Optimum Use of High Performance Concrete in Prestressed Concrete Super-T Bridge Beams

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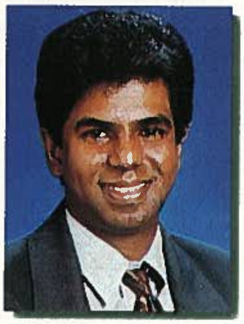

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This investigation studied the use of high performance concrete in precast, prestressed concrete Super-T highway bridge beams. A parametric study was undertaken to investigate the structural and economic aspects of using high performance concrete. It was found that high performance concrete does offer some savings when used in beams with geometry consistent with that currently used in practice. High performance concrete may also offer indirect cost savings because it permits a reduction in the weight of beams. It was also found that high performance concrete may permit the use of beams with shallower sections and reduce overall deflections.

Advancements in materials technology and new production techniques have led to the development of high performance concrete (HPC).

HPC is defined by the American Concrete Institute (ACI) as concrete in which certain characteristics are developed for a particular application.[1] Foremost among these properties are high strength and increased durability.

The use of high strength, high performance concrete with strengths greater than 50 MPa (7250 psi) has become increasingly common in the design and construction of structures, particularly bridges. The applications of HPC in bridges have been discussed in different forums around the world. For example, in October 1997, the Precast/Prestressed Concrete Institute (PCI) organized the PCI/FHWA Symposium on HPC in New Orleans, Louisiana.[2] In September 2000, PCI will host the PCI/FHWA/*fib* International Symposium on HPC in Orlando, Florida.

In recent years, many research projects have been undertaken to develop formulas suitable for the design of HPC members. Designers are now in a position to use high performance concrete without the uncertainties that existed previously. An overview of the technical and economic issues associated with HPC in the precast/prestressed concrete industry, including a comprehensive list of references, was presented in the special issue of the PCI JOURNAL on high strength prestressed concrete.[3,4]

Many authorities worldwide are exploring the possibilities of using HPC in bridges. For example, in the United States, the Federal Highway Administration (FHWA) initiated a major program in 1993 to implement the use of HPC. This program includes the construction of demonstration bridges, monitoring the performance of these bridges and disseminating the information about the bridges at showcase workshops. Russell and Vanikar[5] have summarized the results of this program to date.

The potential structural and economic benefits from the use of HPC for continuous precast, prestressed I-girders have been assessed by Hassanain and Loov.[6] Russell[7] reported that the use of high strength concrete in prestressed concrete girders allows for longer span lengths, wider girder spacings, or shallower sections.

Despite the above research efforts, there still remain several unanswered questions regarding the use of HPC, especially relating to the structural and economic advantages of its use. This paper explores the structural and economic advantages when using HPC in precast, prestressed concrete bridge beams in Australia. The results of a parametric study, undertaken to investigate the advantages of using high performance concrete in standard "Super-T" sections currently used in practice, are presented and discussed in this paper.

SUPER-T BEAMS

Super-T beams are steel reinforced precast, prestressed T-shaped beams used for medium- to long-span bridges.

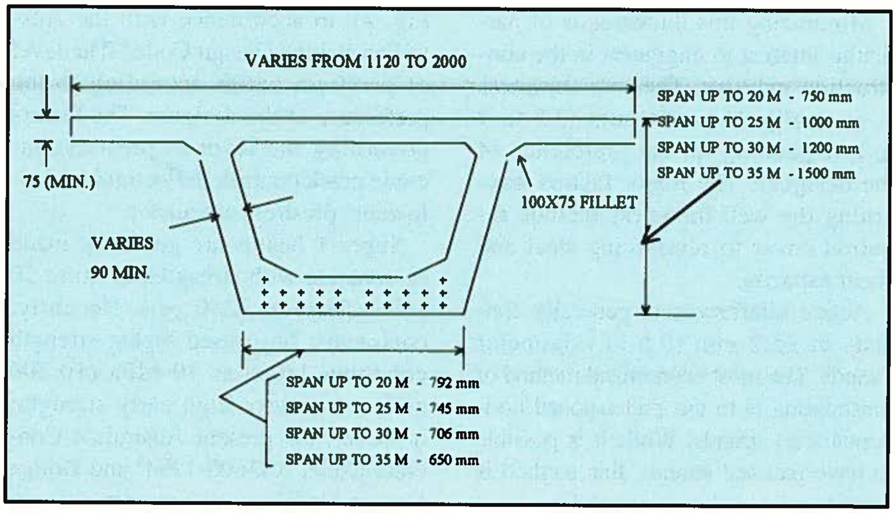


Fig. 1. Details of Super-T beams. Note: 1 mm = 0.0394 in.

They have been used in many highway overpasses (for example, the City Link Project in Melbourne, Australia).

These bridges require minimal scaffolding or formwork during construction. The standard cross sections currently used by VicRoads (the State of Victoria Road and Bridge Authority) are shown in Fig. 1. A major advantage of the Super-T beam is that once the precast concrete section is installed on-site, a stable working platform is provided by the beam itself.

The most important aspect in the design of concrete bridge beams is the selection of a beam cross section of suitable shape and size. In general, these parameters are governed not only by structural constraints, but also by practical considerations such as standard formwork sizes, forming methods, constructability and transportation constraints.

In addition to this, the layout or spacing of beams across the bridge is required, as well as superimposed loads. Current practices relating to the construction of bridge beams have been ascertained through consultation with various professionals associated with the design and construction of these beams.

