported

The GraS condition included conventional HMA milling to a depth of 218 mm (8.6 in.) with a ±6 mm (¼ in.) surface tolerance. The HMA surface was then cleaned and cement-treated bedding material was placed on the milled surface using ready-mixed concrete trucks. The cement-treated bedding material was a dry mixture of six parts fine aggregate to one part portland cement. After the cement-treated bedding material was placed on the milled HMA surface, it was screeded to the appropriate depth and leveled using a leveling screed provided by the Fort Miller Co. The screed was supported by rails and placed parallel to the milled portion of pavement, which was leveled and adjusted to provide the required cement-treated bedding material surface. Once screeded, the cement-treated bedding material was compacted using a small plate tamper, and the process was repeated until the surface was uniform and compacted. The cement-treated bedding material was then wetted and the PCIPs were placed on its surface. Structural grout was pumped into the longitudinal and transverse joints. Then, flowable bedding grout was pumped beneath the panels to ensure uniform support. Similar to the AS condition, the GraS condition can support traffic loads in the ungrouted condition, allowing the grout to be placed during the following night's lane closure.[7]

## Grout supported

The GroS condition included milling the HMA pavement to a depth of 218 mm (8.6 in.) with a ±6 mm (¼ in.) surface tolerance. The surface was then cleaned with a power broom and the PCIPs were placed on the milled HMA surface. The PCIPs were raised to the proper elevation and cross slope using integrally cast leveling feet. The four leveling feet on each panel were adjusted by pneumatic drills to bring the panels into position with a maximum 3 mm (1⁄8 in.) elevation differential allowed between panels.

Structural grout was pumped into the transverse and longitudinal joints, and then a rapid-setting bedding grout was pumped beneath the panel. For this support condition, panel placement and grouting must take place the same night because the panels cannot support traffic in the ungrouted condition. Furthermore, because the HMA pavement for the GroS condition is not milled to the precise tolerance of the AS condition, the panels cannot support construction loads such as those imparted by cranes used for lifting panels, either before or after leveling.[7]

## Design considerations

Each of the support conditions was developed to address different potential problems in the construction process, including variable milling practices, variable existing cross slopes, difficulty placing cement-treated bedding material, and timing construction activities for short lane closure periods. **Table 1** outlines the advantages and disadvantages anticipated for each support condition.

The goal of analyzing the different support conditions was to quantify these relative advantages and disadvantages and to determine which factors played the most significant roles in construction.

# Construction activities

Construction of the trial section took place from September 12 to 16, 2016. The trial section was constructed in the northbound lanes of Highway 400, approximately 60 km (40 mi) north of Toronto, ON, Canada (**Fig. 2**).

**Figure 3** shows the overall layout of the northbound lanes with the 100 m (330 ft) trial section in the rightmost lane (lane 3).

