Flexural Strength Criteria for Opening Concrete Roadways to Traffic

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After a concrete pavement is placed, a period of time is required for the concrete to gain strength. The pavement can be opened to traffic only after it has achieved adequate strength. Various criteria have been used for opening concrete roadways to traffic. Most criteria are based on the accumulated judgment of specifying agencies or other authorities. Little or no engineering analysis exists to substantiate most opening-to-traffic criteria currently in use. Rational criteria for opening concrete pavements to traffic are presented. On the basis of Miner's hypothesis of accumulated fatigue, flexural strength opening criteria are presented for concrete roadways (municipal and highway) subjected to construction and public traffic. The criteria are appropriate for new construction, reconstruction, and concrete overlays except bonded concrete overlays.

In many cases, traditional concrete paving practices will meet the needs of the specifying agency, contractor, and motoring public. However, increasing traffic volumes and public demand often require pavement construction to be accelerated as much as possible. Accelerated concrete pavement construction techniques (*1*) can meet these needs. This is often referred to as "fast track" concrete paving. Minimizing the time a roadway is out of service or accelerating new construction is the objective of fast track concrete paving.

SELECTION OF OPENING-TO-TRAFFIC CRITERIA

After the pavement is placed, a period of time is required for the concrete to gain strength. The pavement can be opened to traffic, both construction and public traffic, only after it has achieved adequate strength.

Various criteria have been used for opening to traffic. Generally, opening to traffic has been based on a minimum time requirement or a minimum concrete strength requirement. In some cases, a combination of time and strength is specified. Most criteria are based on the accumulated judgment of specifying agencies and other authorities. Little or no engineering analysis exists to substantiate opening-to-traffic criteria currently in use.

Report Objectives

This report presents rational criteria for opening concrete roadways to traffic. The criteria presented are based on flexural strength and apply to new construction, reconstruction, and concrete overlays, except bonded concrete overlays. (Criteria for opening bonded concrete overlays to traffic are not discussed in this report.) The criteria presented are appropriate for conventional and accelerated (fast track) paving projects.

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Strength or Time?

Criteria for opening concrete roadway pavements to traffic have generally been based on time or strength. In some cases a combination of strength and time is used. Time to opening, whether measured in hours or days, is the most convenient criterion. Time is easily measured and, therefore, less debatable. More elaborate methods are required to determine the in-place strength of concrete.

Time alone, however, is insufficient to predict concrete pavement strength. The ability of a given pavement to carry anticipated loads is a function of the strength of the concrete. Time, as a measurement criterion for opening to traffic, is used as an indirect method of estimating concrete strength. The general relationship between time at early ages (less than 28 days) and strength is well-known (see Figure 1).

The rate of concrete strength gain is affected by a number of factors other than time, including

- Water-to-cement ratio,
- Properties of cement (composition and fineness),
- Aggregate properties,
- Presence or absence of admixtures and pozzolans,
- Concrete temperature,
- Consolidation, and
- Curing conditions.

Any or all of these factors can vary under field conditions. To account for these factors and the known imprecision of using time alone as an estimate of in-place concrete strength, pavement designers have often taken a conservative approach to establishing time-to-opening requirements for concrete pavements.

Strength as Opening-to-Traffic Criterion

If strength is used as an opening-to-traffic criterion, many of the uncertainties of estimating concrete strengths based solely on time are eliminated. Field methods to estimate the in-place concrete strengths are more direct methods for determining when to open a pavement to traffic. In-place concrete strength, not time, is the better criterion for opening pavements to traffic.

Determining In-Place Concrete Flexural Strength

The concrete pavement's in-place flexural strength can be determined by nondestructive testing (NDT) measurements of the pavement, such as

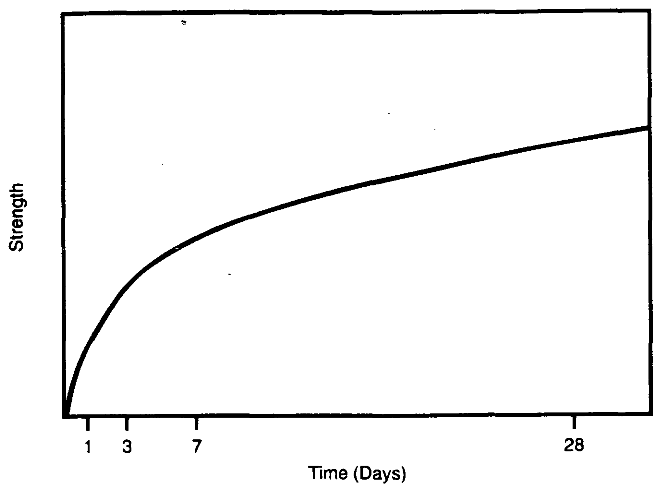

FIGURE 1 General relationship between concrete strength and time (*5*).

