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EVALUATION OF SUGGESTED PAVEMENT UTILITY-CUT PATCHING TECHNIQUES

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الخلاصـــة :

يمثل ترقيع أخاديد الخدمات في شوارع المدن مصدر قلق لكثير من المسؤولين المعنيـين نظراً لأثرها السيء على طبقات الرصف . ومن أهم آثار الترقيع السلبية فقدان الرصف لكلٍ من قدرته الإنشائية وقدرته على إعطاء مستوى تحمل جيد . وتعاني مدينة الرياض بشكل خاص من هذه المشكلة حيث إنَّ معظم هذه الأخاديد تنشأ في شوارع وطرق حديثة البناء .

إنَّ الهدف الرئيس من هذا البحث هو دراسة عدد من أساليب ترقيع هذه الأخاديد والتي من المتوقع أنْ تقلل من تلف طبقات الرصف . وقد عملت لهذا الغرض تجارب ميدانية حيث صمم وأُنـشيء سبعة عشر مقطعا مختلفا . وتختلف هذه المقاطع من حيث عرض الطبقة الاسفلتية (العلوية) والتي تمتد الى مابعد الأُخدود وهو مايمكن أن نطلق عليه (مفتاح) (Key) وتختلف كذلك من حيث سماكة الطبقة الاسفلتية . وقد تَـمَّ استخدام نوعين من المقاطع وذلك من حيث شكل الأُخدود : النوع الأول مقطع رأسي الجوانب (U-Sections) أما المقطع الآخر فهو ذو جوانب مائلة (V-Sections) . وقد استخدم جهاز المطرقة الساقطة لتقويم مقدرة التحمل الإنشائية للمقاطع المختلفة . ودلَّـت النتائج على أنَّ زيادة عرض الطبقة الاسفلتية إلى مابعد حافة الأُخدود (مفتاح) يقلل من انحراف الرصف في كثير من المقاطع كذلك دلَّ التحليل الاقتصادي على جدوى معظم المقاطع التي درست .

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ABSTRACT

Utility Cut Patchings (UCP) in city streets are a major concern for various city authorities because of their detrimental effect on pavements. Major effects are loss in both the structural capacity and the riding quality of the pavement. The city of Riyadh, in particular, is experiencing a special problem since most utility cuts are being constructed on recently-built highways and streets.

The main objective of this research was to investigate a number of patching techniques which potentially can reduce pavement deterioration. A field experiment was designed and seventeen sections were constructed utilizing different patching techniques. Variations among sections included use of variable key-widths and depths for the asphalt concrete layer for U-shaped utility cuts. In addition V-shaped patched sections were also investigated. Falling Weight Deflectometer (FWD) was used to evaluate the structural capacity of test sections. Results indicated that deflection of pavements would be reduced if different key-widths are used. In addition, economical analysis of the suggested patching techniques assert the feasibility of most of them.

EVALUATION OF SUGGESTED PAVEMENT UTILITY-CUT PATCHING TECHNIQUES

INTRODUCTION

Riyadh, the capital city of the Kingdom of Saudi Arabia, has witnessed widespread urban expansion, which has resulted in the construction of roads to provide access to the dispersed newly and developed areas. The total area of paved roads in Riyadh exceeds 160 million square meters. The construction of utilities, however, was lagging in most cases. Gradual provision of utilities has been done in stages, and this frequently resulted in the construction of one or more utility patches in newly-built roads. For sewage utility alone, it is estimated that more than 2 925 000 square meters of cuts in the roads were made by 1988. Other types of utilities include water, electricity, and telephones.

Construction of utilities in streets usually results in noticeable decline of both riding quality and structural integrity of pavements. Current rehabilitation and overlay design procedures for pavements utilize deflection measurements prior to determining the needed thickness of an overlay. It has been established that utility cut patching can result in structural deterioration of existing pavements [1, 2]. An increase in deflections was observed in pavements directly after construction of utilities [3].

In this latter study, FWD measurements were taken at 49 different locations and the results have shown that the ratio of the average deflection at center of patch to that for uncut pavement section was in the order of 2 to 1.

The impact of utility cuts on the remaining life of existing pavements may be very pronounced. One study [2] suggests that loss in pavement life due to utility cuts is about 40 percent for major arterials and 15 percent for residential areas. The resulting direct cost impacts can be estimated based on current overlay cost.

The objectives of this study were: (1) to evaluate the effectiveness of various patching techniques in reducing pavement deterioration; and (2) to study the economic feasibility of these patching techniques.

EXPERIMENTAL INVESTIGATION

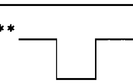
Based on a review of the major factors related to utility cut patching [3] it was concluded that the most critical factors are the trench width and the ratio of the thickness of asphalt layer of patch to that of the uncut section. In addition, the interface between the existing pavement and the trench is considered as a weak plane due to two factors. First, it is difficult to obtain a high degree of compaction using conventional compacting techniques and second, this interface represents a continuous vertical crack in the pavement. It is hypothesized that if the patch is constructed in such a way that this vertical crack is staggered in the top asphalt layer and/or if this asphalt layer thickness is increased then the ratio of deflection in the patch to that of existing pavement would be reduced. Staggering of the crack in the top layer can be accomplished by increasing the width of the cut in the top layer as shown in Figures 1 and 2. The distance between the edge of the original cut and that of the extended cut will be referred to as key-width (kw).

In order to test experimentally the effectiveness of the above hypothesis, test sections were constructed on a utility cut 110 cm wide and 150 cm deep. A total of 17 test sections were constructed, including a con-

Table 1. Dimensions of Test Sections.

