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Effect of Curling on As-Constructed and Early Life Smoothness of PCC Pavements

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ABSTRACT

Pavement smoothness is a key factor in the performance and economics of a pavement facility. This paper presents the results of a study of the effect of curling on as-constructed and early life smoothness of Portland cement concrete pavements (PCCP) in Kansas. Six test sections on three newly built PCCP projects on I-70 and I-135 were selected. Material properties of different layers were collected. As-constructed and periodic (at 4-month intervals) profile measurements were taken by a South Dakota-type profiler on each wheel path of both driving and passing lanes. International Roughness Index (IRI) was used as the smoothness statistic.

A digital method was developed to separate curling from the measured profiles using Fast Fourier Transform (FFT). IRI values were calculated for the curled profile as well as for the profiles without curling. The contribution of curling to the measured smoothness was found to be significant. A set of models was developed to describe curling and early life smoothness in terms of different construction, geometric and climatic variables. The as-constructed and early life curling were found to be significantly affected by the PCCP slab thickness and the stabilized base stiffness. If curling could be minimized then as-constructed smoothness, in terms of IRI, becomes function of the PCCP slab thickness, 28-day compressive strength of concrete, change in plasticity index of subgrade soil after lime treatment, and strength of the base layer. Several recommendations were developed to minimize the effect of curling on as-constructed smoothness.

Key words: pavement curling—pavement materials—portland cement concrete

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INTRODUCTION

Smoothness of a newly constructed Portland Cement Concrete Pavement (PCCP) is now a major concern in the highway industry. State highway agencies have recognized pavement smoothness as an important measure of pavement performance. Pavement smoothness is mostly controlled by the longitudinal profile of the road. Smoothness is an important indicator of riding comfort and safety. Several factors contribute to the pavement roughness: built-in construction irregularities, traffic loading, environmental effects, and construction materials (*1*). Construction irregularities can cause variations in the pavement profile from the design profile. Environmental effects such as temperature and moisture gradient across the thickness of slab can cause curling, which in turn, affects the smoothness of the pavement (*2*).

The American Concrete Institute (*3*) defines curling as "the distortion of any originally essentially linear or planar member into a curved shape such as the warping of a slab due to creep or to differences in temperature or moisture content in the zones adjacent to its opposite faces". A concrete slab tends to curl when it is subjected to a temperature and/or moisture gradient across the thickness of the slab. Curling induces stresses in the slab as the pavement is restrained by its weight and the reaction from the subgrade. The thermally induced stress caused by such interaction can be a significant factor in contributing to early pavement cracking (*4*). This may be critical, particularly within a few hours after placement, since concrete in the early stage of hydration may have insufficient strength to prevent cracking. Ytterberg (*2*) reported that curling is caused by drying shrinkage and by moisture and temperature gradients across the thickness of the slabs. Negative drying shrinkage and moisture gradients are usual in slabs on grade and they cause upward curling. Negative moisture gradients and upward curling are increased if the slab is made from high shrinkage concrete, or if the slab is exposed to low humidity air, or if the subgrade or sub-base under the hardened slab has a high moisture content. The most common positive temperature gradient with its downward edge curling is that caused by heat from the sun on the upper slab surface (*2)*. Upward edge curling is caused by negative moisture gradients, can be increased by cold slab surface temperatures or by hotter slab bottom temperatures.

Tremper and Spellman (*5*) made displacement profilograms of a number of highway pavements. They found that upward curling was the dominant condition. The upper portion of a pavement slab is nearly always drier than the bottom part, and that upward curling due to a moisture difference may be offset by wholly or partially in the afternoon by a higher temperature at the top than the bottom. Temperature rise due to solar radiation was not thought to be high enough to produce downward curling in the daytime. At night, the upward curling increased and reached to maximum (*5*).

OBJECTIVES

The objectives of this study was to evaluate and quantify the effect of curling on as-constructed and short-term smoothness of PCC pavements, and to identity the factors that affect curling and roughness, so that the occurrence of curling could be minimized through modifications to the design and/or construction practices.