- Maturity methods (ASTM C 1074),
- Pulse velocity method (ASTM C 597),
- Pullout method (ASTM C 900), and
- Breakoff method (ASTM C 1150).

Generally, these nondestructive measurements are correlated to compressive strength as determined by cylinders (ASTM C 39). Correlation to third-point flexural strength can also be made.

A concrete pavements in-place flexural strength can also be determined by concrete cylinders made and stored in the field (ASTM C 31, paragraph 9.3) and tested in compression (ASTM C 39). The compressive strength is correlated to third-point flexural strength. Concrete beams made and stored in the field (ASTM C 31, paragraph 9.3) can also be used to determine the in-place flexural strength (ASTM C 78 and C 293) of concrete pavement.

It is important to note that it is not imperative to use flexural beam testing to determine opening strengths. Instead, compressive strength measurements or NDT measurement can be made, then correlated to third-point flexural strengths. These are often more practical methods to determine opening strengths.

The nondestructive methods, particularly maturity and pulse velocity testing, offer several advantages over cylinder or beam testing:

- Allow a more accurate reflection of the actual conditions in the pavement,
- Require less cumbersome equipment at the field site,
- Eliminate problems associated with making and handling beams and cylinders,
- Allow strength determinations to be made at an earlier age, and
- Allow rapid determination of concrete strength.

Factors Affecting Opening Strength Criteria

Recognizing that strength, not time, is the preferred method of determining opening criteria, the question arises: "What strength is required to open a concrete pavement to traffic?"

The flexural strength required for opening depends on a number of pavement-specific factors:

- Pavement application (new construction, unbonded overlay, concrete overlay of existing asphalt);
- Type, weight, and frequency of anticipated loadings;
- Distance and distribution of loads from edge of pavement;
- Moisture and temperature gradients through the depth of the slab;
- Foundation support characteristics;
- Pavement thickness;
- Concrete modulus of elasticity;
- Presence or absence of tied concrete shoulder or curb and gutter; and
- Longitudinal joint load transfer efficiency.

Accounting for all combinations of these variables to determine the opening strength for a concrete pavement would not be practicable. Defining the values of certain factors, or a range of values of these factors, is necessary if practical opening criteria based on flexural strength are desired.

Pavement Application

The opening criteria differ for various concrete pavement applications because traffic loads induce different critical stresses depending on the application. For typical concrete slabs in new construction and unbonded concrete overlays, it is generally recognized that traffic (wheel) loads cause critical flexural tensile stresses at the bottom of the slab and flexural compressive stresses at the top (*2–4*).

Concrete's tensile strength is significantly less than its compressive strength. The 28-day tensile strength is about 8 to 12 percent of compressive strength (*5*). Therefore, opening criteria based on flexural tensile strength are appropriate for most concrete pavement applications.

Bonded concrete overlays are an exception. In most bonded concrete overlays, the new concrete is generally not in tension from applied traffic loadings. Because bonded overlays are usually thinner than the existing concrete on which they are placed, the concrete overlay is in compression when wheel loads are applied (see Figure 2). The interface bonding the overlay to the existing concrete experiences horizontal shear forces from applied traffic loads.

At early ages, the bonded interface is also subjected to horizontal shear and direct tensile forces caused by temperature and moisture variations through the depth of the overlay (*6*). Therefore, the development of bond strength may be more important to opening bonded overlays to traffic than the overlay's compressive or flexural concrete strength. The criteria presented in this report are not appropriate for bonded concrete overlays.

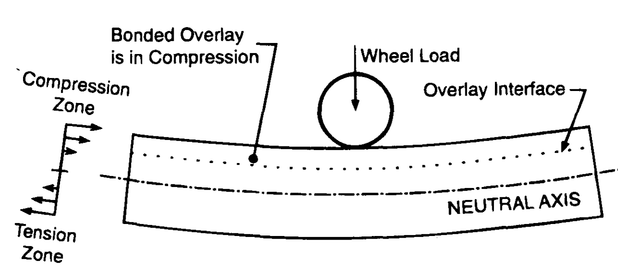

FIGURE 2 Stress distribution in bonded concrete overlay.