Super-T beams are cast in a fixed steel mold with a depth of 1500 mm (59 in.) and a taper of 1:10.556 on each side. Fillet sizes are fixed, and are especially important to allow concrete to be cast into the mold properly. Beams shallower than the 1500 mm (59 in.) depth of the mold are made using "removable plinths." The top flange is formed on top of the steel mold. Hence, its width is reasonably variable, and it can be of any thickness greater than 75 mm (3 in.).

The void can be formed by placing a polystyrene section in the mold when the concrete is cast. End blocks are achieved by not including the void for a distance of around 750 to 1000 mm (29.5 to 39.4 in.) from each end.

The impact that these forming techniques have on design are:

- Four discrete beam depths are possible: 750, 1000, 1200 and 1500 mm (29.5, 39.4, 47.2 and 59 in.). Depths other than this are not preferred and are not economical due to formwork constraints.
- Due to the taper of the steel mold, the bottom flange is wider for shallower beams.
- The internal dimensions of the beam are flexible, as the void size is flexible.
- The top flange dimensions are relatively flexible. The width may be anywhere between 1120 and 3000 mm (44 and 118 in.), while the thickness can be any value larger than 75 mm (3 in.).
- There is generally no difference in formwork costs for the different section depths.

The thickness of the bottom flange is generally governed by the space and cover required to accommodate the reinforcing bars and prestressing steel. Ideally, the thickness should be minimized, as the concrete in this section is not effective in the cracked state; and it also adds significantly to the weight of the section.

Minimizing this thickness is of particular interest to engineers in the construction industry. The web thickness is generally 90 to 100 mm (3.5 to 4 in.), depending on the preference of the designer. The major factors governing the web thickness include required cover to reinforcing steel and shear capacity.

Active reinforcement generally consists of 15.2 mm (0.6 in.) diameter strands. The most economical method of prestressing is to use pretensioned horizontal steel strands. While it is possible to have inclined strands, this method is considered to be less economical.

In general, some tendons are debonded, which is achieved by placing the tendon in a hollow tube prior to casting the concrete. Shear reinforcement generally consists of stirrups; however, an alternative method is the use of welded wire fabric mesh. The use of mesh has the potential to reduce labor costs during precasting. More research and development is required in this area.

DESIGN CONSIDERATIONS

In general, the applicable loading condition is T44 truck loading (see Fig. 2), in accordance with the Australian Bridge Design Code.[8] The level of prestress varies according to the preference of the designer. The factors governing the level of prestress include crack control, deflections and allowable prestress at transfer.

Super-T beams are generally made of concrete with strengths of 40 to 50 MPa (5800 to 7250 psi). Recently, contractors have used higher strength concretes [such as 70 MPa (10,200 psi)], to achieve high early strength; however, the present Australian Concrete Code, AS3600-1994[9] and Bridge Design Code[8] cover concrete only up to 50 MPa (7250 psi).

A comprehensive literature review was conducted to find the latest design equations applicable for both normal and HPC. Key areas which are affected by concrete strength, and thus influence design include stiffness, tensile strength, shrinkage, creep, stress-strain behavior, shear capacity and long-term deflections. The equations which are applicable to HPC are presented in the next section.

With a substantial number of different designs required, clearly, manual calculations are difficult to perform. Hence, a spreadsheet was created to complete all designs. The spreadsheet was required to satisfy the following requirements:

- Calculate all loads in accordance with Austroads.[8]
- Check all strength and serviceability requirements for normal strength concrete in accordance with AS3600[9] and for HPC using appropriate equations as per literature survey.
- Allow sufficient detail for accurate design, i.e., detailed section dimensions and sufficient levels of passive and active reinforcement.
- Provide minimal input to efficiently run the parametric study.

CASE STUDY

The bridge selected for the case study is shown in Fig. 3.

– Bridge layout: Four Super-T beams, at a spacing of 2 m (6.6 ft) center-to-center. Two design lanes.
– Total bridge width: 8 m (26.3 ft).
– Total carriageway width: 6.6 m (21.7 ft).

The spreadsheet mentioned earlier was separated into components relating to section properties, design loads, prestress losses, moment capacity, deflections, strength at transfer, design of shear reinforcement, crack control and a summary of the data.