Section No.	Configuration**	kw (cm)	t (cm)	t/t_e	Length (m)
1*	1	0	15.0	1.0	50
2	1	20	15.0	1.0	50
3	1	40	15.0	1.0	50
4	1	60	15.0	1.0	50
5	1	80	15.0	1.0	50
6	1	20	7.5	0.5	40
7	1	40	7.5	0.5	40
8	1	60	7.5	0.5	40
9	1	80	7.5	0.5	40
10	1	20	22.5	1.5	40
11	1	40	22.5	1.5	40
12	1	60	22.5	1.5	40
13	1	80	22.5	1.5	40
14	2	0	15.0	1.0	40
15	2	20	15.0	1.0	40
16	2	40	15.0	1.0	40
17	2	60	15.0	1.0	40

*Control Section **



Config. 1

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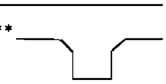

Config. 2

trol section. Two distinct configurations for utility cut sections were utilized: a rectangular section (U-shaped) and a partially sloped section with 1:1 slope (V-shaped). For the rectangular section key width was varied between 20 and 80 cm while for the V-shaped it was varied between 20 and 60 cm. Typical layouts of the U- and V-shaped test sections are shown in Figures 1 and 2 respectively. The thickness of the asphalt layer was varied in the rectangular configuration only. These thicknesses were 7.5 cm, 22.5 cm, and 15 cm; the last being also the thickness of the asphalt layer for the original pavement and the sloped configuration. Table 1 gives detailed information on dimensions of the 17 test sections. A typical cross section showing backfill properties is given in Figure 3.

The effectiveness of each test section in reducing pavement deterioration caused by UCP was judged by measuring deflection for each test section and comparing it with that of the control section. FWD was used to measure the deflection at four distinct points, namely: center, inner, and outer edges of the patch, and existing pavement far from the cut. These points are shown in Figure 4. Deflections at these points will be referred to as: *DC, DI, DO,* and *DE,* respectively.

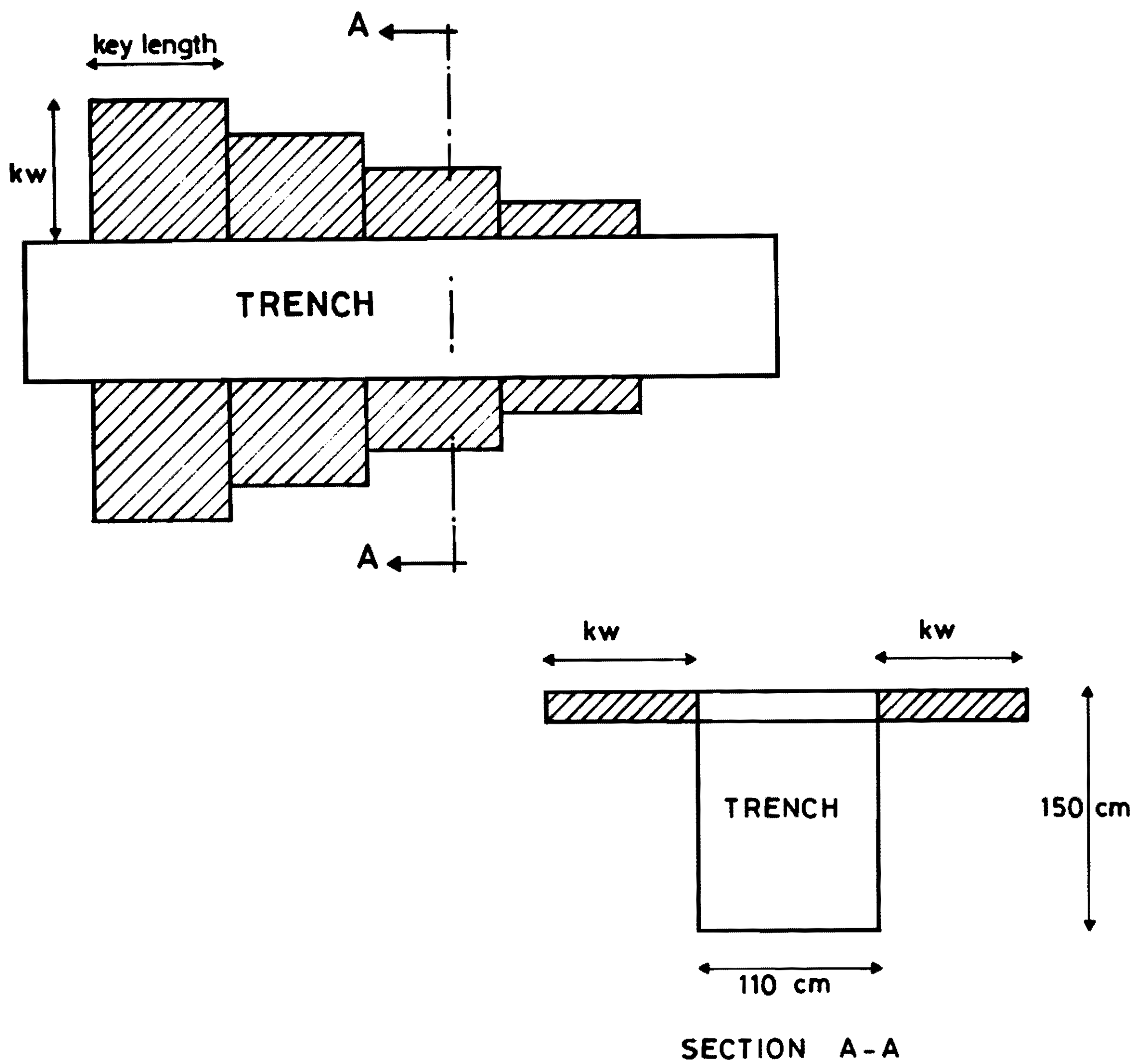

Figure 1. A Typical Rectangular Test Section.

TEMPERATURE CORRECTION FACTORS

The measurements of FWD deflections were taken at different surface temperatures. In order to conduct the analysis, correction of these measurements to a standard temperature is essential. A standard temperature of 40°C, which is believed to be representative of Riyadh streets' temperature, was selected for this study.