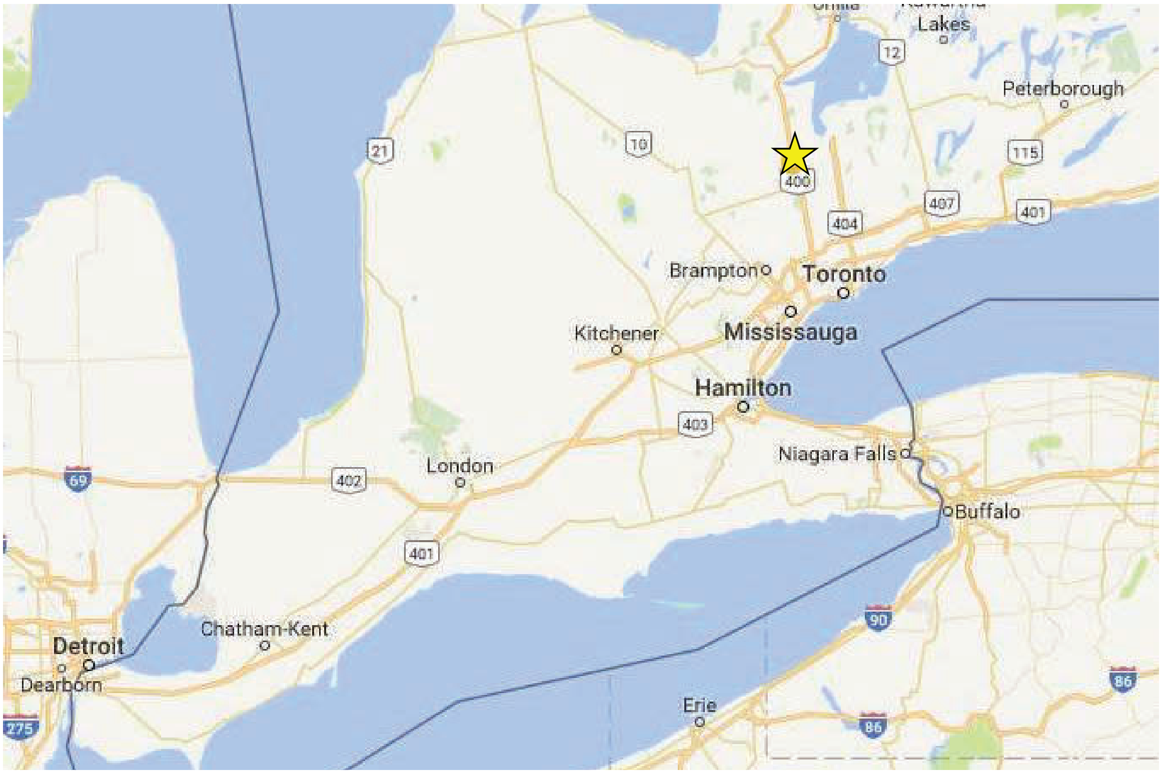



**Figure 2.** Trial site location map. Map data: Google, ©2017.

**Table 1.** Anticipated advantages and disadvantages for different support conditions

| | Advantages | Disadvantages |
|---|---|---|
| Asphalt supported | • PCIP can support traffic immediately after placement.<br>• No specialty bedding material is required (cement-treated bedding material, rapid-setting grout). | • It requires a very precise milling/surface cleaning operation.<br>• Inexperienced milling crews should have preconstruction proof of concept. |
| Grade supported | • A similar strategy is common in previous precast concrete pavement placement in Ontario.<br>• PCIP can support traffic immediately after placement.<br>• The high smoothness of a milled surface is not required. | • More time and expertise are required for placement of cement-treated bedding material.<br>• It requires extra material (cement-treated bedding material, water) and machines (screed, compaction equipment) to be brought on-site. |
| Grout supported | • The high smoothness of a milled surface is not required.<br>• Panels can be adjusted to suit conditions easily on-site. | • The time for rapid-setting grout to achieve 5 MPa strength must be built into the schedule.<br>• Higher costs are associated with leveling lifts and high volumes of rapid-setting grout. |

Note: PCIP = precast concrete inlay panel. 1 MPa = 0.145 ksi.

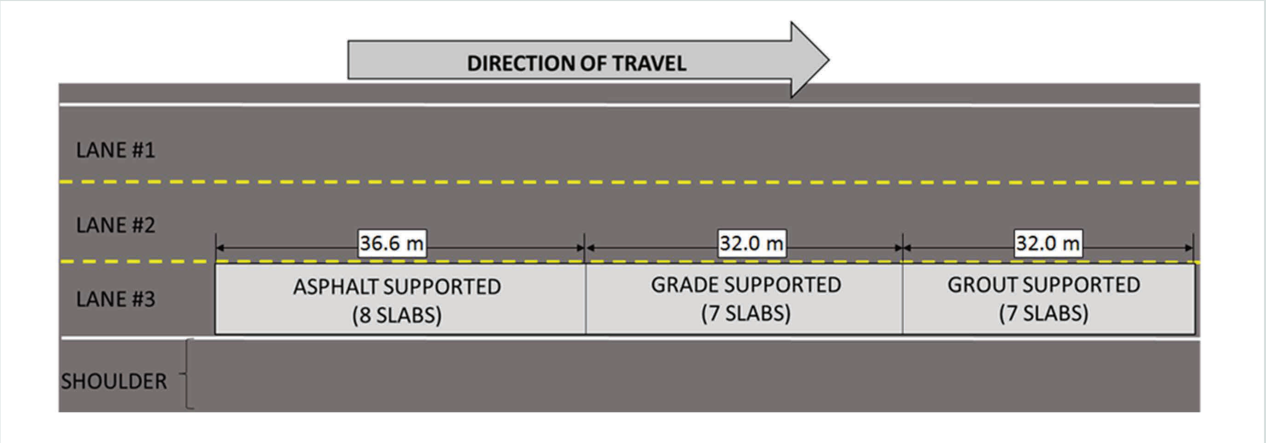



**Figure 3.** General layout of trial section on highway. Note: # = no. 1 m = 3.28 ft.

The typical eight-hour overnight construction window specified by the MTO is from 10 p.m. until 6 a.m. However, some exceptions were made for this trial project. Progressive lane closures were used, with lane no. 3 closing at approximately 8:30 p.m., at which point work could begin on the portion of lane no. 3 adjacent to the shoulder. At 10:30 p.m., the closure was expanded to include lane no. 2, preserving lane no. 1 for traffic.

The timing of construction activities associated with each support condition was tracked throughout the trial section construction. The individual construction activities were combined into an overall construction period for each support condition (**Fig. 4**). The different nights during which the construction activities occurred are noted on each plot in Fig. 4. For example, in the AS construction, saw cutting (A1) took place on the first night while asphalt milling (A2) and PCIP placement (A4) took place on a subsequent night. The total construction time is shown continuously; however, between each night is a daytime period in which all lanes were opened to traffic. All panels associated with a given support condition were placed during one night of construction, with the panels for different support conditions placed on consecutive nights.

While each support condition's construction is unique, as outlined previously, general aspects of the construction are shared. Figure 4 shows each support condition's construction separated into activities that were similar for all support conditions.