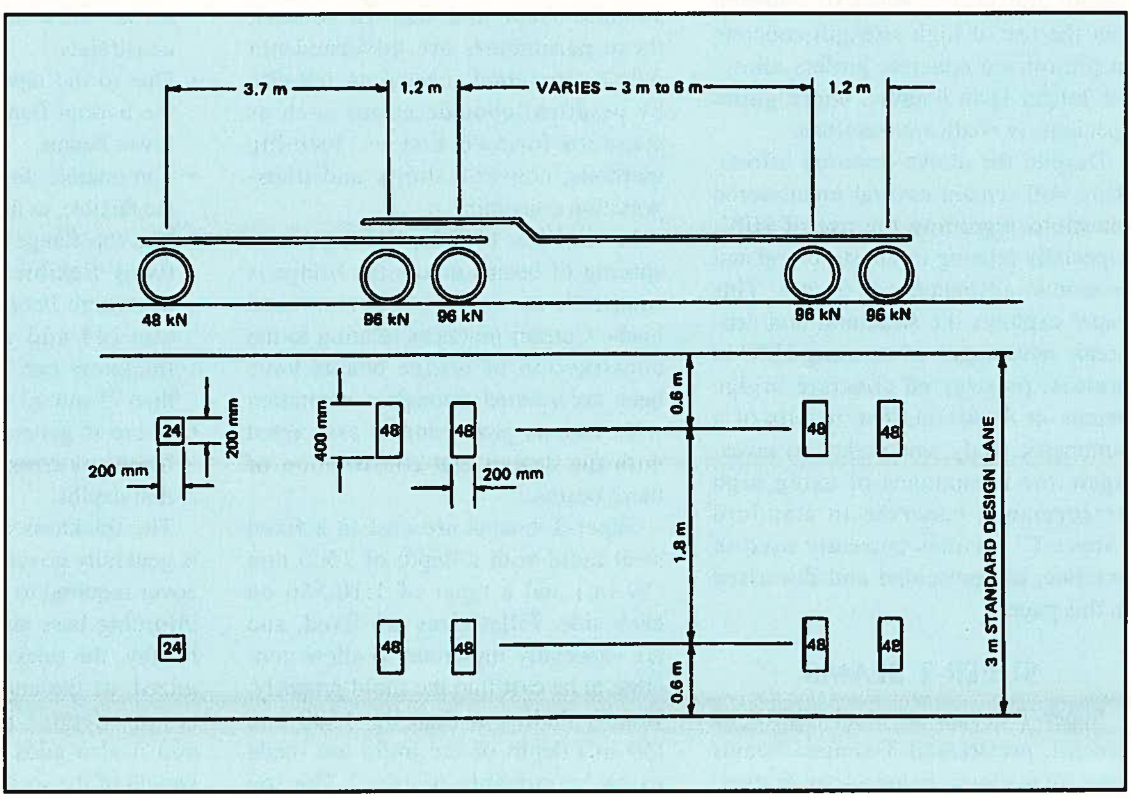


Fig. 2. T44 Truck loading. Note: 1 m = 3.28 ft.

Section Properties

This component requires the entry of all section dimensions, prestressing tendon details and longitudinal passive reinforcement details. The beam is separated into three cross sections: end block, intermediate section, and middle section. Intermediate and middle sections have the same cross section, but different prestressing steel requirements.

This feature is introduced to account for debonding of tendons. The end block is simply the section without the void. For the parametric study, it was assumed that the end block ends 1 m (3.3 ft) from the end of the beam and the intermediate section ends approximately at quarter span.

The section properties component calculates the area, centroid location, moment of inertia and section moduli of both the beam alone and the composite beam and slab. Eccentricities of prestressing tendons, as well as areas of both prestressing and passive reinforcement are also calculated.

The concrete strength at transfer and at 28 days for both the beam and the slab are required input. The modulus of elasticity is then calculated by the following equation suggested by Mendis et al.[10] This equation is similar to the equation given in AS3600 (which is similar to the equation given in the ACI Code), for normal strength concrete, but applicable to both normal and HPC.

In SI units:

$$E_c = 0.043\eta\rho^{1.5}\sqrt{f_c'} \pm 20 \text{ percent} \tag{1a}$$

where

$\eta = 1.1 - 0.002 f_c' \leq 1.0$

in which E_c and f_c' are in MPa units.

In U. S. units:

$$E_c = 0.23\eta\rho^{1.5}\sqrt{f_c'} \pm 20 \text{ percent} \tag{1b}$$

where

$\eta = 1.1 - 1.4 \times 10^{-5} f_c' \leq 1.0$

in which E_c and f_c' are in psi units.

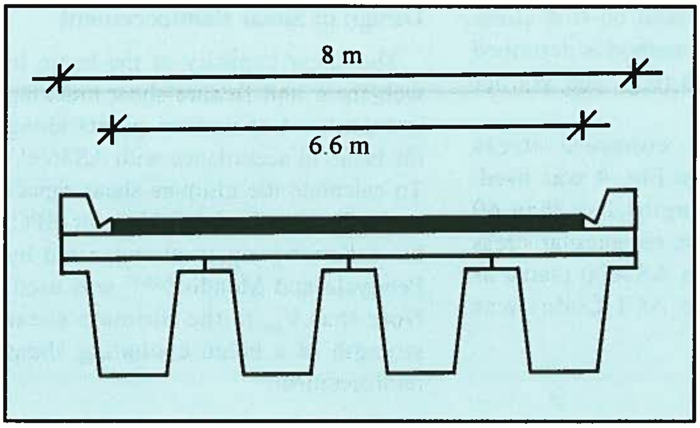


Fig. 3. Typical bridge section. Note: 1 m = 3.28 ft.

Design Loads

Calculation of dead loads is based on the self-weight of the beam, the self-weight of the slab and the superimposed loads. The superimposed loads are assumed to be 6.15 kN/m (422 lb/ft) based on the weight of the kerb, channel, fencing and railings. The weight of the asphalt is assumed to be 1.65 kN/m (113 lb/ft).

Calculation of live loads is based on the bridge section shown in Fig. 3. By adopting a standard 3.1 m (10.2 ft) design lane, each beam supports half a lane; hence, half the load for that lane.

The critical live load case is chosen from a calculation of design forces due to T44 Truck Loading in accordance with Austroads Code.[8] Following this, the first flexural frequency of the bridge is calculated from which the dynamic load allowance is obtained from Austroads Code.[8]

Design moments and shear forces are calculated for both the ultimate and serviceability limit states. Load factors are used for the critical load case (i.e., T44 plus self-weight plus superimposed load) according to the Austroads Code.[8] Design moments and shear forces for the ultimate limit state are calculated for various points along the beam.