The temperature correction factors were determined based on an extensive testing of an existing pavement during various hours of the day, where surface temperature ranged between 21°C and 65°C [3]. Due to the short period of time during which deflection measurements were taken, any variation in deflection was attributed to changes in temperature. Linear regression analysis was employed to establish relationship between deflection (δ) and temperature (T) as follows:

$$\delta = 0.010145\, T + 3.945 \qquad (R^2 = 0.97) \quad (1)$$

where δ is in microns (10^{-6} m) while T is in degrees celsius (°C).

Correction factors (F) for various temperatures were established based on Equation (1). Table 2 summarizes the corrected deflection for all test sections. These deflections are the averages of three measurements which all were taken at the same section.

STRUCTURAL EVALUATION OF TEST SECTIONS

The corrected measured deflections *DC, DI, DO,* and *DE* were used as the basis for evaluating the structural condition of the various test sections immediately after construction. Analysis of variance (ANOVA) and regression analysis were used to determine the effect of the two tested variables;

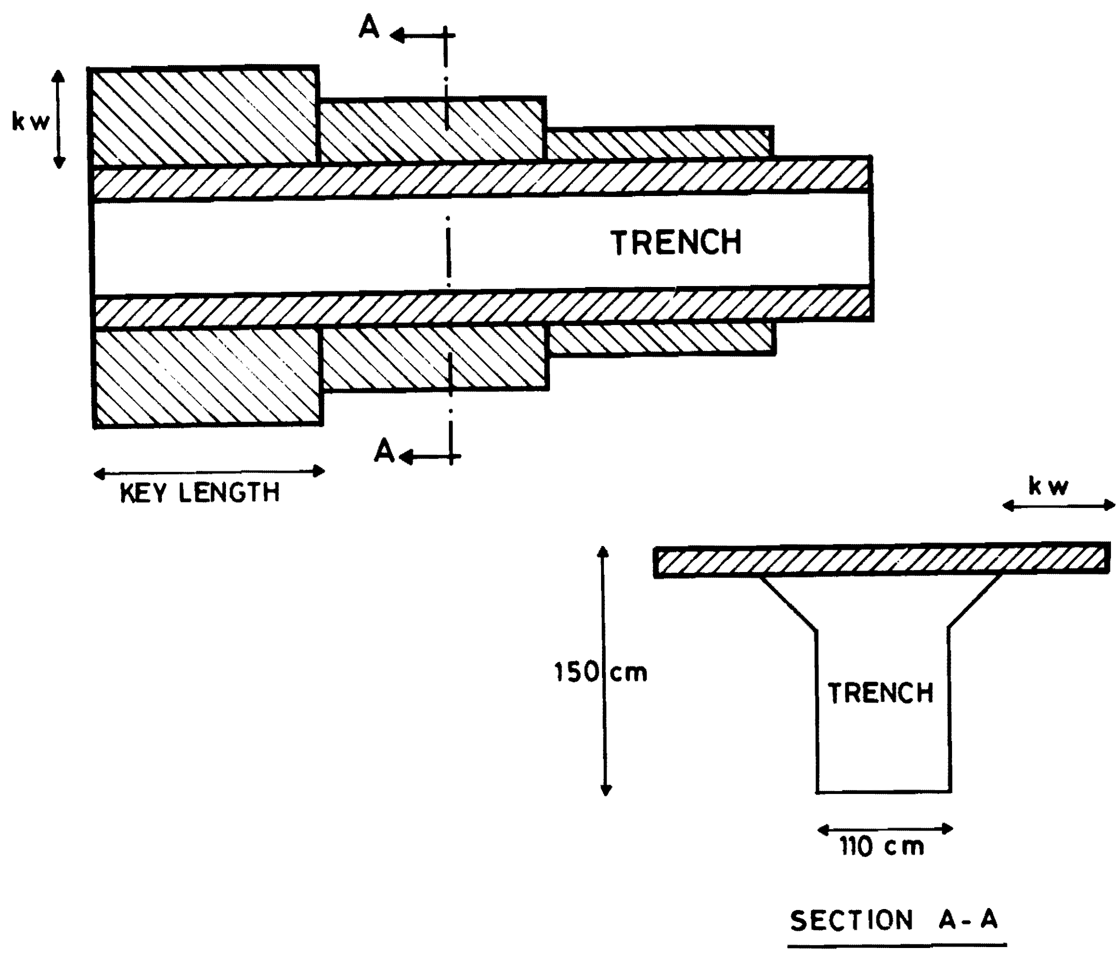

Figure 2. A Typical V-shaped Test Section.