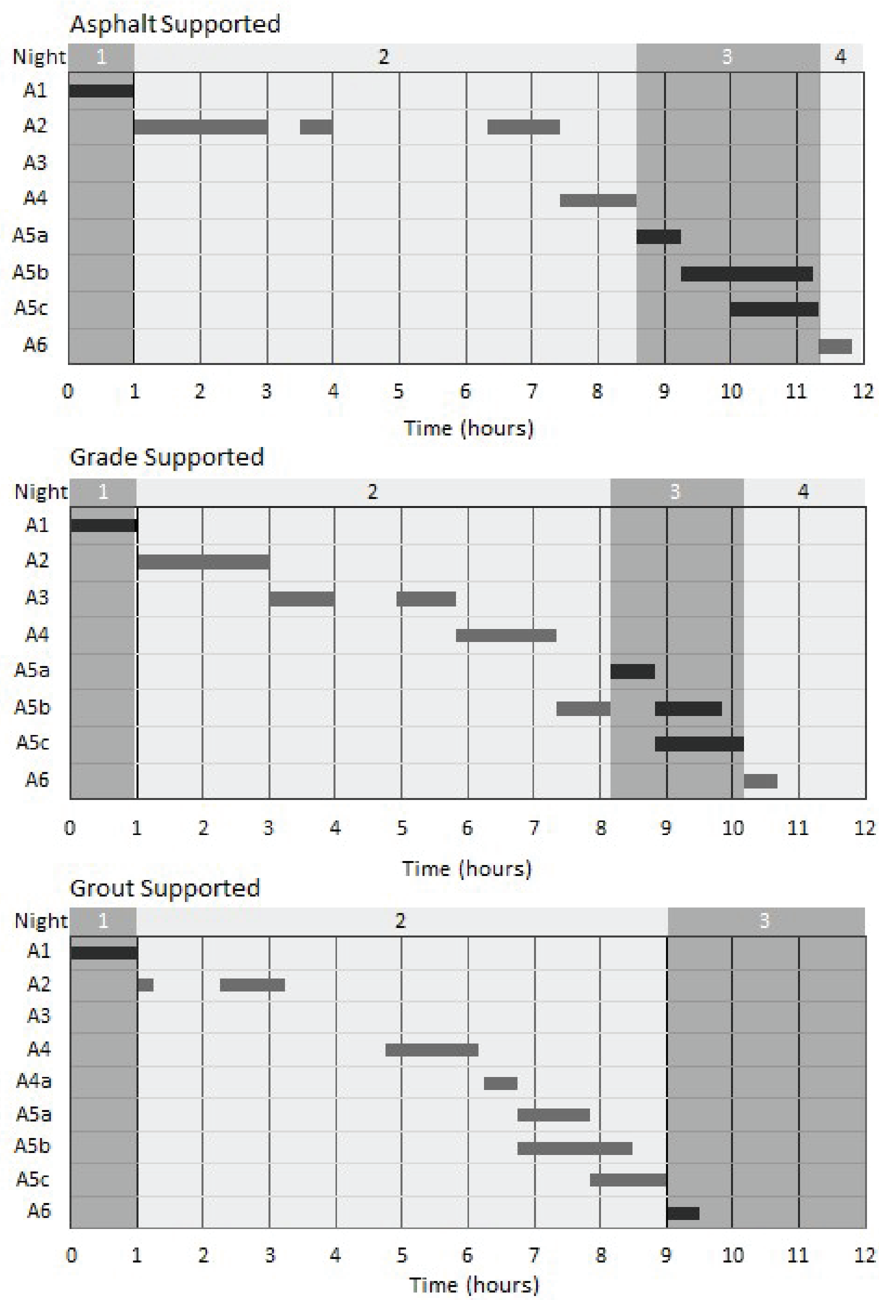
The extents of the HMA removal were marked during the first night of construction using full-depth saw cuts. The saw cuts were intended to provide a clean vertical surface after the HMA milling was completed. Saw cutting is the first night of construction for each support condition in Fig. 4.

Eight panels were placed for the AS condition, while seven panels were placed for the GraS and GroS conditions. Figure 4 shows the observed duration of each construction activity, beginning with saw cutting on the first night. Notable gaps in a construction activity, such as those in asphalt milling and surface cleaning (A2) for the AS condition, indicate a pause in that activity. In this case, the first small pause is the time between the first pass of the milling machine and the second. Because of the progressive closures, only the right side of lane no. 3 was initially milled to avoid encroaching on traffic in lane no. 2. When lane no. 2 was closed, the milling resumed. The second pause is the time during which the milled surface was checked for compliance to the specifications after the first milling crew had left the site. More milling was required, so a second milling crew was brought on-site, at which point the milling was completed.

A similar pause occurred with the preparation of the support conditions (A3) for the GraS condition. The break in construction activity was caused by material issues with the cement-treated bedding material. The moisture content of the fine aggregate in this mixture was too high, which caused the cement-treated bedding material to clump together. The first shipment of material was rejected, and the pause is the time spent waiting for a second shipment to arrive. In addition, the panel placement (A4) and the longitudinal edge grouting (A5b) for the GraS condition took place the same night, despite the original plan to grout the following night. This was due to overmilling; the HMA removal had deviated beyond the specified width, and the resulting gap between the PCIP and the existing HMA pavement was too large to expose to traffic. As a result, the longitudinal joints were grouted the same night to close this gap.

A pause also occurred between A2 and A4 for the GroS condition. This represents time when manual chipping of the HMA surface was performed due to improper milling. Panel placement began after the chipping and cleaning was completed.

The trial construction was the first time that PCIPs were constructed with each support condition. As such, no significant improvement based on the learning curve was seen on




| | |
|---|---|
| A1 | Saw Cutting Milling Extents |
| A2 | Asphalt Milling and Surface Cleaning |
| A3 | Preparation of Support Conditions |
| A4 | PCIP Placement from Trucks |
| A4a | PCIP Alignment using Leveling Feet |
| A5a | Placement of Transverse Joint Grout |
| A5b | Placement of Longitudinal Edge Grout |
| A5c | Placement of Flowable Bedding Grout |
| A6 | Transverse Joint Grout Saw Cutting |

**Figure 4.** Construction activity timing for each support condition. Note: PCIP = precast concrete inlay panel.

the project. In future applications, addressing the problems that resulted in construction delays would result in faster installations. Furthermore, if the PCIP design was used on a larger scale, different construction activities could progress at the same time with multiple crews. Two construction crews worked on the trial section due to the relatively small scale of the project. One crew focused on grouting the previous night's panels, while the other crew focused on placing the panels. This organization resulted in construction activities progressing one at a time (Fig. 4).

The trial construction provided opportunities to assess the construction procedure for PCIPs and to identify opportunities to improve the process in the future. The milling procedure produced a clean vertical face on the longitudinal edges. Although the saw cuts provided a visual demarcation of the milling extents, they were not required to produce vertical edges and could likely be omitted for future projects with PCIP. A wider grinding head on the milling machine would improve the constructibility of all of the support conditions by requiring fewer passes for the milling operation.