Prestress Losses

In all cases, it is assumed that pretensioning is to be used; hence, losses are calculated to account for elastic deformation of concrete, shrinkage, creep and relaxation of tendons. Equations have been used rather than charts to calculate some coefficients; for example, in the case for creep and shrinkage, the equations suggested by Gilbert[11] were used.

It was found from the literature review that the creep coefficients suggested by Setunge and Padovan[12] are the most consistent with experimental results while other methods tend to overestimate the creep factor substantially. These creep factors are given in Table 1. Note that the creep factor is the ratio of creep strain to elastic strain under conditions of constant stress.

All the other prestress losses are calculated using standard procedures outlined in Austroads Bridge Design Code.[8]

This component of the spreadsheet also calculates the "Level of Prestress, K" where:

$$K = \frac{\text{Decompression Moment}}{\text{Unfactored Maximum Moment}} \tag{2}$$

A beam is considered to be partially prestressed if $0.3 < K < 0.8$, and is fully prestressed if $K > 0.8$.

Ultimate Moment Capacity

The moment capacity is checked at midspan and at quarter-span (where tendons are first debonded) using a

Table 1. Basic creep factors for various concrete compressive strengths.

Specified compressive strength, MPa (psi)	60 (8700)	70 (10150)	80 (11600)	100 (14500)
Basic creep factor	1.5	1.2	0.9	0.5

general analysis based on trial stress distributions. This method is described in other textbooks (e.g., see Warner and Faulkes[13]).

For HPC, the concrete stress block[14,15] shown in Fig. 4 was used. For concrete strengths less than 60 MPa (8700 psi), the rectangular stress block suggested in AS3600 (same as that given in the ACI Code) was used.

Deflections

A deflection limit of $L/300$ has been adopted. For HPC, the long-term deflections multiplier, k_{cs}, as referenced in the Australian Concrete Code, AS3600,[9] is replaced by the following formula.[10] Note that k_{cs} is a factor used in serviceability design to take account of the long-term effects of creep and shrinkage of concrete.

$$k_{cs} = \mu \left[2 - 1.2 \left(\frac{A_{sc}}{A_{st}} \right) \mu \right] \geq 0.8$$

In SI units:

$$\mu = \frac{50}{f'_c} \leq 1 \tag{3}$$

in which f'_c is in MPa units.

In U. S. units:

$$\mu = \frac{7250}{f'_c}$$

in which f'_c is in psi units.

For deflections due to most loadings, the deflection at midspan has been calculated using standard formulas. For upward deflection (camber) due to prestress, an equation was derived by integrating the bending moment diagram due to prestress.

Design of Shear Reinforcement

The shear capacity of the beam in web-shear and flexure-shear cracking is calculated at various points along the beam in accordance with AS3600.[9] To calculate the ultimate shear capacity in flexure-shear cracking for HPC, the following equation suggested by Pendyala and Mendis[15,16,17] was used. Note that V_{uc} is the ultimate shear strength of a beam excluding shear reinforcement:

In SI units:

$$V_{uc} = \beta_1 \beta_2 \beta_3 \beta_4 b_v d_o \left(\frac{A_{st} f'_c}{b_v d_o} \right)^{1/3} \tag{4a}$$

where

$\beta_4 = 1$ for $f'_c < 50\,\text{MPa}\,(7250\,\text{psi})$

$\beta_4 = 1.25 - 0.005\, f'_c \geq 0.9$

in which f'_c is in MPa units.

In U. S. units:

$$V_{uc} = 125 \beta_1 \beta_2 \beta_3 \beta_4 b_v d_o \left(\frac{A_{st} f'_c}{b_v d_o} \right)^{1/3} \tag{4b}$$

where

$\beta_4 = 1.25 - 3.45 \times 10^{-5} f'_c \geq 0.9$

for $50\,\text{MPa}\,(7250\,\text{psi}) \leq f'_c \leq$

$100\,\text{MPa}\,(14{,}500\,\text{psi})$

in which f'_c is in psi units.

Note that β_1, β_2, and β_3 are determined as given in AS3600 (also, see Appendix at the end of this paper).

The critical section and failure mechanism (i.e., web-shear cracking, or flexure-shear cracking) is identified and the required reinforcement spacing can be calculated.

PARAMETRIC STUDY

The parametric study utilized the aforementioned design method to investigate the use of HPC compared to normal strength concrete. The parametric study was divided into two components. The first component investigated the advantages of using HPC in standard sections within the recommended span range.

Conversely, the second component investigated the advantages of using high performance concrete in standard sections outside the recommended span range. The important findings of the parametric study are presented in this paper. More details are given elsewhere.[18]

In both components of the parametric study, some general assumptions were made to simplify the design and provide consistency between the designs to allow a reasonable comparison between the designs within each study.