TEST SECTIONS

Profile data was collected on six (*6*) PCCP sections in Kansas built in the Summer and Fall of 2000. All sections are jointed plain concrete pavements with 5-meter joint spacing and doweled joints, and are located on Interstate routes 70 and 135. All sections have 100 mm stabilized drainable subbase, known as bound drainable base (BDB) in Kansas, and 150 mm lime-treated subgrade. A drainable base is defined as the one with a minimum of 303 m/day (1000 ft/day) permeability. Most of the subgrade materials are fine and plastic. The effect of lime-treatment was variable as indicated by the before- and after-lime treatment plasticity index values shown in Table 1. Subbase stabilization was done with cement and cement-fly ash binder. The 28-day compressive strength of BDB materials was quite variable and varied from 0.90 MPa to 4.44 MPa (shown in Table 1).

TABLE 1. Base and Subgrade Properties

Section	Plasticity Index (%)			Subgrade Material Passing 75-micron Sieve (%)	BDB Compressive Strength (MPa)
	Before Lime Treatment	After Lime Treatment	Change		
PTS-1	22.5	20.0	2.5	96	0.90
PTS-2	20.5	18.5	2.0	96	N/A
STS-1	20.0	N/A	-	90	1.93
STS-2	23.0	N/A	-	90	2.24
TTS-1	26.5	19.5	7.0	97	4.44
TTS-2	20.0	21.5	0.5	97	4.11

Two of the I-70 sections, located near Paxico (PTS-1 and PTS-2), consist of 320 mm concrete slab while the other two on I-70 in Topeka (TTS-1 and TTS-2) have 280 mm slabs. The two test sections on I-135 in Salina (STS-1 and STS-2) have 290 mm concrete slabs. Both I-70 and I-135 are 4-lane divided highways. All test sections consist of 32 continuous slabs (i.e. 160 m long) and are located in one direction. Two different compositions of aggregates were used in the concrete as shown in Table 2. Sixty percent fine and 40% coarse aggregates were used for concrete on the Paxico test section. All other sections had 45% coarse aggregate and 55% fine. Concrete on all sections were air-entrained. The water-cement ratio varies from 0.45 on the Salina test section to 0.49 on the Paxico test section. The Paxico section had the highest 3-day modulus of rupture values (4.1 MPa) of concrete but the lowest 28-day core compressive strength (31.7 MPa).

TABLE 2. Concrete Mix Design Properties

Section	% Aggregate in Mix		% Air	Water-Cement Ratio	Cement Content (kg/m^3)	28-day Core Compressive Strength (MPa)	3-day Modulus of Rupture (MPa)
	Coarse	Fine					
PTS-1	40	60	6.5	0.49	330	31.7	4.10
PTS-2	40	60	6.5	0.49	330	31.7	4.10
STS-1	45	55	7.0	0.45	325	44.5	3.30
STS-2	45	55	7.0	0.45	325	44.5	3.30
TTS-1	45	55	7.5	0.47	335	41.4	3.92
TTS-2	45	55	7.5	0.47	335	41.4	3.92

DATA COLLECTION

Data was collected in different phases of construction. Data collected can be divided into three categories: a) Inventory data; b) climatic data; and c) profile data. Inventory data includes layer and material properties data, such as, Plasticity Index (PI) of subgrade soil (before and after lime treatment), compressive strength of concrete used for the BDB layer, concrete properties etc. as shown in Tables 1 and 2. Inventory data also include road structure and geometry data as well as traffic data in terms cumulative 80-kN (18 kip) Equivalent Single Axle Loads (ESAL). Climatic data includes temperature data of pavement top and bottom during the day of construction (thermocouples were used for this purpose) as well as mean monthly precipitation data and air temperature data.

After construction, profile data was collected periodically as shown in Table 3. As–constructed data was collected two to three weeks after construction before opening the sections to traffic. After the sections were opened to traffic, profile data was collected up to 24 months at approximately every four-month intervals. Profile measurements were done on both wheel paths of both lanes (driving and passing) using a South Dakota-type Profiler and three replicate runs were made. The South Dakota-type profiler used in this study was an International Cybernetics Corporation (ICC) profiler with laser sensors. Profile data was collected at about 75 mm (3 inch) intervals with the profiler operating at highway speed.