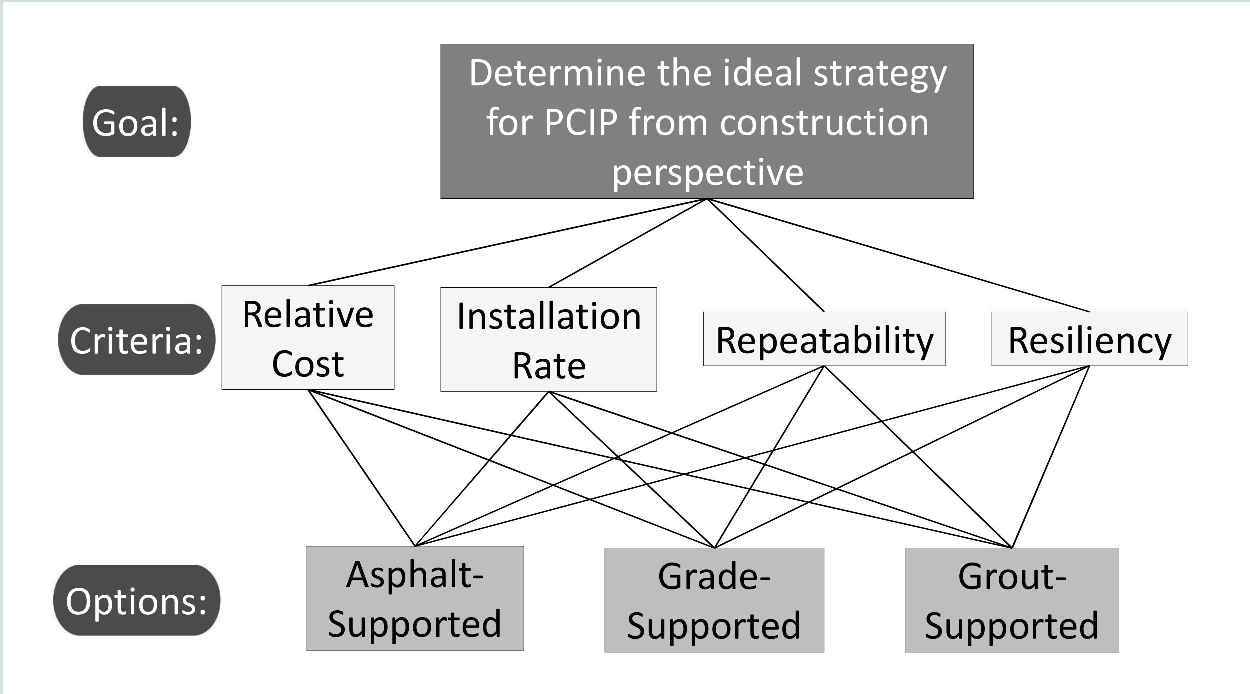



**Figure 5.** Analytic hierarchy process for the evaluation of PCIPs. Note: PCIP = precast concrete inlay panel.

In the design phase, a gap was provided along the longitudinal edges between the PCIP and adjacent HMA pavement to facilitate placing the panels without disturbing the adjacent HMA pavement and to provide space for edge grouting reinforcement. To address traffic safety concerns caused by this gap, hollow structural steel (HSS) members were attached to the longitudinal edge of the panels to close the gap. The trial construction showed that the placement of the panels could be performed with enough accuracy that this edge gap could be minimized, thereby eliminating the need for the HSS members and longitudinal reinforcement.

## Research methodology

The feasibility of the PCIP rehabilitation technique is highly dependent on its constructibility, which varies for each of the three support conditions. The constructibility of the support conditions was compared using the AHP.

The AHP is a multicriteria decision-making tool widely used in the engineering field.[11] It provides a method of reaching sound, justifiable decisions based on both quantitative and qualitative criteria. For qualitative criteria, input is required from users to determine the importance, preference, or value of one criterion over another based on the individual's personal experience and judgment. Based on these inputs and quantitative data, weightings of the criteria and rankings of the options are established.[12]

The AHP can be easily constructed; does not require those providing input to have technical expertise with decision-making tools; and can incorporate input from many individuals, enabling groups to reach an agreement on shared values.[13] The statistical significance of AHP results has been questioned in the past, and the traditional AHP does not quantify uncertainty due to variations in assigned values.[14,15] Therefore, sensitivity analyses were performed for this study, using reasonable limits for each criterion, to evaluate the statistical significance of the support-condition assessment results.

An AHP is conducted through four main steps. First, the goal of the analysis is determined, which in this case is determining the PCIP support condition that is ideal for construction. Second, options are identified and a set of criteria are established that can be used to compare and differentiate the options. Third, the performance of each option is compared with regard to the criteria.

These comparisons are made pairwise, such that each option is compared to every other option. A similar comparison is performed between each of the criteria to determine the relative importance or weight of each criterion. Finally, the priorities for each criterion are combined into an overall or global priority that indicates the ideal option based on the relative performance of each option for each criterion.[16]

An AHP was used to rank the three support-condition options—AS, GraS, and GroS—based on four constructibility criteria: relative cost, installation rate, repeatability, and resiliency. The AHP organizes the problem into a hierarchy that includes the goal, criteria, and options (**Fig. 5**).