- All cross-sectional dimensions were consistent with those currently in use in the industry. The only sections investigated here were those shown in Fig. 1.
- All sections form part of a bridge illustrated in Fig. 3. Hence, for a Super-T section, the top flange width was fixed at 2000 mm (79 in.).
- All designs satisfied the following criteria when subjected to loadings in accordance with the Austroads Code:[8]
  - Strength requirements: Flexural strength, strength at transfer and shear strength.
  - Serviceability requirements: Deflections, crack control.
- All prestressing tendons were 15.2 mm (0.6 in.) diameter at 50 mm (2 in.) spacing, which is consistent with current practice. Mild reinforcing steel consisted of 16 mm (0.63 in.) diameter bars at 50 mm (2 in.) spacing. Steel bars [16 mm (0.63 in.) in diameter] were adopted here for simplicity in detailing the bottom flange reinforcement (i.e., ar-

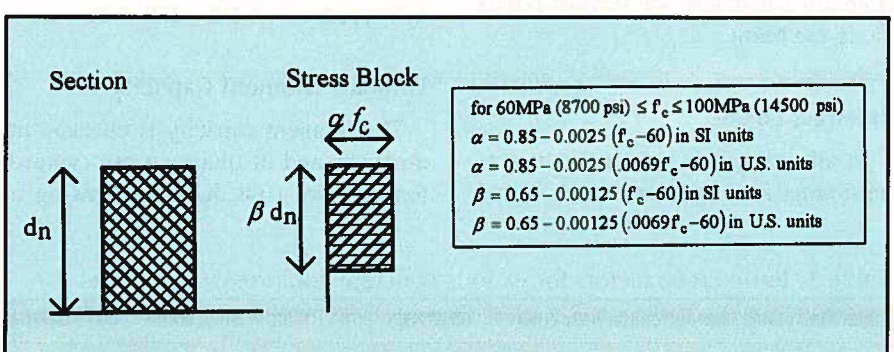


Fig. 4. Stress block showing various interaction parameters.

rangement allows the same bar spacing as the tendons).

- From the quarter span, approximately half of the tendons were debonded, depending on strength requirements.
- All sections had an end block of 1 m (3.28 ft) length on each end. Further debonding of the tendons occurred in the end block.
- All beams were simply supported.
- Concrete strength at transfer was assumed to be 80 percent of the specified 28-day strength.
- Prestressing steel was placed in the bottom rows first, for most efficient use. Mild reinforcing steel was then placed in the remaining space, where required. Nominal prestressing steel (one bar in each web) was placed near the top of the section.

The key variables were:

- Concrete strengths: 40, 60, 80 and 100 MPa (5800, 8700, 11,600 and 14,500 psi).
- Spans: 17, 20, 25, 30 and 38 m (56, 66, 82, 99 and 125 ft).
- Quantity of longitudinal steel.
- Quantity of prestressing steel (i.e., level of prestress).
- Quantity of shear reinforcement.

Prestress Levels

To derive the allowable prestress levels, a short investigation was undertaken using a 1000 mm (39.4 in.) deep Super-T beam for a fixed span of 25 m (82 ft). For each concrete strength, four different designs were done. First, the minimum prestress level, which is governed by serviceability constraints, was determined and a beam was designed using this level of prestress.

The next step required determining the maximum prestress level, which is determined by allowable stresses at transfer, and designing a beam using this prestress level. Finally, two other beams were designed, using prestress levels in between the maximum and minimum prestress levels established earlier.

For higher concrete strengths greater than or equal to 80 MPa (11,600 psi), the allowable stress at transfer was high enough to allow a fully prestressed design. In this case, the maximum prestress level was defined as the

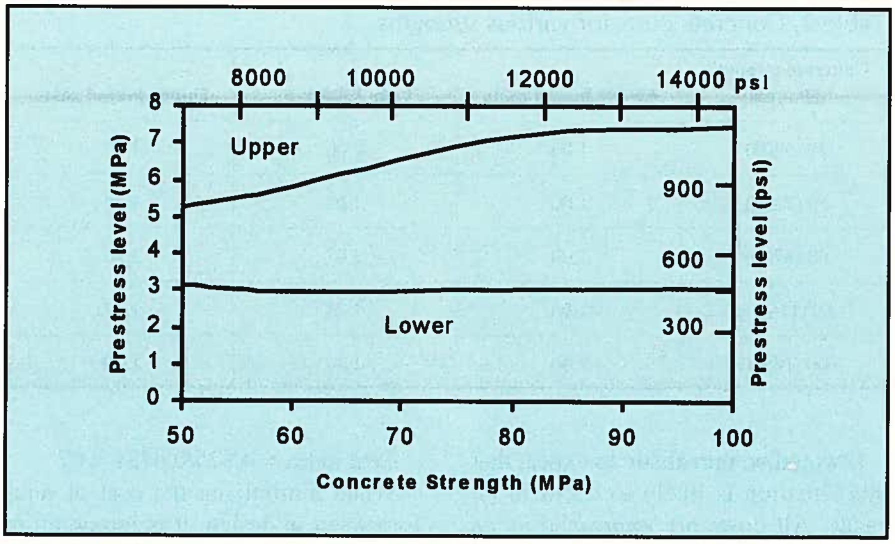


Fig. 5. Envelope of viable prestress levels

level at which flexural strength requirements are satisfied; hence, no mild steel longitudinal reinforcement is necessary. To quantify the efficiency of a design, two measures can be used, namely, the mass of the beam and the cost of the beam. Details of the designs are given elsewhere.[18]

From these results, the following conclusions can be made:

- As concrete strength increases, a larger range of prestress levels (K) are viable as shown in Fig. 5.
- It is possible to take advantage of the larger range of prestress levels permitted by HPC, by increasing the prestress level. This can reduce the cost of steel as well as decrease the mass of the section, because prestressing steel requires less space to provide the same tensile force as mild reinforcing steel; hence, the bottom flange thickness is reduced.
- It appears that the optimum design occurs when the maximum allowable prestress level is used.