BASIS FOR FLEXURAL STRENGTH OPENING CRITERIA

For concrete pavements other than bonded overlays, wheel loads usually cause critical flexural tensile stresses in the bottom of the concrete slab. These stresses can be mathematically calculated. With the stresses known, it is possible to determine the required concrete strength for opening to traffic by applying principles of mechanistic pavement design.

Flexural Fatigue Concept

In concrete pavement design, the most common fatigue-cracking criterion is based on the Miner hypothesis (*7*). Each load application consumes a portion of the pavement's fatigue resistance. The fatigue resistance not consumed by one load is available for repetitions of other loads. The Miner hypothesis can be expressed as

$$\text{Percent Fatigue Damage} = 100\sum n/N$$

where n is the expected number of load repetitions of each load and N is the allowable number of load repetitions for each load.

N is determined from established relationships, such as in Figure 3, and n is established from the expected traffic on the pavement. Over the pavement's life, the total fatigue consumed should not exceed 100 percent. By using this hypothesis, it is possible to rationally determine the flexural strength required to open a concrete pavement to traffic.

Traffic Loadings

To determine the required flexural strength for opening to traffic, an estimate of the type, number, and weight of the applied loads is needed. A concrete pavement may be subjected to two general categories of traffic early in its life—construction loads and public traffic loads.

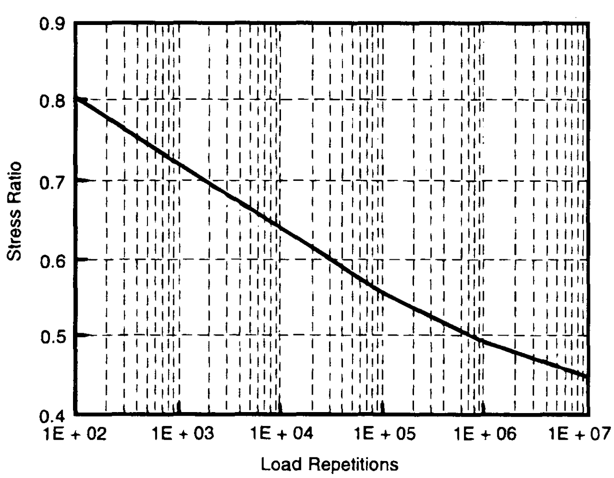

FIGURE 3 Relationship between stress ratio and load repetitions (*2*).

The contractor's equipment causes construction loads. Two types are typical on early-age concrete pavements: span saws for joint construction and trucks for material hauling.

Public traffic includes vehicles normally associated with highway use—automobiles, trucks, and buses. The number and weight of public traffic typically varies depending on the type of roadway. Interstate routes and other highways carrying large numbers of vehicles generally carry greater numbers of heavier loads than municipal streets.

Location of Applied Loads

The location of the applied wheel load has a significant effect on the stress in a concrete pavement. For most conditions, the critical flexural stress occurs when the wheel loads are at the pavement edge, midway between transverse joints (see Figure 4).

The critical flexural stress decreases as the wheel load moves away from the edge of the pavement, eventually reaching an interior slab loading condition. The number of loads expected near the edge of the pavement depends primarily on the following four factors:

- Width of driving lane,
- Type of traffic (construction or public),
- Edge protection (barricades to prevent traffic from dropping off the edge of a newly constructed concrete slab), and
- Presence or absence of curb and gutter.

Moisture and Temperature Gradients

In addition to traffic loading, concrete pavements are also subject to stresses from temperature and moisture differentials through the depth of the slab. Moisture changes, particularly moisture loss from the pavement surface, cause upward concave deformation. This induces compression in the bottom of the slab. This compressive

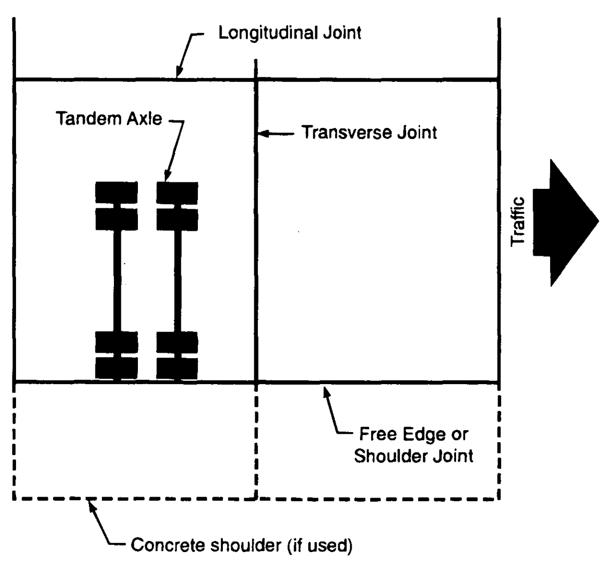

FIGURE 4 Axle load position for critical load repetitions.

stress is subtractive from the critical wheel-load stress. Stresses due to temperature differentials through the depth of the slab can be additive or subtractive from wheel-load stress. During the day, when the top surface is warmer than the bottom, tensile-restraint develops at the slab bottom. During the night, the temperature distribution is reversed and tensile-restraint stresses develop at the slab surface. Usually, the combined effect of moisture and temperature gradients are subtractive from critical mid-panel wheel-load flexural stresses (*2*).