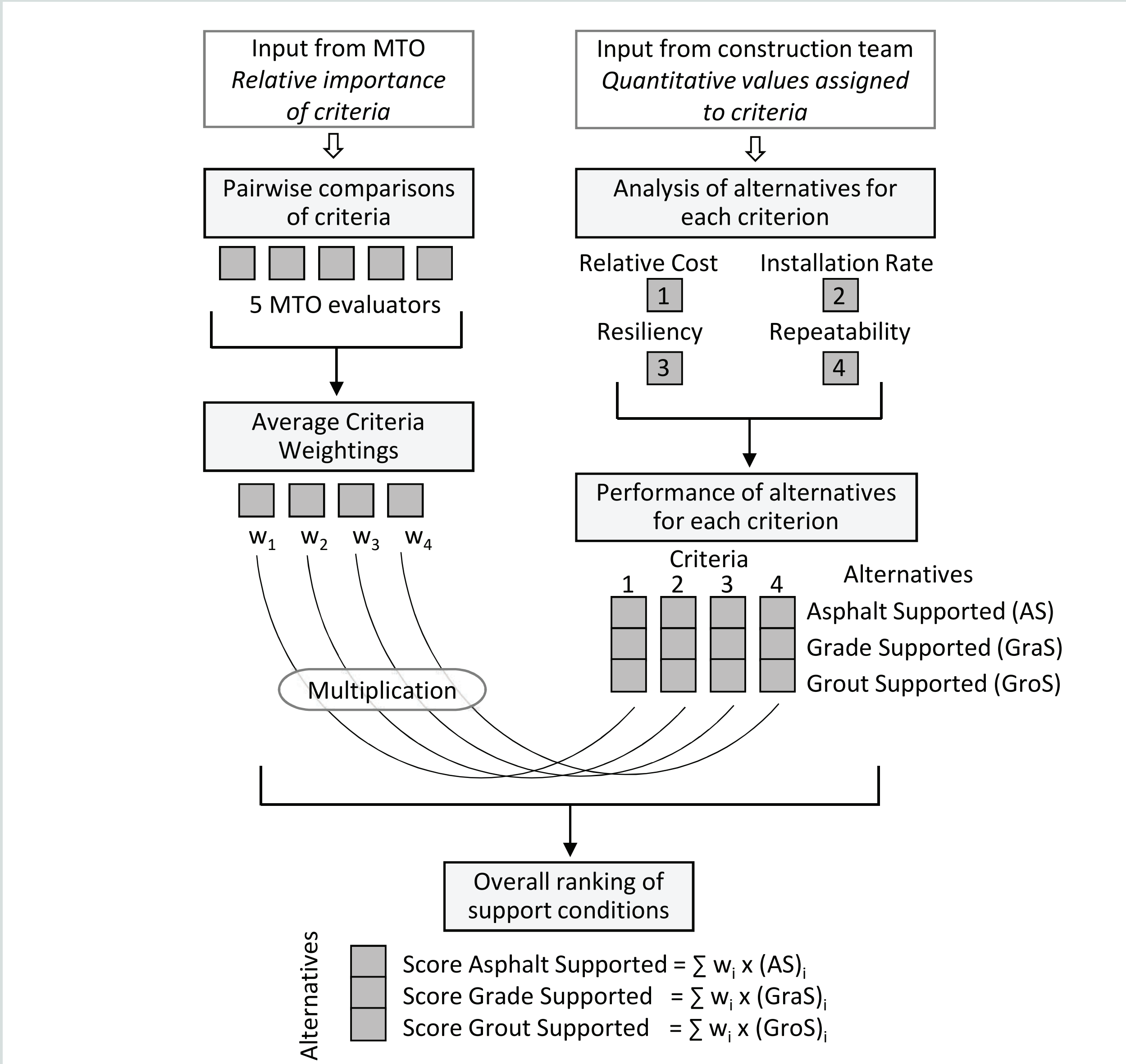



**Figure 6.** Flow chart of analytic hierarchy process steps for ranking support conditions. Note: $(AS)_i$ = performance of asphalt-supported option for criterion *i*; $(GraS)_i$ = performance of grade-supported option for criterion *i*; $(GroS)_i$ = performance of grout-supported option for criterion *i*; *i* = criterion number; MTO = Ministry of Transportation of Ontario; $w_1$ = average weighting for relative cost criterion; $w_2$ = average weighting for installation rate criterion; $w_3$ = average weighting for resiliency criterion; $w_4$ = average weighting for repeatability criterion; $w_i$ = average weighting for criterion *i.*

**Figure 6** shows an overview of the AHP used to rank the options based on constructibility. The input from MTO staff was used to determine the relative importance of the criteria used for the analysis. Input from the contractor's construction team was then used to compare the three options according to the four criteria. These inputs were then combined into a final priority, which took the shape of an overall ranking.

Each step of this analysis is described in the following sections to outline the process used to determine the overall ranking of the support conditions.

## Constructibility criteria

The constructibility criteria form the basis for comparing the options. These criteria were developed based on input from the stakeholders in the trial project. Each criterion was developed to represent a different factor that an agency would consider when comparing rehabilitation options.

### Relative costs

This criterion reflects the cost of each support condition relative to the other options. The cost of a given rehabilitation technique is typically important for a transportation agency because it must justify all costs to taxpayers. The PCIP strategy is a specialized rehabilitation technique developed to address the high user costs associated with the short service life and frequent repairs required when using the mill-and-replace strategy. For this reason, a higher initial construction cost might be acceptable, assuming that the PCIP would have a longer service life before needing substantial road reconstruction and long-term road closures. Costs in this study only reflect the initial construction costs because the life-cycle costs will depend on the strategy's service life, which is currently unknown.

### Installation rate

The second criterion is the rate at which the panels could be installed under typical conditions. Agencies have an interest in reducing the construction times on their high-volume roads to minimize the impact on users. The time required to repair a given length of road is a function of the installation rate. Although actual construction times were measured, these measurements do not account for any time savings based on the learning curves that are typically realized in construction applications. The installation rates are not expected to be representative of a full-scale PCIP project. Therefore, the nightly installation rates used in the AHP are estimates based on the contractor's experience with the trial section and road construction.

### Repeatability

Repeatability is a subjective criterion that indicates the ease of installation. This criterion reflects the construction benefits of having fewer, simpler installation steps. While construction on a high-volume highway project is likely to be performed by a trained and effective construction crew, a highly repeatable operation would have fewer sources for error during construction, resulting in fewer opportunities for cost and time overruns. The repeatability criterion is related to installation rate, but also indicates the potential for errors that can have an impact beyond the installation rate.

### Resiliency

The resiliency criterion is also subjective and reflects the ability of the given support condition to be adjusted during construction to accommodate unforeseen on-site conditions. On-site conditions are difficult to predict but might include insufficient HMA pavement depth after milling, overmilling (both depth and width), unexpected weather events, and deteriorated HMA base layers.