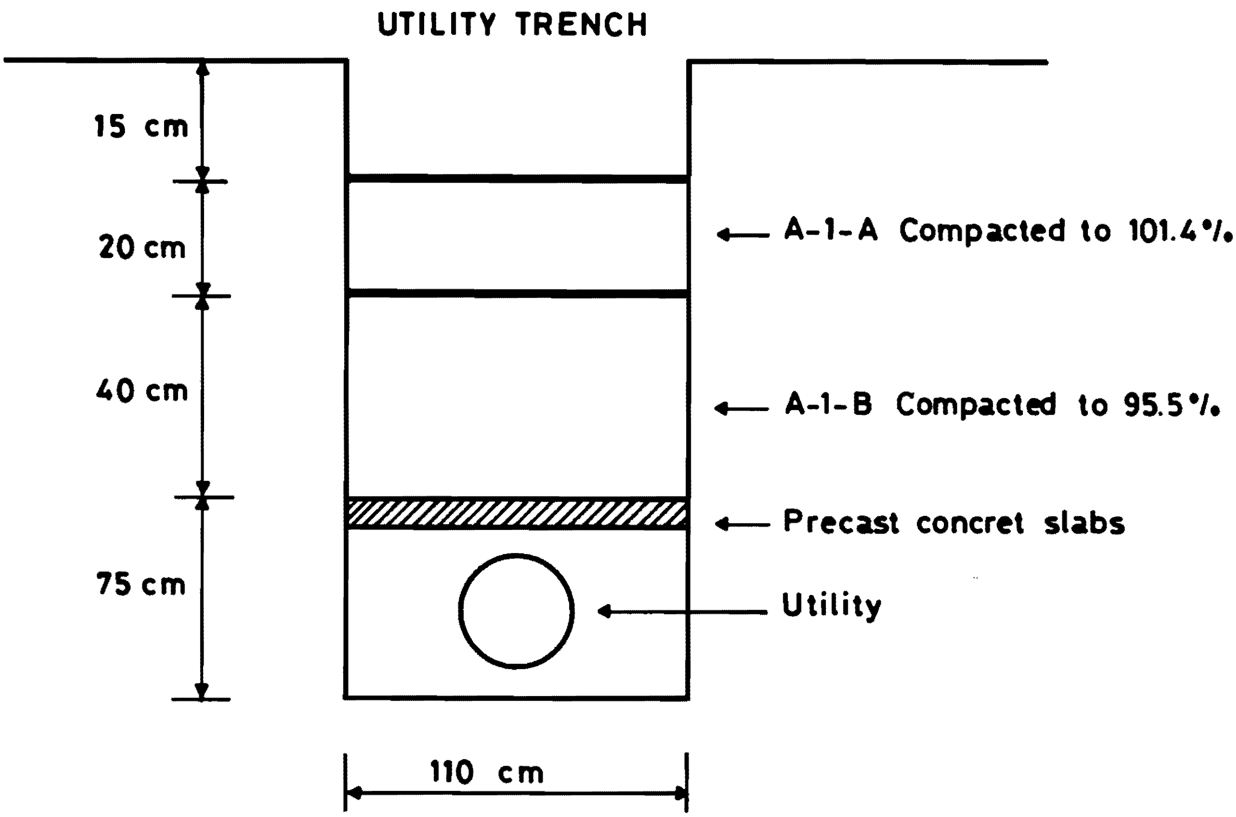

Figure 3. A Typical Cross Section Showing Backfill Materials.

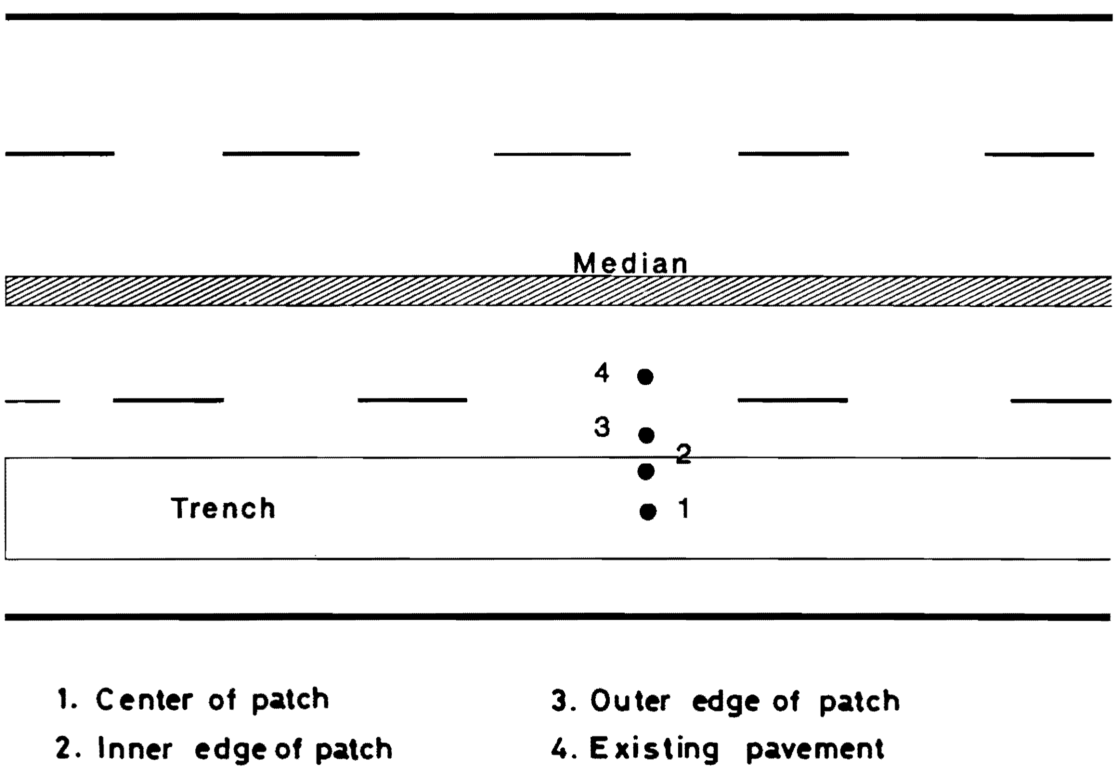

Figure 4. Location of Deflection Measurement.

key-width (kw) and thickness of asphalt layer (t), on patch deflection.

Since all measurements were made in the same site and since the materials as well as the compaction procedure and the backfill material were all the same it was possible to assume that the variability is mainly caused by the changes in the upper layer. In addition, it is well known that the pavement deflection under or close to the load is more influenced by the upper layer modulus while the deflection at greater distances away from the load is affected more by the subgrade modulus. All this has led to the decision to use the peak deflection (deflection under the center of the load) to compare the structural capacity of various test sections.