TABLE 3. Dates of Profile Data Collection

Pavement Age During Profiling	Date of Data Collection	Season
As-constructed	October 2000	Fall
4-Month	February 2001	Spring
8-Month	July 2001	Summer
12-Month	November 2001	Winter
16-Month	February , 2002	Spring
20-Month	June 2002	Summer
24-Month	November 2002	Winter

DATA ANALYSIS

International Roughness Index (IRI) was used as a summary statistic. IRI values were computed from the profile data using the RoadRuf software developed by the University of Michigan Transportation Research Institute (*6*). As-constructed IRI values for all sections are shown in Figure 1. It is to be noted that these IRI values represent the average IRI of both wheel paths and lanes with three replicate runs on each wheel path. The figure shows that the Paxico test sections had the lowest as-constructed IRI. The other sections had somewhat similar as-constructed IRI values.

Figure 2 shows the variation of the IRI values with respect to time. Almost all sections exhibit definite patterns and some of the variations could be attributed to the seasonal changes. IRI values for section TTS-1 were the highest for all cases. Topeka test sections (TTS-1 & 2) have higher grade than any other sections. It is to be noted here that, 8-month data for PTS-1 and PTS-2 were not available as those sections were used as work-zone during that time period.

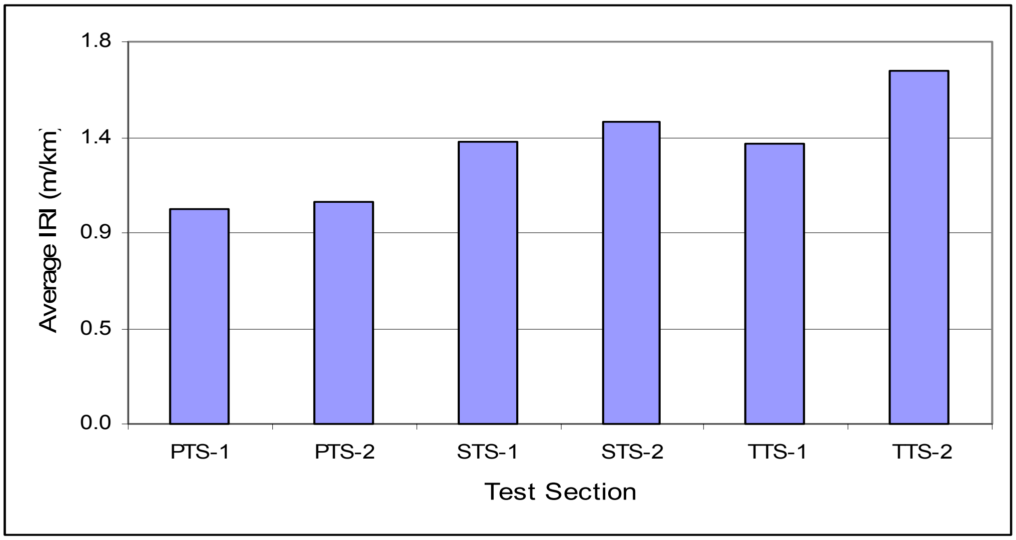


FIGURE 1. As-Constructed IRI Values of Different Sections

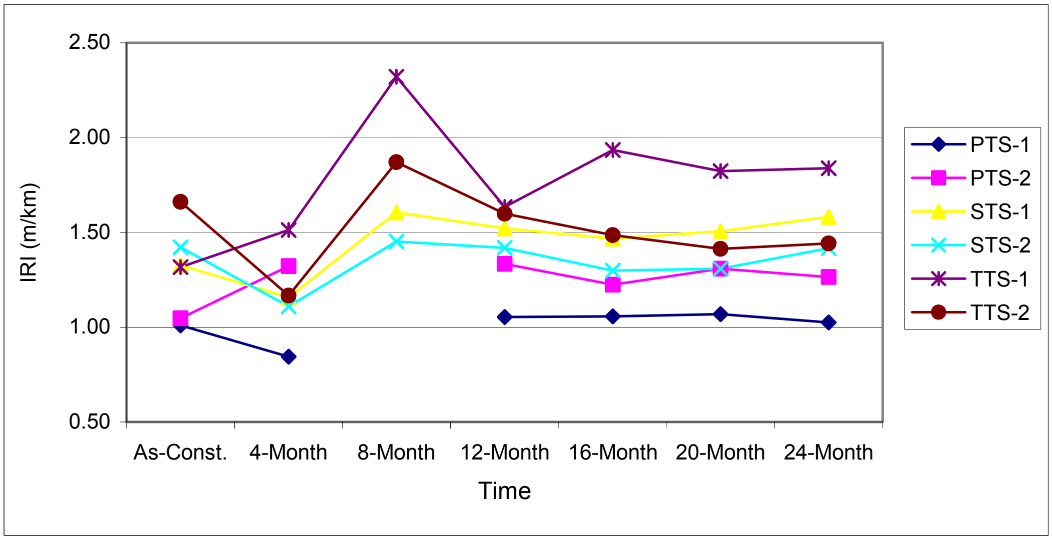
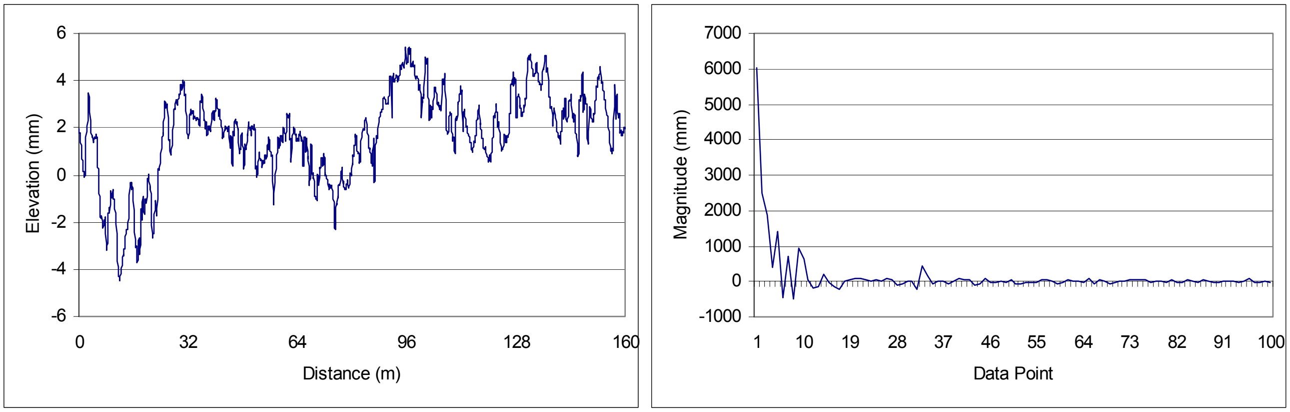


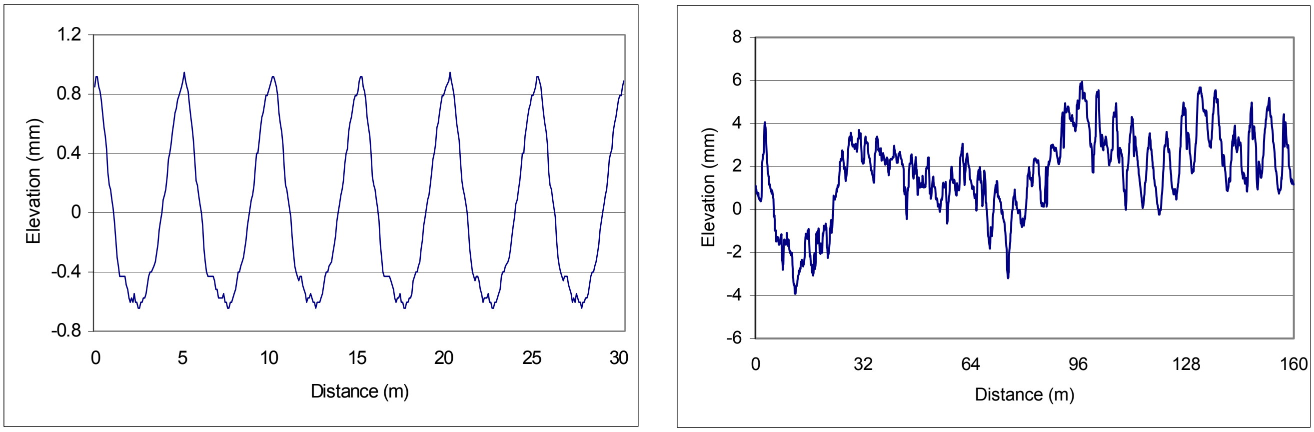
FIGURE 2. Variation of IRI with respect to Time