The result of this study has been the formulation of a design procedure which has resulted in the "optimum" beam design. The optimum beam design is a design such that the cost and mass are minimized (in all cases both were coincident, for a section of fixed depth). In addition, all the beams were required to satisfy all strength and serviceability requirements.

It is necessary to use the optimum design for the study, as comparisons would be meaningless if, for example, a sub-optimal normal strength concrete beam is compared with an optimal high performance concrete beam. If that were the case, an engineer would not know if there were real benefits in using HPC, or if the benefits were merely the results of the design process. Clearly, by comparing optimum designs, this problem is avoided.

Parametric Study No. 1

In this study, beams were designed for a range of spans using the "optimum design" procedure described earlier. For each span, the appropriate section as detailed in Fig. 1 was used. All aspects of section geometry were the same for any given span, except for bottom flange thickness, which is generally governed by the number of rows of reinforcement used.

For each span, the beam was designed using a range of concrete strengths. A cost analysis of all optimal designs was then undertaken. In order to determine the conditions necessary for an optimal design, the data obtained were analyzed in a computerized optimization procedure, similar to linear programming.

Costs of concrete assumed in the analysis are listed in Table 2. "Year 2000 costs" were obtained from information supplied by ready-mix concrete companies. The other two categories, minimum and maximum costs, are referred to as upper and lower bounds, respectively. The lower bound of costs assumes cost is constant for all concrete strengths.

Table 2. Concrete costs for various strengths.

Concrete strength MPa (psi)	Lower bound costs	Year 2000 costs	Upper bound costs
40 (5800)	1.00	1.00	1.00
50 (7250)	1.00	1.03	1.09
60 (8700)	1.00	1.07	1.16
80 (11600)	1.00	1.22	1.37
100 (14500)	1.00	1.46	1.70

It would be unrealistic to expect that this situation is likely to occur in all cases. All costs are expressed as an index reflecting the ratio of the cost of a particular strength of concrete to the cost of 40 MPa (5800 psi) concrete, as shown in Table 2.

All steel costs are expressed as an index reflecting the ratio of the cost of steel to the cost of 40 MPa (5800 psi) concrete. The indices are calculated below:

Cost of 40 MPa (5800 psi) concrete: 181 Aus$/m^3 (approximately 85 US$ per cu yd)

Cost per unit mass of reinforcing steel = 181/2500 = 0.0724 Aus$/kg = 0.02 US$ per lb

Steel cost = 1.44 Aus$/kg = 0.4 US$ per lb

Cost index of reinforcing steel = 1.44/0.0724 = 20

Prestressing steel cost = 4.875 Aus$/kg = 1.352 US$ per lb

Cost index = 4.875/0.0724 = 67

When minimizing the cost of reinforcement in design, it is important to note that prestressing steel costs about 23 percent less than mild steel reinforcement in order to provide the same amount of force. In addition to this, prestressing steel provides more than four times as much force per unit area than mild steel, thus reducing the space requirements.

Effect of Concrete Strength on Cost

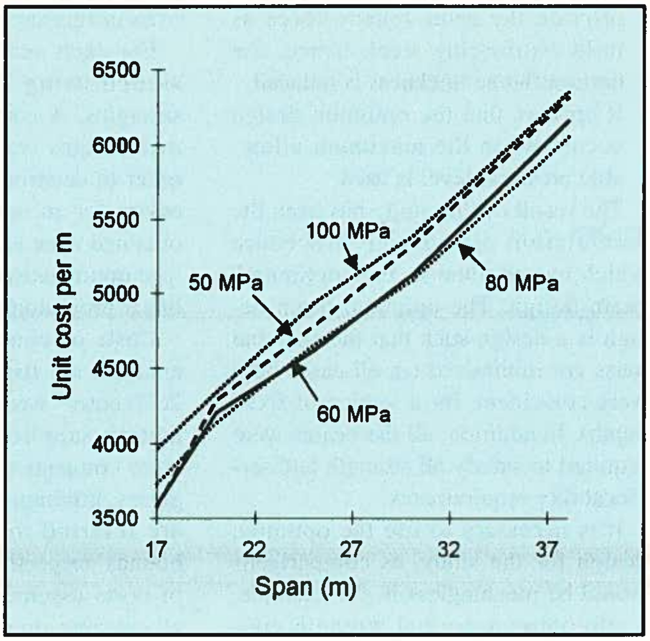
Fig. 6 shows the effect of concrete strength on cost at Year 2000 prices. Use of HPC in a standard section can reduce costs in the following ways:

- It allows a change in the composition of passive and active reinforcement to reduce total steel cost. It has already been shown that active reinforcement is less expensive in providing sufficient moment capacity than passive reinforcement.
- Because a higher quantity of prestressing steel is possible, which requires less space to provide the same tensile force as passive steel, a smaller flange depth is attainable.
- In some cases, HPC reduces the quantity of shear reinforcement. This is limited, as many designs required nominal shear reinforcement anyway.

Use of HPC in the range of 60 to 80 MPa (8700 to 11,600 psi) offers some cost advantages for all spans other than the 17 m (56 ft) span. For the 20, 30 and 38 m (66, 99 and 125 ft) spans, there is a slight savings in using 80 MPa (11,600 psi) concrete rather than 60 MPa (8700 psi) concrete. For the 25 m (82 ft) span, there is a slight savings in using 60 MPa (8700 psi) concrete rather than 80 MPa (11,600 psi) concrete.