Figure 5 compares the deflection measured at the center of patch (DC) for the control section (Section No. 1) and the 16 remaining test sections. It is readily observed that, if the 7.5 cm section is excluded, DC in the control section is the highest and hence using the key has improved the structural capacity of the pavement (lower deflection). It is essential to note that the existing pavement, where those test sections were constructed, varied in strength from one point to the other. A previous study [3] has indicated that this condition can greatly influence deflection in the patch. To alleviate any effect of differences in existing pavements, patch deflections were put in terms of ratio to the existing pavement deflection as follows:

$$DCR = DC/DE \quad (2)$$

$$DIR = DI/DE \quad (3)$$

$$DOR = DO/DE \quad (4)$$

where DCR, DIR, and DOR are ratios of deflection at center, inner edge, and outer edge of patch respectively, to the deflection of existing pavement, DE.

Table 3 shows the average corrected deflection ratios for the specific combinations of kw and t used in this study. In this table the ratio t/t_e is used to indicate the asphalt layer thickness of sections, t_e being the asphalt layer thickness of the existing pavement (15 cm). Two-factor ANOVA was used to determine the significance of these two variables (and their interaction) at the 5% significance level. The results of this analysis are given in Table 4 and suggest that for DCR both kw and t are significant but not their interaction. For DIR, however, the effect of the two variables and their interaction are significant. The deflection ratio for the outer edge,

Table 2. Average Corrected Deflection* for Test Sections.

Section No.	Configuration	DC	DI	DO	DE
1**	1	735.00	755.00	465.00	195.00
2	1	578.33	603.33	502.50	278.33
3	1	557.50	595.83	464.17	215.83
4	1	535.00	625.00	439.17	211.67
5	1	544.17	585.00	359.17	179.67
6	1	631.67	669.17	673.33	225.00
7	1	761.67	655.83	699.17	158.33
8	1	752.50	724.17	650.00	200.83
9	1	1061.67	899.17	717.50	177.50
10	1	310.00	351.67	415.00	162.50
11	1	427.50	491.67	486.67	203.33
12	1	377.50	335.83	317.50	191.67
13	1	426.67	369.17	325.83	192.50
14	2	595.00	452.50	452.50	135.00
15	2	595.00	547.50	417.50	122.50
16	2	477.00	445.00	402.50	127.50
17	2	605.00	650.00	570.00	177.50

* Deflection in Micrometer
** Control Section

Table 3. Average Deflection Ratio for Various Key-widths (kw) and Asphalt Thickness Ratios (t/t_e).

t/t_e / kw (cm)	0.5	1.0	1.5
DCR			
20	2.8085	2.5894	2.0220
40	2.0828	2.1018	6.2834
60	1.9237	3.9454	3.2588
80	4.8412	2.5237	2.2408
DIR			
20	2.9774	2.1678	2.1650
40	4.1691	2.7623	2.4132
60	3.6634	2.9565	1.7904
80	5.0921	3.5253	1.9337
DOR			
20	3.0074	1.8104	2.5443
40	4.2520	2.1667	2.3839
60	3.2018	2.0818	1.6979
80	4.1888	2.1481	1.6933

DOR, is significantly influenced by the thickness of the asphalt layer and not by the key-width. Since this point is mainly located on the existing pavement it is expected that its deflection is more likely to be affected by the strength (thickness) of the top layer rather than the key-width.

In order to determine the best estimates for the three dependent deflection ratios corresponding to the tested levels of key-width and thickness of asphalt layer, the following model was used:

Predicted Deflection Ratio,

$$\hat{Y}_{ijk} = \hat{\mu}_{..} + \hat{\alpha}_i + \hat{\beta}_j + \widehat{(\alpha\beta)}_{ij} \quad (5)$$

where

$$\hat{\mu}_{..} = \bar{Y}_{...} = \frac{\Sigma\Sigma\Sigma\ (\text{Deflection Ratio})_{ijk}}{36}$$

$$\hat{\alpha}_i = \bar{Y}_{i..} - \bar{Y}_{...}$$

$$\hat{\beta}_j = \bar{Y}_{.i.} - \bar{Y}_{...}$$

$$\widehat{(\alpha\beta)}_{ij} = \bar{Y}_{ij.} - \bar{Y}_{i..} - \bar{Y}_{.j.} + \bar{Y}_{...}$$

The results of these calculations for the three deflection ratios are given in Table 5. Since these ratios indicate the amplitude of deflection at the three points in the trench with respect to the deflection in existing uncut section, it is apparent that the structural deterioration due to utility cuts is appreciable and varies from one location to the other. Let us