DIGITAL SEPARATION OF CURLING

Thus far no universally accepted method has been proposed to identify and separate curling from the profile data. Byrum (*7*) has proposed an empirical method to quantify the effect of as-constructed curling from the roughness data obtained by a K.J. Law 690 DNC high-speed profiler in the LTPP program. Curling was separated digitally based on the Fast Fourier Transform (FFT) of the pavement profile obtained with the South Dakota-type profiler. MATLAB software was used for this purpose. It was assumed that curling is uniform for all slabs. An example of separation of curling from the profile data is presented here for the right wheel path of the driving lane on STS-2.



(a) Elevation Plot **(b) FFT of Elevation**



(c) Elevation of Curled Profile **(d) Elevation of Profile Without Curling**

FIGURE 3. Example of Digital Separation of Curling

Uniform curling was detected using elevation data from the profile of this section. The elevation plot of this section (160 m long) is shown in Figure 3(a). The FFT of these elevation data is shown in Figure 3(b). The figure shows spikes at every 32 data-point intervals. These spikes are the Fourier components of the fundamental frequency. The first distinguishable spike in Figure 3(b) (at 33 data points) represents a wavelength that is most likely caused by curling and also shows the distinct harmonics associated with it. Thus these spikes represent a wavelength of one slab length [5 m = 16.404 ft = (No. of data points (2,100) × sample interval (3 in.))/(33-1)) where 33 is the Fourier coefficient and “1” is the origin indexing used by MATLAB] and all of its harmonics. Then these spikes were separated from the other FFT coefficients. The inverse FFT of these separated spikes resulted in the separated curled profile of the section as shown in Figure 3(c). It shows the profile of six (6) curled slabs. The subtraction of the separated curled profile from the actual elevation profile resulted in the profile due mainly to the construction process (Figure 3(d)). IRI values were calculated for the profiles with and without curling. The IRI values for the original profile and the profile without curling were found to be 1.47 m/km and 1.18 m/km, respectively. The IRI value for the profile data from the separated curled portion (shown in Figure 3(c)) was 0.66 m/km. For this particular section, the contribution of curling was approximately 20% of the total roughness. It is to be noted that the IRI's calculated for the separated curling profile and profile without curling will not add up algebraically equal to the actual profile IRI since the IRI calculation algorithm is nonlinear. This technique was not found to be applicable to some sections. It is possible that some curled slabs do not curl uniformly enough to produce distinguished spikes in the Fourier components at wavelengths that are multiples of the slab length. This is especially true during early life of some concrete pavements.

CONTRIBUTION OF CURLING

Table 4 shows the contributions of curling to roughness for all test sections in the form of percent reduction of IRI values, obtained after subtracting curled profiles from the original profiles. The effect of curling on as-constructed smoothness was the highest for the Topeka test sections. The contribution of curling to roughness was the lowest 16 months after construction. After 20 months, on STS-1 section, curling contributed as much as 39% to the total roughness. It also shows that contributions of curling to roughness during this measurement period were much higher than other measurement periods. Since these measurements were taken during summer time, the contribution of curling to the measured roughness appears to be the highest for the summer months. This is quite plausible given the temperature gradients developed in the PCCP slabs during hot summer days and relatively cooler nights in Kansas.

TABLE 4. Decrease in IRI Values After Separation of Curling for Different Time Period

Section	Reduction in Average IRI Values (%)						
	As-Constructed	4-Month	8-Month	12-Month	16-Month	20-Month	24-Month
PTS-1	5.5	*	#	5.3	2.4	23.8	3.7
PTS-2	4.5	6.4	#	8.1	0.7	26.7	4.7
STS-1	3.7	*	9.5	5.1	6.7	38.9	7.0
STS-2	7.8	*	6.7	10.5	4.0	34.1	7.8
TTS-1	16.5	7.2	2.8	4.7	0.5	11.3	12.3
TTS-2	12.7	*	30.5	5.5	2.32	14.8	15.8

* Digital separation technique didn't work
# Used as work-zone

MULTIPLE REGRESSION ANALYSIS

Multiple regression analysis was used to find the functional relationship between IRI values for curled profiles and profiles without curling at different time periods and significant factors that influence IRI. The general form of the model is:

$IRI=a+bX1+cX2+\ldots$
(1)

where
X1, X2, .. are the independent variables;
a is the intercept; and
b, c, …. are the correlation coefficients.