## Pairwise comparisons of criteria

A pairwise comparison consists of comparing two criteria at a time and assigning a value representing the ratio of importance of criterion A to criterion B ($w_A/w_B$). The evaluator selects a value from the fundamental scale, which contains integer values ranging from 1 to 9 and their reciprocals ($^1/_9$ to $^1/_1$). A value of 1 indicates that the criteria are of equal importance, a value of 9 indicates that criterion A is extremely dominant over criterion B, and the reciprocals are assigned to indicate the dominance of criterion B over criterion A. This fundamental scale was derived mathematically to ensure that a small change in the selected scale value will not have an unduly large influence on the resulting priorities determined by the AHP. The scale is also designed to be intuitive to use for assigning values to comparisons.[13]

Past and present MTO engineers performed the pairwise comparisons, and this input was used to calculate weightings for the constructibility criteria. Each of the six MTO engineers was closely involved with the development of the PCIP trial and had substantial knowledge of the project and rehabilitation operations on provincial highways. **Table 2** illustrates an example of a pairwise matrix used to develop rankings of relative importance of the criteria. This matrix contains the input from one evaluator, and each evaluator completed a similar matrix. In the example shown, relative cost was five times as important as resiliency to PCIP construction, while resiliency was $^1/_9$ as important as installation rate.

The normalized eigenvector of the pairwise comparison matrix values represents the relative weightings for each criterion, shown in the last column of Table 2. The weightings were compared with a consistency ratio of 10% to ensure that the pairwise comparisons were made to an acceptable level of consistency throughout. The consistency ratio is a function of the maximum eigenvalue compared with that of a random matrix. The consistency measure ensures that if component A is found to be more important than component B and B is found to be more important than component C, then component A should be more important than component C.[12] The individual

**Table 2.** Pairwise comparison matrix example

| | Ratio of importance of criterion A to criterion B $w_A/w_B$ | | | | Relative criterion weighting |
|---|---|---|---|---|---|
| | Cost | Installation rate | Repeatability | Resiliency | |
| Relative cost | 1 | ⅓ | 3 | 5 | 0.250 |
| Installation rate | 3 | 1 | 5 | 9 | 0.566 |
| Repeatability | ⅓ | ⅕ | 1 | 5 | 0.138 |
| Resiliency | ⅕ | ⅑ | ⅕ | 1 | 0.046 |

weightings from each evaluator were averaged to produce the average relative criteria weightings (**Table 3**).

Installation rate and relative cost, weighted at 0.497 and 0.272, respectively, were determined to be the most important criteria. Repeatability and resiliency were relatively less important, with weightings of 0.154 and 0.077, respectively. MTO feedback indicated that the contractor should meet a minimum level of competency and that the repeatability should not be a deciding factor. Similarly, it was stated that comprehensive site investigation prior to construction could reduce the risk of unexpected site conditions, thereby reducing the importance of resilience. These statements indicate that the relative weightings would be subject to change under other construction and contracting conditions.

## Evaluation of support conditions

Contractor personnel closely involved in the trial construction provided feedback regarding the constructibility of each support condition. The five personnel included crew foremen and project managers. Each evaluator assigned values for the three support conditions indicating installation rate, repeatability, and resiliency. The assigned value for installation rate is an estimated number of panels that could be installed per night, and repeatability and resiliency are scores on a scale of 1 to 10, with 1 being the least repeatable or resilient and 10 being the most repeatable or resilient.

The cost of each support condition was considered to be private information, but typical unit costs for the construction operations were provided to develop a cost estimate. This estimate was based on the cost of installing 10 panels, and the contractor deemed it a reasonable approximation of the costs.

The assigned values for repeatability and resiliency correspond to observations and comments made by the contractor's personnel regarding the construction process. For example, the AS condition was deemed to have the lowest repeatability, as seen from the average values in Table 3. This can be partly attributed to the inconsistent control of the milling depth, which was found to be a limiting factor for the AS panels.

The GroS option was identified as being the most stress-free option due to less stringent milling requirements and a more forgiving leveling procedure. Leveling feet were installed in all panels as a precaution, though they were only used for the GroS option. The leveling feet were an integral design feature to the GroS condition and a resiliency-increasing contingency in the other options. For the purposes of this study, the levelling feet in the GraS and AS conditions were not considered because they were not used in these cases. The use of the leveling feet indicates a higher level of inherent resiliency in the GroS method. The contractor comments indicated that this feature should be a contingency system built into all future applications of PCIP.

The GraS panels required extra steps compared with the other support conditions due to the preparation of the cement-treated bedding material. This resulted in a slower installation rate for the GraS condition than other options. The feedback received was that the additional steps for this option seem counterproductive because the overall goal of PCIP is to minimize the construction periods.

The evaluations from all surveyed members of the construction company were combined to produce average values FOR THE CRITERIA FOR EACH OF THE SUPPORT CONDITIONS (TABLE 3). The average values were then subjected to an eigenvector analysis, similar to that outlined for the criteria weighting, which produced a performance value for weighting each support-condition option within each evaluation criterion. The product of the performance values and the average relative criteria weightings determined overall scores for each support condition.

## Overall scores of support conditions

**Table 4** summarizes the overall scores for each support condition based on the products of the relative criteria weightings and performance values for weightings. The overall score is the sum of the products across all criteria for a given support condition. Based on the construction-related criteria, the GroS condition was the highest-scoring method for PCIP installation. The AS technique was the second-highest-ranked option.

**Table 3.** Quantitative performance values of evaluation criteria

| Criterion | Average relative criteria weighting | Average values | | | | Performance value for weighting of options in each criterion | | |
|---|---|---|---|---|---|---|---|---|
| | | Unit | AS | GraS | GroS | AS | GraS | GroS |
| Cost | 0.272 | $ | 106,855 | 108,621 | 107,072 | 0.335 | 0.330 | 0.335 |
| Installation rate | 0.497 | Panels/night | 40 | 30 | 43 | 0.354 | 0.265 | 0.381 |
| Repeatability | 0.154 | /10 | 5.4 | 8 | 8 | 0.252 | 0.374 | 0.374 |
| Resiliency | 0.077 | /10 | 6.4 | 5.8 | 6.2 | 0.348 | 0.315 | 0.337 |

Note: AS = asphalt supported; GraS = grade supported; GroS = grout supported.