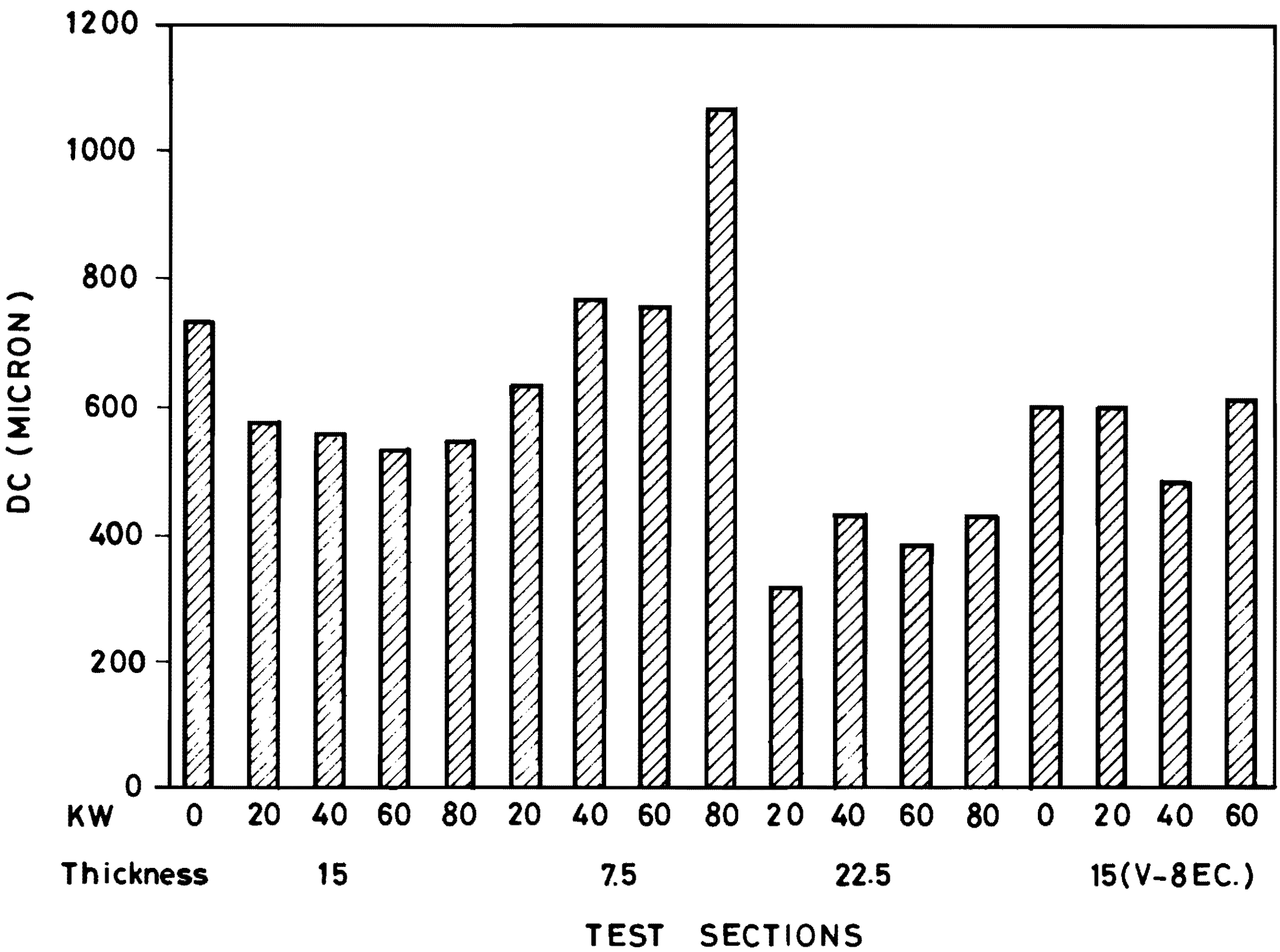

Figure 5. Comparison of DC Deflection Measurements for Test Sections.

Table 4. Analysis of Variance for Deflection Ratios.

Source of Variation	DF	ANOVA SS	Mean Square	F Value	$PR>F$
DCR					
kw	3	12.983	4.33	5.97	0.0034
t	2	37.909	18.94	26.14	0.0001
$kw \times t$	6	8.724	1.45	2.00	0.1046
Residual	24	17.426	0.73		
Total (Corr.)	35	77.005			
DIR					
kw	3	5.686	1.90	9.50	0.0003
t	2	21.895	10.96	54.85	0.0001
$kw \times t$	6	4.933	0.82	4.12	0.0056
Residual	24	4.781	0.20		
Total (Corr.)	35	37.319			
DOR					
kw	3	1.919	0.64	1.70	0.1945
t	2	20.40	10.19	27.04	0.0001
$kw \times t$	6	3.933	0.66	1.74	0.1554
Residual	24	9.0448	0.38		
Total (Corr.)	35	35.289			

Table 5. Results of Best Estimate for Deflection Ratios.

t/t_e / kw (cm)	0.5	1.0	1.5
DCR			
20	2.8045	2.0828	1.9237
40	4.8412	2.5894	2.1018
60	3.9454	2.5237	2.0223
80	6.2834	3.2588	2.2408
DIR			
20	2.9774	2.1678	2.1650
40	4.1691	2.7623	2.4132
60	3.6634	2.9565	1.7904
80	5.0921	3.5253	2.0150
DOR			
20	3.0070	1.8104	2.5443
40	4.2520	2.1665	2.3839
60	3.2018	2.0817	1.7978
80	4.1094	2.1481	1.6940

assume that the critical deflection ratio for each combination of key-width and thickness is the maximum value for that combination. The critical values which are given in Table 6 indicate that for a patched pavement the minimum deterioration occurs when the key-width is 60 cm and the thickness ratio is 1.5.

Regression analysis was also performed on deflection ratio data to correlate deflection ratios with the key-width. Due to the fact that the thickness of asphalt layer might affect deflection ratios, deflection ratio models were established for fixed levels of asphalt thickness. However, regression models were only established for *DCR* and *DIR* since the effect of *kw* on *DOR* was found to be insignificant. The results of this analysis are given in Table 7. The correlation coefficients for all these models except one, are relatively high, which means that deflection ratio can be predicted with a relatively high accuracy from the key width. However, more data are needed to test and verify these models before they can be generalized.

To determine the benefit of using a V-shaped trench *vs* the conventional rectangular trench, results of deflection for both types were analyzed using two-

Table 6. Critical Deflection Ratios (max. for a given kw and t/t_e).

t/t_e / kw (cm)	0.5	1.0	1.5
20	3.0070	2.1678	2.5443
40	4.8412	2.7623	2.4132
60	3.9454	2.9565	2.0221
80	6.2834	3.5253	2.2408

Table 7. Regression Models for Deflection Ratios *vs* kw for a Given Thickness Ratio.