Construction, geometric, climatic and traffic data were used as independent variables. Models were selected based on a number of statistical information such as R^2 value, t-test statistic, as well as engineering judgment. Separate models were developed for each time period for the curled profile and the profile without curling. The models for the IRI from the original profiles have been discussed elsewhere (*8*). Table 5 lists the significant independent variables, parameter coefficients, and statistical information for the modes obtained by a statistical software SYSTAT (*9*). No feasible models were obtained for the 24-month measurements.

TABLE 5. Models Derived for the Study

Without Curling			Curling		
Variable	Parameter Estimate	R^2 Value	Variable	Parameter Estimate	R^2 Value
As-constructed IRI					
Intercept	-3.750	0.892	Intercept	-0.400	0.640
THICK	0.053		THICK	0.001	
BDBSR	0.787		BDBSR	0.240	
4-Month IRI					
Intercept	-1.600	0.763	Intercept	-0.452	0.708
THICK	0.009		CSTR	0.021	
CHGPI	-0.011		GRADE	0.006	
BDBSR	0.022				
8-Month IRI					
Intercept	-7.200	0.737	Intercept	2.223	0.639
THICK	0.030		GRADE	0.047	
GRADE	0.292		PASS200	-0.042	
12-Month IRI					
Intercept	0.563	0.607	Intercept	4.566	0.813
CSTR	0.018		THICK	0.002	
GRADE	0.167		GRADE	0.024	
			PASS200	-0.052	
16-Month					
Intercept	0.404	0.756	Intercept	-1.303	0.837
THICK	0.036		CSTR	0.036	
BDBSR	0.432		BDBSR	0.014	
GRADE	0.103		GRADE	0.041	
PASS200	0.012				
20-Month					
Intercept	-0.150	0.732	Intercept	4.934	0.745
THICK	0.006		THICK	0.004	
GRADE	0.238		GRADE	0.022	
			PASS200	-0.061	

THIK: Thickness of concrete slab (in mm);

BDBSR: Compressive strength of BDB layer (in MPa);

CHGPI: Change in Plasticity Index due to subgrade stabilization (in %);

GRADE: Vertical grade (in %);

CSTR: 28-day core compressive strength of concrete (in MPa)

PASS200: Subgrade materials passing 75-micron sieve (in %);

These models show that IRI values from profiles without curling, and curled profiles are influenced by: the thickness of the concrete slab, compressive strength of the BDB layer, 28-day core compressive strength of concrete, change in Plasticity Index of subgrade soil due to lime treatment, vertical grade of the road, and % subgrade materials passing 75-micron sieve. Positive parameter estimates denote that with increase in the value of the parameter, the IRI value will increase. Higher IRI would result from a concrete mixture whose 28-day compressive strength is higher. This is to be noted that such a mixture usually will have a lower water-cement ratio, and will be somewhat difficult to handle. The higher the thickness of the slab, the higher the IRI value. Similar observations have been made by Perera and Kohn (*10*) in their analysis of Long Term Pavement Performance (LTPP) profile data. The strength of the stabilized base also affects the as-built curling. The models show that higher base strength results in higher curling. It can be assumed that if the base is very stiff it will be somewhat “unyielding,” and the profile of the base would significantly affect curling of the concrete slab.

CONCLUSIONS

Based on this study following conclusions can be made:

1. Contribution of curling to the roughness of newly built concrete was found to be significant.

2. IRI values calculated form profiles without curling are affected by compressive strengths of concrete and BDB layers, change in the Plasticity Index values of subgrade due to soil treatment and vertical grade of the road. Higher IRI would result from stronger concrete and stiffer base. This is also true for higher slab thickness.

3. As-constructed and early life curling of PCC pavements are affected by the slab thickness, stiff base, stronger concrete, and vertical grade. Increase in values of these parameters will result in increase in curling resulting in higher values.

4. Traffic does not have any effect on curling.

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