The complex situation of differential conditions at the slab's top and bottom and the uncertainty of the zero-stress position make it difficult to compute these restrained stresses with any degree of confidence or verification. Therefore, for purposes of establishing opening-to-traffic strength criteria, these stresses are considered to be off-setting and are neglected in the analysis.

Foundation Support

The support given to concrete pavements by the subgrade and subbase, where used, affects the flexural strength required to open a pavement to traffic. Subgrade and subbase support is usually defined in terms of the Westergaard modulus of subgrade reaction (k).

ASTM D1196 (*8*) can be used to determine the k-value. However, this test is time consuming and expensive. Methods of correlating approximate k-values to other simpler tests (*2,9*) are adequate for determining opening flexural strength requirements. Higher k-values indicate a stiffer foundation. When other factors are constant, increasing the k-value decreases the wheel-load stress in the concrete pavement (*2*), lowering the flexural strength required for opening to traffic.

Using the concept of effective modulus of subgrade reaction (*2,10*), appropriate k-values can be selected for characterizing foundation support. In this report, effective k-values of 27 MPa/m (100 pci), 54 MPa/m (200 pci), and 136 MPa/m (500 pci) are chosen to represent concrete pavements constructed on compacted natural subgrade, granular subbase, and asphalt or cement stabilized subbase, respectively.

Pavement Thickness

Slab thickness has a significant effect on pavement stresses. Increasing pavement thickness decreases the pavement stress (*2*), lowering the flexural strength required for opening to traffic.

OPENING-TO-TRAFFIC FLEXURAL STRENGTH CRITERIA

Analysis Procedures

An extensive analysis has been made of concrete pavement subjected to traffic loads early in its life (*9*). Flexural stresses were determined with the finite element computer program ILLISLAB (*11*) for a variety of conditions. This early-age fatigue analysis was extensive because stress and strength are related to modulus of elasticity and increase at different rates. The increase in stresses associated with increased modulus of elasticity are offset to various degrees by flexural strength increases.

The relationship between the calculated stress ratio and the number of allowable loads shown in Figure 3 was used where

$$N = 10^{(0.97187 - \mathrm{SR})/0.0828} \qquad \text{for SR} > 0.55$$

$$N = \left(\frac{4.2577}{\mathrm{SR} - 0.43248}\right)^{3.268} \qquad \text{for } 0.45 < \text{SR} < 0.55$$

$$N = \text{unlimited} \qquad \text{for SR} < 0.45$$

The fatigue analysis was conducted for the following traffic and pavement design conditions:

- Sawing equipment loadings,
- Construction vehicle loadings,
- Traffic channelized away from pavement edge by barricades,
- Traffic allowed to approach free edge of pavement, and
- Tied concrete shoulders or tied adjacent lane.

Complete tables of these analyses can be found elsewhere (*9*). Summaries are presented in Tables 1, 2, 3, 4, and 5 as follows.

Construction Traffic—Span Saw Loading

Analysis was made for a 6575 kg (14,500 lb) span saw applied to a 6.10 × 7.32 m (20 × 24 ft) concrete slab as shown in Figure 5.

Required flexural strengths for span saw operations are shown in Table 1. Fatigue damage was calculated for 10 span saw load applications. The values in the table are based on one-half of 1 percent fatigue consumption. A minimum modulus of rupture a maximum of 1.04 MPa (150 psi) was selected as this relates to the minimum practical flexural strength for sawing joints in concrete pavement (*10*).