Model	R^2
Thickness = 0.5 t_e	
$DCR = 2.0834 + 0.0477\ kw$	(R^2 = 0.70)
$DIR = 2.5159 + 0.0292\ kw$	(R^2 = 0.72)
Thickness = 1.0 t_e	
$DCR = 1.7481 + 0.0173\ kw$	(R^2 = 0.85)
$DIR = 1.7863 + 0.0213\ kw$	(R^2 = 0.97)
Thickness = 1.5 t_e	
$DCR = 1.8542 + 0.0044\ kw$	(R^2 = 0.70)
$DIR = 2.3640 + 0.0054\ kw$	(R^2 = 0.24)

way ANOVA. Since only one level of asphalt thickness was used ($t = 15$ cm), the V-section was only compared with rectangular test sections having the same asphalt thickness. Results of this analysis indicated that deflection ratios of the V-section are significantly higher than those of the U-section at 5% significance level. The results are shown in Table 8. Due to the added difficulty of constructing a V-section, its use is not recommended.

OVERLAY AND COST ANALYSIS

It has been shown above that utility-cut patching induces some deterioration in pavement structure, often necessitating overlaying all or part of the affected pavement. The cost of overlaying a given pavement section depends on the required overlay thickness which is a function of the extent of pavement deterioration.

The required overlay thickness for each test section was estimated using FWD measurements and the AASHTO method for overlay design [5]. A typical example of overlay thickness calculations is given in the appendix. The results are shown in Table 9. The control section requires the largest overlay thickness (19.5 cm) while a section with a thickness ratio t/t_e of 1.5 requires the smallest overlay thicknesses. Other sections, however, gave intermediate values.

In order to further compare the above suggested patching techniques, the total cost of each test section was estimated. The total cost includes the cost of patching the utility cut (using various techniques) and the cost of the required overlay. The cost of patching includes the cost of the AC layer as well as the additional cost of work and/or materials needed over those required for the control section.

Using the above calculated overlay thicknesses and unit cost values presented in Table 10 the cost of overlaying two 3.65 m wide lanes was estimated. For each section, the total cost and the percent of extra cost over that of the control are shown in Table 11. These results show that for most sections there is a reduction in total cost (minus sign) over that of the control. The highest reduction in total cost was obtained for section No. 10 (20 cm key-width and a t/t_e ratio of 1.5). Other sections of the same *AC*

Table 8. Analysis of Variance for the Effect of Trench Type (Configuration) and Key-width.

Source of Variation	Sum of Square	DF	Mean Square	F Ratio	Sig. Level
			DCR		
kw	2.74	3	0.91	2.121	0.1377
Config	13.80	1	13.80	32.066	0.0000
kw × Config	8.75	3	2.92	6.778	0.0037
Residual	6.89	16	0.43		
Total (Corr.)	32.18	23			
			DIR		
kw	0.82	3	0.27	1.153	0.3581
Config	7.48	1	7.48	31.502	0.0000
kw × Config	8.38	3	2.79	11.764	0.0003
Residual	3.80	16	0.29		
Total (Corr.)	20.49	23			
			DOR		
kw	1.56	3	0.52	1.079	0.3860
Config	17.51	1	17.51	36.228	0.0000
kw × Config	3.38	3	1.13	2.330	0.1131
Residual	7.73	16	0.48		
Total (Corr.)	30.19	23			

Table 9. Required Overlay Thickness for Various Test Sections.

Section No.	*kw* (cm)	t/t_e	Overlay Thickness** (cm)
1*	0	1.0	19.5
2	20	1.0	15.5
3	40	1.0	16.5
4	60	1.0	16.0
5	80	1.0	15.5
6	20	0.5	16.0
7	40	0.5	17.5
8	60	0.5	15.0
9	80	0.5	18.0
10	20	1.5	3.5
11	40	1.5	5.0
12	60	1.5	2.0
13	80	1.5	10.5
14	0	1.0	8.5
15	20	1.0	15.0
16	40	1.0	12.5
17	60	1.0	17.5

* Control
**Based on 10^9 EAL_{18} traffic and terminal serviceability index of 2.5.

Table 10. Unit Cost Values Used in Cost Analysis.

Material or Construction Type	Cost
Asphalt Concrete	145 SR/m^3
Aggregate Base	30 SR/m^3
Prime Coat	0.78 SR/m^3
Milling	3 SR/m^2
Cut	25 SR/m^3

Table 11. Construction, Overlay, and Total Cost of Various Test Sections.

Section No.	Construction Cost SR/m	Overlay Cost SR/m	Total Cost SR/m	% Extra Cost
1*	24.8	206.0	230.8	0
2	37.4	164.0	201.4	−13.0
3	50.0	174.6	224.6	−3.0
4	62.6	169.4	232.0	0.5
5	75.2	164.0	239.3	4.0
6	24.5	169.4	193.9	−16.0
7	33.6	185.4	219.0	−5.0
8	42.8	158.8	201.6	−13.0
9	52.0	190.6	242.6	5.0
10	52.0	37.0	89.0	−61.0
11	69.7	53.0	122.7	−47.0
12	87.4	21.2	108.6	−53.0
13	105.1	111.2	216.3	−6.0
14	43.3	90.0	133.3	−42.0
15	55.9	158.8	214.7	−7.0
16	68.5	132.0	200.5	−13.0
17	81.1	185.2	266.3	15.0

*Control section.

thickness also showed a large reduction in total cost even though their construction costs are relatively high. This is due to the small overlay thickness required for these sections.

For each set of sections constructed with the same *AC* thickness there is a trend for an increase in total cost as the key-width increases. Furthermore, the 20 cm key-width sections gave the lowest total cost, which can be explained by the fact that these sections have the least construction cost.

So, as far as cost is concerned, section No. 10 is the best patching alternative. Furthermore, all sections constructed with a 20 cm key-width are the best in their respective classes.