**Table 4.** Overall scoring of support conditions

| Support condition | Contribution of option's performance in each criterion | | | | Overall score |
|---|---|---|---|---|---|
| | Cost | Installation rate | Repeatability | Resiliency | |
| AS | 0.085 | 0.176 | 0.039 | 0.027 | 0.326 |
| GraS | 0.084 | 0.132 | 0.058 | 0.024 | 0.297 |
| GroS | 0.104 | 0.189 | 0.058 | 0.026 | 0.376 |
| Total | 0.272 | 0.497 | 0.154 | 0.077 | 1 |

Note: AS = asphalt supported; GraS = grade supported; GroS = grout supported.

All three options were ranked closely to one another, with only an approximately 20% difference between the highest- and lowest-ranked support conditions. The findings are supported by the results of the trial section construction. Each technique had challenges, but all methods produced functioning panels without any substantial issues.

This result does not eliminate any of the three support conditions, and it is possible that project-specific circumstances could make any of the three studied conditions most applicable. Furthermore, the result was based on a trial with a relatively limited scope. However, based on the limited circumstances of the trial construction, the GroS condition is recommended for future PCIP applications.

## Confidence in the AHP ranking results and significance

The AHP is well suited to consolidating subjective and objective criteria into one result for the purposes of decision making. However, the AHP does not include a method of measuring the statistical significance of the results.[14,15]

One method for analyzing the significance of a given result is to use sensitivity analyses to determine the effects of changes in the input values on the analysis results.

Two sensitivity analyses were conducted to determine the reliability of the results. The first investigated the effects of changes in the criteria weighting (provided by MTO personnel), and the second investigated the effects of changes in the average quantitative performance values (assigned to the criteria by contractor personnel).

## Criteria weighting sensitivity analysis

The individual criteria weightings were generally consistent across all submissions, but some variability was observed. A sensitivity analysis was performed to investigate the sensitivity of the results to this variability. Using the normalised eigenvectors of each pairwise matrix submitted by MTO staff, the maximum and minimum weighting for each criterion was noted. Then one criterion's maximum weighting was considered while the remaining criteria were factored down such that the sum of all weightings remained 1, which is a requirement of the AHP. The weighting of each remaining criterion was not factored below the minimum value observed for that criterion. In this way, the maximum and minimum submitted responses provided the bounds of the sensitivity analysis. The AHP was then conducted again based on the adjusted weightings, producing overall scores for the three support conditions. This process was repeated using the maximum observed weighting for each constructibility criterion. **Table 5** summarizes the results of this analysis.

The results of the AHP were not sensitive to changes in the criterion weights within the limits set for the sensitivity analysis. Only slight changes to the overall scores for each option were observed, and the relative ranking of the options did not change in any case. This provides a degree of confidence in the results, considering the variability that was observed in the criteria weightings.

## Contractor scoring sensitivity analysis

The relative performance of each option for each criterion used in the AHP was based on average values collected from

**Table 5.** Criteria weighting sensitivity analysis

| Support condition | Overall scores adjusted for the maximized criterion weighting | | | | Unadjusted overall score |
|---|---|---|---|---|---|
| | Cost | Installation rate | Repeatability | Resiliency | |
| AS | 0.331 | 0.337 | 0.327 | 0.334 | 0.333 |
| GraS | 0.317 | 0.295 | 0.308 | 0.305 | 0.304 |
| GroS | 0.352 | 0.367 | 0.364 | 0.361 | 0.364 |

Note: AS = asphalt supported; GraS = grade supported; GroS = grout supported.

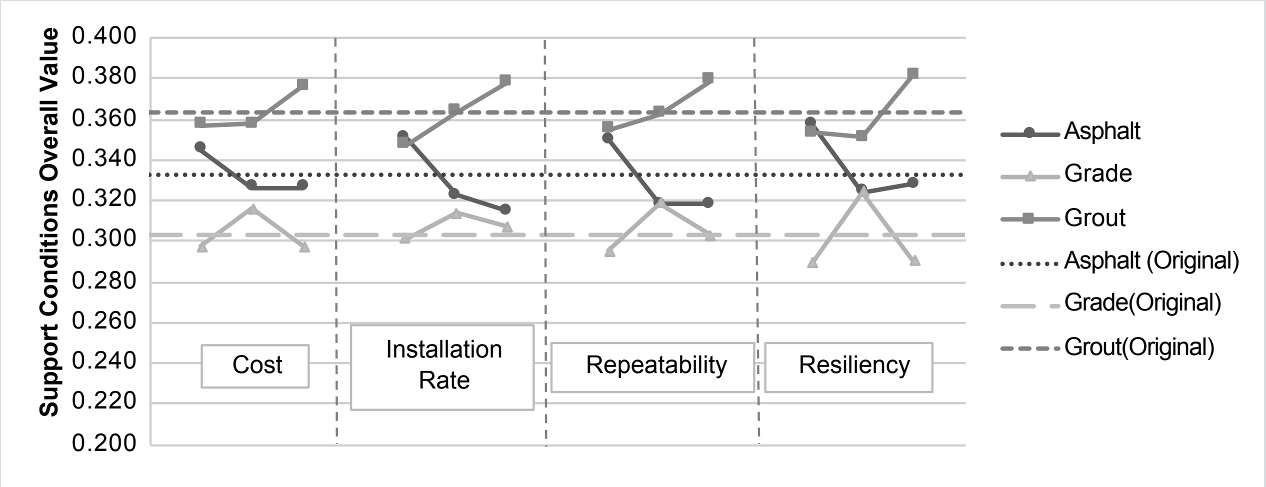



**Figure 7.** Contractor scoring sensitivity analysis results.

several members of the contracting team. As such, a range of responses was collected, and the maximum and minimum values for each criterion were chosen to provide the bounds of a second sensitivity analysis.

In this analysis, the effects of changes to the values for one criterion were analyzed while the other criteria were kept at their average values. For each criterion, the optimum value for one option was selected while the least-desirable values were selected for the other two options. The overall score of the different options was then determined based on an AHP using these adjusted values.