TABLE 1 Opening to Construction Traffic—Span Saws

Thickness mm	(in)	k-value MPa/m	(pci)	Required Flexural Strength[a] MPa	(psi)
150	(6)	27	(100)	1.45	(210)
		54	(200)	1.31	(190)
		136	(500)	1.03	(150)
165	(6.5)	27	(100)	1.31	(190)
		54	(200)	1.10	(160)
		136	(500)	1.03	(150)
180 or greater	(7)	27	(100)	1.03	(150)
		54	(200)	1.03	(150)
		136	(500)	1.03	(150)

[a]From measurements correlated to third-point flexural strength (ASTM C78)

TABLE 2 Opening to Construction Traffic—Construction Vehicles

Thickness mm (in)	k-value MPa/m (pci)	Required Flexural Strength[a], MPa (psi) Number of 15,400 kg (34 kip) TAL: 10	50
150 (6)	27 (100)	2.82 (410)	3.17 (460)
	54 (200)	2.48 (360)	2.69 (390)
	136 (500)	2.07 (300)	2.07 (300)
165 (6.5)	27 (100)	2.48 (360)	2.69 (390)
	54 (200)	2.14 (310)	2.41 (350)
	136 (500)	2.07 (300)	2.07 (300)
180 (7)	27 (100)	2.07 (300)	2.34 (340)
	54 (200)	2.07 (300)	2.07 (300)
	136 (500)	2.07 (300)	2.07 (300)
190 (7.5) or greater	27 (100)	2.07 (300)	2.07 (300)
	54 (200)	2.07 (300)	2.07 (300)
	136 (500)	2.07 (300)	2.07 (300)

[a]From measurements correlated to third-point flexural strength (ASTM C78)

TABLE 3 Opening to Public Traffic—Municipal Streets with Barricades (Without Adjacent Concrete Lane or Tied or Integral Curb and Gutter)

Thickness mm (in)	k-value MPa/m (pci)	Required Flexural Strength in MPa (psi) Estimated ESALs to Design Strength[b]: 100	500	1,000	2,000	5,000
150 (6)	27 (100)	3.38 (490)	3.72 (540)	3.93 (570)	4.61 (590)	4.34 (630)
	54 (200)	2.82 (410)	3.10 (450)	3.24 (470)	3.38 (490)	3.58 (520)
	136 (500)	2.34 (340)	2.55 (370)	2.67 (390)	2.76 (400)	2.96 (430)
165 (6.5)	27 (100)	2.96 (430)	3.24 (470)	3.38 (490)	3.58 (520)	3.79 (550)
	54 (200)	2.42 (350)	2.67 (390)	2.82 (410)	2.96 (430)	3.10 (450)
	136 (500)	2.07 (300)	2.20 (320)	2.27 (330)	2.41 (350)	2.55 (370)
180 (7)	27 (100)	2.55 (370)	2.82 (410)	2.96 (430)	3.10 (450)	3.31 (480)
	54 (200)	2.14 (310)	2.34 (340)	2.48 (360)	2.55 (370)	2.76 (400)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.20 (320)
190 (7.5)	27 (100)	2.27 (330)	2.55 (370)	2.62 (380)	2.76 (400)	2.96 (430)
	54 (200)	2.07 (300)	2.07 (300)	2.20 (320)	2.27 (330)	2.41 (350)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
200 (8)	27 (100)	2.07 (300)	2.27 (330)	2.34 (340)	2.48 (360)	2.62 (380)
	54 (200)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.14 (310)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)

[a]From measurements correlated to third-point flexural strength.
[b]Estimated ESALs that will use the pavement from time of opening until concrete achieves its design (usually 28-day) strength. ESALs are one direction, truck lane.

Construction Traffic—Vehicles

Table 2 presents flexural strength requirements for opening concrete pavements to use by vehicular construction traffic rounded to 0.07 MPa (10 psi).

Table 2 considers typical concrete pavement construction traffic. The most common heavy construction loads are 15,400 kg (34,000 lb) tandem axle load (TAL) dump trucks. Because most construction loads operate away from the pavement edge, all vehicular wheel loads were analyzed at a distance of 0.61 m (2 ft) from the pavement edge. Fatigue consumption from construction vehicles was limited to 1 percent.

A practical minimum flexural strength of 2.07 MPa (300 psi) is shown. This relates to typical concrete pavement flexural strength when joint sawing has been completed (*10*). Construction traffic is usually not allowed on the pavement until joint sawing is completed.

The data in Table 2 can be approximated with the following English unit equation (strengths calculated and the equation derived in English units only):

$$\log(MR) = -1.8425 * \log(t) - 0.0122 * \text{sqrt}(k) + 0.0724 * \log(N) + 4.0870 \quad \text{but not less than 300 psi} \qquad (1)$$

where

MR = modulus of rupture (flexural strength) in psi (100 psi = 0.689 MPa),
t = slab thickness (in.),
k = modulus of subgrade/subbase reaction (lb/in.^{3}),
N = number of expected TAL trucks, and
R^2 adj = 0.998 for Equation 1.