CONCLUSIONS

1. Constructing a utility cut patch with a key or increasing the thickness of the asphalt layer of patch are both effective in reducing patch deflection, however, the effectiveness of the later is more pronounced.
2. Best estimates show that sections with a 60 cm key-width and an asphalt thickness ratio (t/t_e) of 1.5 are the most effective in reducing pavement deflection.
3. Results of economical analysis indicated that sections constructed with a 20 to 60 cm key-width are more economical than those without a key. Furthermore, a maximum reduction in cost was obtained for sections having a 20 cm key-width and an asphalt thickness ratio (t/t_e) of 1.5.
4. Due to the higher construction cost of sections having key widths of more than 20 cm, they are not economical and hence their use is not recommended, although they may be more effective in reducing pavement deflections than other sections. However, it should be emphasized that monitoring the performance of these test sections over a period of time (say 5 to 10 years) is necessary before any final conclusion can be reached.

REFERENCES

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APPENDIX

A typical example of Overlay Thickness Calculation.

Data

Deflection at center of FWD plate = 37.1×10^{-3} in (corrected to 70°F as specified by AASHTO Guide V.1)

Deflection at the radial distance r ($r = 24$ in) = 3.1×10^{-3} in

FWD Load = 18 000 lb

Radius of loading plate, a_c = 5.91 in

Poisson's Ratio (cohesive soil) = 0.5, hence $S_f = 0.2686$

Traffic expected up to 2.5 terminal serviceability, $Y = W_{18} = 10^9$ *EAL*

Total pavement thickness = 13.8 in

Calculations

Step 1

$$E_{sg} = P\ S_f/(d_r\ r) = 18\,000 \times 0.2686/(24 \times 3.1 \times 10^{-3})$$
$$= 64983 \text{ psi.}$$

First, a check has to be made to ensure that the selected outer geophone is located at a distance $1 < r/a_e < 6$, where a_e is the effective radius of the subgrade stress zone.

$a_e = a_c/F_b$ where F_b is a deflection factor.

F_b can be obtained from Figure 5.6 in AASHTO Guide V.2, depending on H_e/a_c value

H_e value can be obtained as follows:

$$H_e = 0.9 \sum_{i=1}^{2} h_i \left[\frac{E_i(1-\nu_{sg}^2)}{E_{sg}(1-\nu_i^2)}\right]^{1/3}$$

$$H_e = 0.9 \left[5.9 \left(\frac{400000(1-0.5^2)}{64983(1-0.35^2)}\right)^{1/3} + 7.87 \left(\frac{30000(1-0.5^2)}{64983(1-0.35^2)}\right)^{1/3}\right]$$

$H_e = 14.43$,

$H_e/a_c = 14.43/5.91 = 2.44 \rightrightarrows F_b = 0.37$ (Figure 5.6 in [5]),

$$a_e = a_c/F_b = 5.91/0.37 = 15.97$$

$$\therefore r/a_e = 24/15.97 = 1.5,$$

which is within the range 1 to 6.

So, the 24 in radial distance for deflection location to be used for subgrade modulus calculation is satisfactory.

Step 2

The second step is to calculate the overlay thickness based on the subgrade modulus and central deflection (corrected to 70°F). The following equation is used to calculate overlay structural number:

$$SN_{OL} = SN_Y - F_{RL}(SN_{xeff})$$

where,

SN_Y is the total structural number of the pavement after the overlay

F_{RL} is the remaining life factor.

SN_{xeff} is the total effective structural number of the existing pavement structure above the subgrade.

SN_Y is obtained from AASHTO Design Nomograph (Figure 3.1 in AASHTO Guide V.1) for 10^9 EAL_{18} and terminal serviceability, *pt,* of 2.5.

$$\therefore SN_Y = 4.15$$

F_{RL} is obtained as follows:

F_{RL} depends on the two factors R_{LX} and R_{LY},

R_{LX} is obtained from Figure 5.13 in AASHTO Guide V.1, based on c_x value.

$$c_x = SN_{xeff}/SN_O\ .$$

SN_{xeff} is obtained from the relationship between the central deflection and SN_{xeff} given by the equation presented on page N-8 of AASHTO Guide V.1. Due to the complicated form of this equation a computer program was used to perform the trial and error calculation of SN_{xeff} corresponding to a central deflection, d_o, of 37.1×10^{-3}.

$$SN_{xeff} = 2.0$$

$$SN_O = D_1\, a_1 + D_2\, a_2\, m_2\ .$$

For the existing pavement $D_1 = 5.91$ in, $a_1 = 0.42$ (for 40 000 psi modulus), $D_2 = 7.87$ in, $a_2 = 0.14$ (for 30 000 psi modulus), and $m_2 = 1$.

$$\therefore SN_O = 3.58$$

$$\therefore c_x = SN_{xeff}/SN_O = 2/3.58 = 0.559.$$

$\therefore R_{LX} = 0.0$ (Figure 5.13 in AASHTO Guide V.1).

$$R_{LY} = (N_{fy} - Y)/N_{fy}$$

where,

N_{fy} is the number of repetitions (EAL_{18}) to failure for $SN_Y = 4.15$, which was obtained above, and terminal serviceability of 2.0

$N_{fy} = 1.42 \times 10^9\ EAL_{18}$

Y is the design number of repetitions which equals $10^9\ EAL_{18}$.

$$\therefore R_{LY} = (1.42 - 1)\ 10^9/(1.42 \times 10^9) = 0.291$$

Using the above values for R_{LX} and R_{LY} the remaining life factor, F_{RL}, was obtained from Figure 5.17 in AASHTO Guide V.1.

$$\therefore F_{RL} = 0.587.$$

Finally, knowing SN_Y, F_{RL}, and SN_{xeff} the required structural number for the overlay is calculated from the following equation:

$$SN_{OL} = SN_Y - F_{RL}(SN_{xeff}) = 4.15 - 0.59(2) = 2.97.$$

Knowing the overlay structural number the overlay thickness is calculated as follows:

Overlay thickness,

$$t = SN_{OL}/a_1 = 2.97/0.42 = 7.07 \text{ in} = 18 \text{ cm}.$$

Due to the complexity of some of the equations involved, a computer program was written to perform the above calculations given deflection, deflection location, traffic, terminal serviceability, properties of surface and base course layers.