In all cases, 100 MPa (14,500 psi) concrete results in the most expensive design, when Year 2000 costs are used. However, in the future, it is likely the cost of very HPC will drop thus increasing the cost effectiveness of these concretes. In addition to these cost comparisons, there are many other advantages in the use of HPC, as discussed below.

Fig. 6. Cost versus span. Note: 1 m = 3.28 ft; Unit cost per m = Unit cost per ft x 0.305; 1 MPa = 145 psi.



Effect of Concrete Strength on Section Mass

The use of HPC allows a higher quantity of prestressing steel which provides a much greater force per unit area than reinforcing steel. This reduces the space required in the bottom flange. It is then possible to decrease the bottom flange depth, thus reducing the total mass of the section.

As shown in Fig. 7, the use of HPC results in a reduction in section mass up to 8 percent in some cases. A decrease in section mass can also contribute to a reduction in the cost of other bridge elements such as piers and foundations supporting the beams.

Effect of Concrete Strength on Deflections

The use of HPC can reduce deflections in two ways:

- By increasing the elastic modulus, the stiffness of the structure is increased.

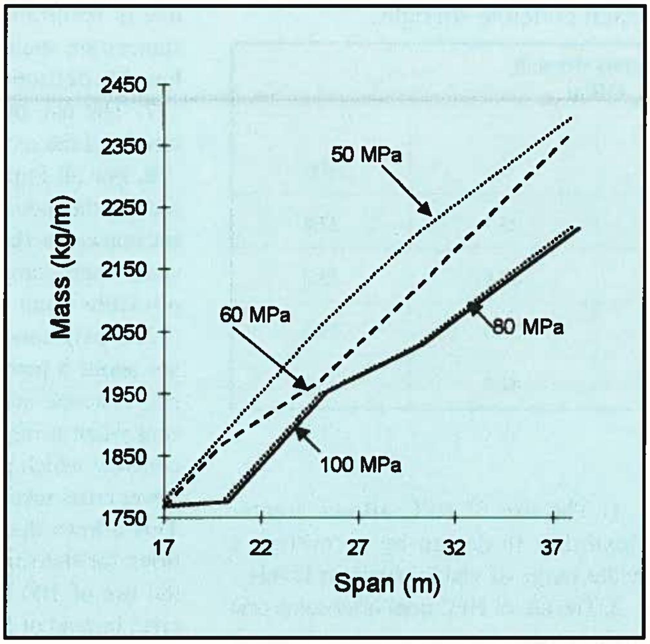


Fig. 7. Mass versus span. Note: 1 m = 3.28 ft; kg/m = 0.67 lb per ft; 1 MPa = 145 psi.

- By allowing a higher level of prestress, the downward deflection of the beam is reduced.

The total deflections for different concrete strengths are illustrated in Fig. 8.

The reduction in long-term deflections achieved by using HPC is substantial, especially for longer spans. Once again, as the designs for 80 MPa (11,600 psi) concrete and 100 MPa (14,500 psi) concrete are essentially the same, for most cases the increase in strength from 80 to 100 MPa (11,600 to 14,500 psi) simply reduces the hog (camber), as the concrete stiffness is increased. The reduction in deflections achieved by using HPC would be most beneficial in cases where there are strict limits on deflections unlike the limit of *L*/300 adopted in this investigation.

Parametric Study No. 2

The objective of this component was to determine how much the maximum possible span of any of the four standard sections can be increased with the use of HPC. This has many implications on other components of bridge construction, as it allows a shallower section to be used for a given span, which can have many practical advantages. The objective of this second component of the parametric study was achieved in the following manner.

For any section of fixed bottom flange depth with maximum (prestressing) reinforcement and remaining space filled with mild steel reinforcement, the maximum span which satisfies all strength and serviceability requirements was determined. This procedure was undertaken for all four standard cross sections for a range of concrete strengths.

The use of higher strength concrete permits longer spans by allowing a higher level of prestress to be applied to the section, as HPC increases the strength of the section at transfer. By including a higher proportion of prestressing steel, the flexural strength of the section is increased, as prestressing steel provides a much greater tensile force per unit area than mild steel reinforcement.

A higher proportion of prestressing steel also reduces deflections; however, for the investigation which follows, maximum spans were limited by flexural strength rather than deflections. It was found that flexural strength at midspan generally governed the design, and it was generally possible for sufficient flexural strength at the quarter span to be attained by changing the number of tendons debonded without exceeding the allowable stresses at transfer. These results are listed in Table 3.

The use of 60 MPa (8700 psi) concrete, in general, offers an increase in maximum span of around 5 percent compared with 50 MPa (7250 psi) concrete. Use of 80 MPa (11,600 psi) concrete offers an increase in maximum span of around 14 to 15 percent compared to 50 MPa (7250 psi) concrete, while 100 MPa (14,500 psi) concrete offers an increase of between 20 and 28 percent.

These increases in maximum allowable span allow a shallower section made from a higher strength concrete to be used instead of a deeper section made from normal strength [50 MPa (7250 psi)] concrete. For example, if a bridge with a span of 33 m (108 ft) was to be built, a 1000 mm (39 in.) deep section using 100 MPa (14,500 psi) concrete could be used, rather than the 1500 mm (59 in.) deep section required if 50 MPa (7250 psi) concrete is used.