TABLE 4 Axle Load Distributions (2) Used in Tables 3 and 5

Axle load kg (kips)		Axles per 1000 trucks[a] Table 3 (Municipal streets with barricades)	Table 5 (Highways with barricades)
Single axles			
1,800	(4)		
2,700	(6)		
3,600	(8)	233.60	
4,500	(10)	142.70	
5,400	(12)	116.76	
6,400	(14)	47.76	
7,300	(16)	23.88	57.07
8,200	(18)	16.61	68.27
9,100	(20)	6.63	41.82
10,000	(22)	2.60	9.69
10,900	(24)	1.60	4.16
11,800	(26)	0.07	3.52
12,700	(28)		1.78
13,600	(30)		0.63
14,500	(32)		0.54
15,400	(34)		0.19
Tandem axles			
1,800	(4)		
3,600	(8)	47.01	
5,400	12)	91.15	
7,300	(16)	59.25	
9,100	(20)	45.00	
10,900	(24)	30.74	71.16
12,700	(28)	44.43	95.79
14,500	(32)	54.76	109.54
16,300	(36)	38.79	78.19
18,100	(40)	7.76	20.31
20,000	(44)	1.16	3.52
21,800	(48)		3.03
23,600	(52)		1.79
25,400	(56)		1.07
27,200	(60)		0.57

[a] excluding all two-axle, four-tire trucks

Public Traffic—Types of Roadways

The type of roadway affects the flexural strength criteria for opening concrete pavements to public traffic. Interstate and other highways carry higher volumes of traffic and in most cases larger numbers of heavy vehicles than municipal streets.

Several factors affect the placement of vehicle wheels relative to the pavement edge. Highways may be constructed with widened outside lanes or tied concrete shoulders, or both; municipal concrete streets often have tied or integral curb and gutter sections. Also, for safety purposes, highways and municipal streets often have barricades at the edge of newly constructed lanes to prevent public traffic from driving off the edge.

Number of Loads (Public Traffic)

To determine the required flexural strength to open to public traffic, the expected number of loads must be estimated. Most concrete pavements are designed using a 28-day average flexural strength to represent concrete strength. If concrete pavements are opened in less than 28 days, an estimate of the public traffic on the pavement between time of opening and 28 days is needed.

Pavement designers often use 8,150 kg (18,000 lb) equivalent single-axle loads (ESALs) as a method of estimating traffic (*12*). Therefore, the number of expected ESALs from time of opening until the pavement achieves its design strength is a convenient measure of traffic. A recent survey of highway practices (*13*) determined that 45 state highway agencies specify a 28-day strength (compressive or flexural).

Minimum Flexural Strength for Opening to Public Traffic

Joints in concrete pavements should be constructed before the pavement is opened to public traffic. One study (*10*) indicates that joint sawing operations are usually complete before the pavement

TABLE 5 Opening to Public Traffic—Highways with Barricades (Without Widened Lane or Tied Concrete Shoulder)

Thickness mm (in)	k-value MPa/m (pci)	Required Flexural Strength[a] in MPa (psi) Estimated ESALs to Design Strength[b] 100	500	1000	2000	5000
200 (8)	27 (100)	2.55 (370)	2.82 (410)	2.96 (430)	3.10 (450)	3.24 (470)
	54 (200)	2.14 (310)	2.34 (340)	2.41 (350)	2.55 (370)	2.69 (390)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.14 (310)
215 (8.5)	27 (100)	2.34 (340)	2.55 (370)	2.62 (380)	2.78 (400)	2.96 (430
	54 (200)	2.07 (300)	2.07 (300)	2.20 (320)	2.27 (330)	2.41 (350)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
230 (9)	27 (100)	2.07 (300)	2.27 (330)	2.41 (350)	2.48 (360)	2.69 (390)
	54 (200)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.20 (320)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
240 (9.5)	27 (100)	2.07 (300)	2.07 (300)	2.20 (320)	2.27 (330)	2.41 (350)
	54 (200)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
250 (10)	27 (100)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.20 (320)
	54 (200)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
265 (10.5) or greater	27 (100)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
	54 (200)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)
	136 (500)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)

[a]From measurements correlated to third-point flexural strength.
[b]Estimated ESALs that will use the pavement from time of opening until concrete achieves its design (usually 28-day) strength. ESALs are one-direction, truck lane.

reaches 2.07 MPa/m (300 psi) flexural strength. While this value may vary depending on aggregate type, weather conditions, and sawing methods, it provides a practical lower limit for opening to public traffic.