For instance, while considering the effects of skewing the input values of installation rate, the input values for cost, repeatability, and resiliency were kept at their average. The installation rate was skewed in favor of one option by selecting the maximum installation rate (optimum) for that option while selecting the minimum installation rate (least desirable) for the other two options. The AHP analysis was performed using these adjusted values. Then the process was repeated to skew the criterion in favor of a different option. After repeating this process for each of the three options for one criterion, the process was repeated for another criterion. The sensitivity analysis required 12 iterations in total.

**Figure 7** shows the results of the contractor scoring sensitivity analysis. The results are presented in terms of the overall scores for the three options and are organized by the criterion being manipulated. The original scores for each option are included with the sensitivity analysis results for comparison.

The cost values were developed based on unit costs and did not have a maximum and minimum response to define the range of the sensitivity analysis. In this case, a 10% decrease in the calculated cost was defined as the optimum value, while a 10% increase in cost was considered the least-desirable value.

The sensitivity analysis reflects the possible results when considering the entire range of performance values that were provided by members of the contracting team. The results indicate that even considering the variability of the values assigned for each criterion and each option, the GroS option was still consistently ranked as the preferred option. In two iterations, the AS condition was ranked slightly higher than the GroS option by 0.4%, which was considered to be approximately equal.

Based on this analysis, the overall score of the options was not found to be sensitive to the effects of changing the quantitative performance values within the defined bounds. This supports the conclusion that based on the trial installation of PCIP technology, the GroS option was the most favorable from a construction viewpoint.

## Conclusion

The PCIP trial construction process was completed successfully and provided insight into the relative merits of the three support conditions that were investigated. The three subpanel support conditions constructed were AS, GraS, and GroS.

Each PCIP support condition was found to be feasible with seven or eight panel sections of each type successfully installed. Construction for each support condition was performed without extending beyond the permitted lane closure time of 6 a.m. This project was the first time this type of construction was performed, and consequently an improvement based on the learning curve was not realized. It is reasonable to assume that any subsequent installation of PCIP with one of the tested support conditions would produce a higher installation rate than that observed on-site.

An AHP was used to compare the support conditions based on their relative performance in four evaluation criteria: cost, installation rate, repeatability, and resiliency. The importance of each criterion to a transportation agency was established by pairwise comparisons of the criteria performed by MTO staff. The average results of the comparisons indicated that the order of the criteria ranked from most to least important was installation rate, cost, repeatability, then resiliency.

Members of the contractor's team that installed the trial PCIP project assigned quantitative performance values to installation rate, repeatability, and resiliency for each of the support conditions. Actual cost information was not made available, so the cost of each support condition was based on unit costs. The averages of these quantitative performance values were used for the AHP. General comments about each support condition were also collected. The comments indicated that the GroS design was straightforward and repeatable. The AS design relied on milling performance, which was found to be variable during the trial construction. The extra materials involved in the GraS condition were expected to reduce the installation rate.

The AHP analysis indicated that the GroS condition was the most favorable from a construction standpoint, with AS and GraS ranking second and third, respectively. Although the results obtained using the AHP are based on a relatively small trial project, they provide a reasonable basis upon which an agency could specify a PCIP support condition. Two sensitivity analyses were conducted to consider the effects of changes in the criteria weighting and the contractor's assigned performance values. The limits of these analyses were set to the maximum and minimum responses obtained from the MTO and contractor. The sensitivity analyses found that the ranking of the support conditions was largely insensitive to reasonable changes. In some iterations, the AS and GroS conditions were similarly ranked, but most of the sensitivity analysis iterations still indicated that the GroS condition was the preferred option.

Constructibility of the support condition is a critical factor for the success of PCIP as a repair strategy because rapid construction is an essential requirement. The constructibility evaluation shows that multiple PCIP support conditions can be feasibly constructed, and the results should inform any future applications of this strategy. Furthermore, the concepts of constructibility and decision-making criteria described in this paper may be applied to other applications of precast concrete pavement.

## Performance to date

Although this analysis considers the construction operations, the field performance of the trial section will also help determine the preferred support condition. The field section is being monitored with subpanel instrumentation and ongoing periodic site evaluations, and none of the rehabilitated sections have shown any failures related to support conditions to this point. Preliminary findings indicate that the trial section is functioning well under service conditions. No substantial difference in performance has been noted between the three support conditions to date.[17,18] Field performance evaluations to supplement the findings of this construction evaluation are ongoing.

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## Notation

$(AS)_i$ = performance of asphalt-supported option for criterion $i$

$(GraS)_i$ = performance of grade-supported option for criterion $i$

$(GroS)_i$ = performance of grout-supported option for criterion $i$

$i$ = criterion number

$w_1$ = average weighting for relative cost criterion

$w_2$ = average weighting for installation rate criterion

$w_3$ = average weighting for resiliency criterion

$w_4$ = average weighting for repeatability criterion

$w_A/w_B$ = ratio of importance of criterion A to criterion B

$w_i$ = average weighting for criterion $i$

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## Abstract


Precast concrete inlay panels (PCIPs) are a new rapid repair technique developed to address deep-seated rutting issues in asphalt pavements. Providing a uniform, stable support layer for precast concrete pavement is critical to its performance, and constructibility of this support is a key factor in the feasibility of PCIPs as an overnight repair technique. Three methods of PCIP support (asphalt supported, grade supported, and grout supported) were developed, designed, and constructed in a trial installation in Ontario, Canada. An analytic hierarchy process (AHP) analysis was performed to evaluate the performance of the options based on four construction-related criteria: cost, installation rate, repeatability, and resiliency. Input from the construction contractor and the Ministry of Transportation of Ontario was considered. This paper describes the support options, trial construction operations, and AHP evaluation. The results indicate that the grout-supported condition is most favorable and is recommended for future applications of PCIP for conditions similar to the trial section.



## Keywords

Analytic hierarchy process, constructibility, pavement rehabilitation, precast concrete pavement, support conditions.

## Review policy

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