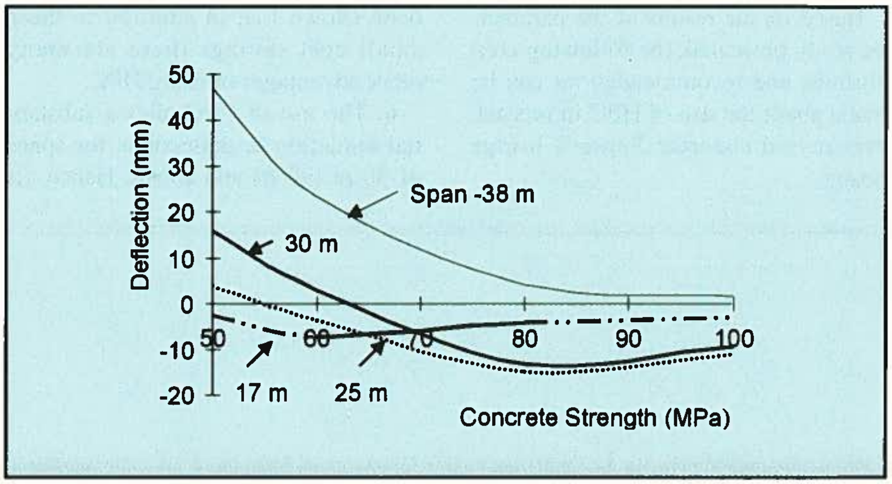


Fig. 8. Total long-term deflections. Note: 1 m = 3.28 ft; 1 mm = 0.0394 in.; 1 MPa = 145 psi.

Table 3. Maximum possible span (m) for each concrete strength.

Section depth (mm)	Concrete strength (MPa)			
	50	60	80	100
750	22.4	23.6	25.7	27.8
1000	25.9	27.3	30.4	33.2
1200	32.2	33.8	37.0	39.6
1500	36.2	37.9	41.3	43.8

Note: 1 mm = 0.0394 in.; 1 m = 3.28 ft; 1 MPa = 145 psi.

In general, using a shallower section will not result in direct cost savings for spans at the upper limit for a particular section, as the shallower section is not the optimum section. There are, however, many practical advantages to be gained from using a shallower section, including:

- Reducing the total height of the bridge. This is useful where architectural constraints exist and also has the additional benefits of reducing the cost of approaches and supports. In the example above, the height of the bridge could be reduced by 0.5 m (20 in.).
- Decreasing the mass of the structure, which reduces loadings on bridge supports, may reduce construction and transportation costs.
- Benefits in replacing existing bridges, especially where constraints exist with vertical clearances.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the parametric study presented, the following conclusions and recommendations can be made about the use of HPC in precast, prestressed concrete Super-T bridge beams:

1. The use of HPC allows greater flexibility in design by permitting a wider range of viable prestress levels.

2. The use of HPC does offer some cost savings when used in standard Super-T beam sections. Typically, these cost savings are in the order of 4 to 5 percent at Year 2000 concrete costs for most longer spans. If the cost of HPC is reduced in the future, the cost savings will increase.

3. When optimizing design according to cost and section mass, the level of prestress should be maximized. Design is generally governed by flexural strength and strength at transfer.

4. For spans of 20 m (66 ft) and greater, the optimum design for 80 and 100 MPa (11,600 and 14,500 psi) concrete was fully prestressed, while for 50 and 60 MPa (7250 and 8700 psi) concrete, the optimum designs were partially prestressed.

5. By examining the cost savings in bridge beams achieved by using HPC alone, many designers may not consider that the relatively small cost savings justify the use of HPC. It has been shown that in addition to these small cost savings there are many other advantages of using HPC.

6. The use of HPC allows substantial reduction in deflections for spans of 30 m (99 ft) and above. Hence, its use is recommended where circumstances are such that strict limits on allowable deflections exist.

7. The use of HPC can reduce the weight of the section by up to 8 percent.

8. For all Super-T sections currently used in the industry, use of HPC allows increases in the maximum possible span when compared to the maximum possible span when using 50 MPa (7250 psi) concrete. These increases are about 5 percent for 60 MPa (8700 psi) concrete and can be up to 28 percent when using 100 MPa (14,500 psi) concrete which permits the use of shallower cross sections for any given span. This allows the use of shallower sections for the same span. For example, the use of 100 MPa (14,500 psi) concrete instead of 50 MPa (7250 psi) concrete for a 33 m (108 ft) beam allows a section 33 percent shallower to be used.

FUTURE RESEARCH

In this study, only Super-T beam geometry currently available was investigated. There may be further economic benefits in the use of high performance concrete for alternative geometry of these sections. More research is required in this area. Also further research is needed to determine the optimum level of prestress for these sections.

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APPENDIX — NOTATION

A_{sc} = cross-sectional area of compression reinforcement

A_{st} = cross-sectional area of longitudinal reinforcement provided in tension zone

d_o = distance from extreme compression fiber of concrete to centroid of outermost layer of tensile reinforcement or tendons

E_c = elastic modulus of concrete

f'_c = specified compressive cylinder strength of concrete at 28 days

k_{cs} = factor used in serviceability design to take account of long-term effects of creep and shrinkage

K = level of prestress

V_{uc} = ultimate shear strength of a beam excluding shear reinforcement

β_1 = $1.1(1.6 - d_0/1000)\ 1.1$

β_2 = 1; or = $1 + (N^*/14A_g)$ for members subject to significant axial compression

β_3 = 1; or greater than one for members with significant diagonal compression

ρ = density of concrete