Opening to Public Traffic—Municipal Streets

Before municipal streets are opened to public traffic, safety precautions must be taken to prevent vehicles from driving off the new pavement edge. If adjacent lanes or the curb and gutter are not in place, barricades are used.

With barricades, traffic remains at some distance from the pavement edge. In this report, all pavements with barricades were analyzed with wheel loads at a constant distance of 0.61 m (2 ft) from the pavement edge. Opening flexural strength criteria with barricades present, rounded to 0.07 MPa (10 psi), for municipal pavements are presented in Table 3. The tabulated values are for 1 percent fatigue consumption computed with the axle load distribution shown in Table 4.

If adjacent lanes or tied or integral concrete curb and gutter are present, the opening strengths in Table 3 can be reduced by 35 percent [minimum of 2.07 MPa (300 psi)], whether barricades are present or not. For such conditions, appropriate wheel wander (*2*) was used in the analysis.

The data in Table 3 can be approximated with the following English unit equation (strengths calculated and the equation derived in English units only):

$$\log(MR) = -0.0890 * (t) - 0.2568 * \log(k) + 0.0675 * \log(\text{ESALs}) + 3.5708 \quad \text{but not less than 300 psi} \qquad (2)$$

where

MR = modulus of rupture (flexural strength) in psi (100 psi = 0.689 MPa),
t = slab thickness (in.),
k = modulus of subgrade/subbase reaction (lb/in.^{3}),
ESALs = number of equivalent single-axle loads (18,000 lb) expected on the slab from opening until design strength is obtained, and
R^2 adj = 0.993 for Equation 2.

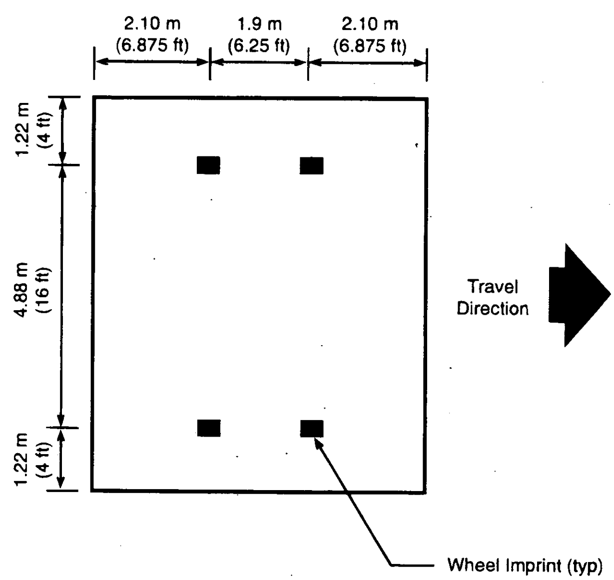

FIGURE 5 Span saw loading.

Opening to Public Traffic—Highways

If adjacent lanes or shoulders are not in place, barricades are used to prevent traffic from driving off the pavement edge. In some highway designs, particularly interstate routes, widened lanes are sometimes used to reduce edge loadings.

Opening criteria for concrete highways with safety barricades in place are presented in Table 5. For Table 5, all wheel loads were analyzed at a constant distance of 0.61 m (2 ft) from the pavement edge. The tabulated values are for 1 percent fatigue consumption computed with the axle load distribution shown in Table 4.

If the highway has a widened truck lane [typically 4.25 m (14 ft) wide] or tied concrete shoulders, the flexural opening strengths in Table 5 can be reduced by 30 percent [minimum of 2.07 MPa (300 psi)], whether or not barricades are present. For such conditions, an appropriate wheel wander (*2*) was assumed in analysis. If the highway is open to public traffic without widened truck lanes or tied concrete shoulders, barricades should be left in place until the concrete reaches 3.1 MPa (450 psi) flexural strength.

The data in Table 5 can be approximated with the following English unit equation (strengths calculated and the equation derived in English units only):

$$\log(MR) = -0.0873 * (t) - 0.2558 * \log(k) + 0.0635 * \log(\text{ESALs}) + 3.5708 \quad \text{but not less than 300 psi} \qquad (3)$$

where

MR = modulus of rupture (flexural strength) in psi (100 psi = 0.689 MPa),
t = slab thickness (in.),
k = modulus of subgrade/subbase reaction (lb/in.^{3}),
ESALs = number of equivalent single-axle loads (18,000 lb) expected on the slab from opening until design strength is obtained, and
R^2 adj = 0.992 for Equation 3.

COMMENTS ON TABLE 4 AND ESALS, AND AN EXAMPLE

In this report, mechanistically based procedures are used to determine flexural strength requirements for opening concrete roadways to traffic. These procedures use the axle-load distributions shown in Table 5. For each 1,000 trucks, the number of expected axles is given in 1,800 kg (2,000 lb) increments (single axle) and 3,600 kg (4,000 lb) increments (tandem axle).

For instance, for every 1,000 trucks on a municipal street, one might expect

- 233.60 single axles weighing 3,600 kg (8,000 lb),
- 142.70 single axles weighing 4,500 kg (10,000 lb),
- 116.76 single axles weighing 5,400 kg (12,000 lb),
- 47.01 tandem axles weighing 3,600 kg (8,000 lb),
- 91.15 tandem axles weighing 5,400 kg (12,000 lb), and
- 59.25 tandem axles weighing 7,300 kg (16,000 lb).

Such load weight distributions can be used to determine the ESALs used in the AASHTO (*12*) procedure for pavement design. Load equivalency factors multiplied by the number of axle loads within a given weight range are totaled to determine total ESALs.

In many cases, however, the axle load distributions are unknown. The pavement design engineer is given only the total number of ESALs or the number of ESALs expected per day on the roadway. Therefore, traffic volumes for opening strength guidelines are presented using ESALs because traffic information is more readily available in this form rather than load weight distribution tables.

To relate expected ESALs to load weight distributions used in the mechanistic analysis, the number of axles equivalent to 1,000 ESALs were computed for the load weight distributions shown in Table 5. The number of axles equivalent to 1,000 ESALs varies slightly with slab thickness and significantly with roadway category (municipal street or highway), as shown in Table 6.

For example, for the municipal street distribution shown in Table 4, it takes about 2,600 trucks to generate 1,000 ESALs. For the highway distribution, about 650 trucks will generate 1,000 ESALs. This is because, in general, highways carry a larger number of heavy trucks than municipal streets.

As an example, consider a municipal street carrying 100 ESALs per day: (a) using the axle load distribution shown in Table 4,

$$100 \text{ ESALs/day} \times (2{,}600 \text{ trucks}/1{,}000 \text{ ESALs}) = 260 \text{ trucks/day}$$

(b) for the highway distribution of Table 4,

$$100 \text{ ESALs/day} \times (650 \text{ trucks}/100 \text{ ESALs}) = 65 \text{ trucks/day}$$

For the highway distribution, 65 trucks will generate 100 ESALs, and 260 trucks of the municipal distribution will generate 100 ESALs.

For the same slab thickness, from a mechanistically based fatigue damage approach, 260 trucks of Table 4 municipal loadings will not cause the same amount of damage as 65 trucks of the highway loadings. Because of the heavier axle loads in the highway distribution, 65 trucks of highway distribution is more damaging than 260 trucks of municipal distribution.

Because 100 ESALs require 65 trucks of highway distribution or 260 trucks of municipal distribution, and, for a specific pavement thickness, 65 highway truck loadings cause more fatigue damage than 260 municipal truck loadings, there will be a difference between the opening-strength criteria for municipal streets and highways for the same slab thickness and ESAL estimate. For example, a 200 mm (8 in.) thick pavement on a granular subbase (k = 54 MPa/m, 200 lb/in.^{3}) expected to carry 2,000 ESALs until design strength is reached can be opened to public traffic at 2.07 MPa (300 psi) when exposed to municipal loadings (Table 3), but should achieve a strength of 2.55 MPa (370 psi) when exposed to highway loadings (Table 5).

CONCLUSION

Throughout the United States a variety of criteria is used to determine whether a newly constructed concrete roadway is capable of carrying construction and public traffic. Although there is inconsistency among specifying agencies, opening criteria are generally based on time, concrete strength, or a combination of time and strength. Through the application of mechanistically based procedures, it is possible to determine flexural strength criteria for opening concrete roadways to traffic. Although it is not possible to account for all combinations of factors affecting opening flexural

TABLE 6 Number of Axle Loads per 100 ESALs

Roadway Category	Number of Axle Loads per 1000 ESALs		
	150 mm (6 in) slab	300 mm (12 in) slab	Average
Municipal/Street	2,564	2,649	2,601
Highway	630	680	655

strength, reasonable values or range of values of these factors can be selected. On the basis of such a selection and analysis, flexural opening strength criteria have been determined for construction and public vehicular traffic on concrete highways and streets. The criteria are appropriate for new construction, reconstruction, and concrete overlays except bonded concrete overlays.

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