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THE DEPARTMENT OF
THE ENVIRONMENT FOR NORTHERN IRELAND

Early Thermal Cracking of Concrete

Summary: This Advice Note explains why the restraint of early thermal movements causes cracking and suggests suitable methods by which cracking can be controlled.

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VOLUME 1 HIGHWAY STRUCTURES: APPROVAL PROCEDURES AND GENERAL DESIGN

SECTION 3 GENERAL DESIGN

BA 24/87

EARLY THERMAL CRACKING OF CONCRETE

Contents

March 1987

1. INTRODUCTION

1.1 Experience has shown that in highway structures designed to BS 5400: Part 4: 1984(1) cracking can occur during construction due to the restraint of early thermal movement in the immature concrete. This form of cracking is distinct from the flexural cracking which can occur due to normal loading of the mature concrete. However, it is just as important to limit the widths of these cracks so as not to impair the appearance, serviceability and durability of the structure.

1.2 In the past, cracking at an early age has generally been attributed to restraint of shrinkage movement. Recent research has shown that for the UK it is restraint of early thermal movement that is the dominant effect. In addition, the problems with early age cracking appear to have become more prevalent in recent years, possibly as a result of improvements in other aspects of construction technology. For instance, the development of higher early strength concretes increases the problems with early age cracking.

2. SCOPE

2.1 This Advice Note outlines the mechanism by which restraint of early thermal movement causes cracking and the factors which are involved. In addition it suggests suitable methods by which the cracking can be controlled.

3. EARLY THERMAL MOVEMENT

3.1 The setting of concrete is a chemical reaction which liberates heat as the cement hydrates. At first the concrete expands as the heat of hydration exceeds the rate at which heat is dissipated. In a thin section the peak temperature rise is soon reached and the initial expansion is then followed by thermal contraction as the concrete cools down to the ambient temperature. This will occur within only a few days in thin sections, but it may take several weeks to complete in very thick sections, especially if they are insulated.

3.2 These volume changes would be of little consequence if the concrete was totally unrestrained. However, in practice, there is always partial or complete movement restraint of any structural member. It is this restraint that causes early thermal movement stresses in the concrete which may ultimately lead to cracking.

3.3 Where a concrete member is restrained, cracking due to early thermal movement is almost inevitable due to the low tensile strength of the immature concrete. In a plain concrete member, if the tensile strength of the concrete is exceeded, one wide crack is induced. This relieves the tension elsewhere and further cracking does not occur. A similar situation also occurs in a lightly reinforced section, where if the force exerted by the whole body of concrete exceeds the strength of the reinforcement, the reinforcement will yield and a few wide cracks at random positions will occur. In order to control this cracking a certain minimum quantity of well distributed steel is required.

3.4 The function of the reinforcement is to control the cracks so that the section remains serviceable. The reinforcement ratios required to achieve this can be calculated using the "bond-slip" hypothesis (see 4.1). This leads to a prediction method (see Section 5) in which both crack spacing and width may be assessed if a minimum reinforcement ratio (sometimes called the "critical reinforcement ratio") is provided to control the cracking. Further reinforcement may then have to be provided so that the width of any fully developed crack is within prescribed limits.

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4. SIGNIFICANCE OF CRACKING

4.1 The cracking of a reinforced concrete member is only a problem when the crack width exceeds a certain value such that the durability and serviceability of the structure, or its appearance, are impaired. Research has shown that flexural cracks tend to taper from a maximum width at the concrete surface to a near zero width at the surface of the reinforcement and then continue as a hairline crack to some internal point. In contrast to these typically tapered flexural cracks, the cracking caused by restrained thermal and shrinkage strains is generally widely spaced, of irregular width, and often extends right through a lightly reinforced section. An important difference from flexural cracking is that the ratio of bond strength to tensile strength is much lower in immature concrete and extensive bond slip can occur.

4.2 The crack width limitations of BS 5400: Part 4: 1984 are nominal values relating to flexural cracks which narrow rapidly with depth. The width to depth characteristics of early thermal cracks, in comparison, vary considerably depending on the type of restraint and the sequence of events in their formation.

4.3 It should be noted that early thermal cracking of concrete can also occur in post-tensioned concrete members prior to prestressing. This is because the section, prior to being prestressed, is effectively a lightly reinforced concrete member. Subsequent prestressing will then close up the cracks except in some circumstances, such as stages construction, where this may be prevented. In these cases either internal restraint due to reinforcement or external restraint by an adjacent section effectively locks-in the crack. Careful consideration needs to be given to the implications of such cracking.

5. PREDICTION METHOD

5.1 An explanation of the theory behind the prediction method is given by B P Hughes (2) and by T A Harrison (3).

5.2 To control crack spacing there must be sufficient reinforcement so that the reinforcement will not yield before the tensile strength of the immature concrete is exceeded. This is achieved by satisfying the equation:-

$A_s f_y \geq A_c f_{ct}*$ .... (1)

or $\rho_{crit} = A_s/A_c = f_{ct}*/f_y$ .... (2)

where: A_s = area of reinforcement in a given direction around the perimeter of a section to prevent early thermal cracking

A_C = area of effective concrete

ρ_{crit} = minimum or critical reinforcement ratio

f_y = characteristic tensile strength of reinforcement. (N/mm²)

$f_{ct}*$ = tensile strength of immature concrete which may be taken as $0.12 (f_{cu})^{0.7}$ (N/mm²)

f_{cu} = characteristic cube strength of concrete. (N/mm²)

5.3 For controlled cracking, the crack spacing S depends primarily on the ratio of the tensile strength of the immature concrete to the average bond strength f_b, between the reinforcement and the immature concrete.

$S_{max} = (f_{ct}*/f_b).\phi/2\rho$ .... (3)

where: S_{max} = maximum crack spacing (mm)
ρ = reinforcement ratio provided
ϕ = bar size (nominal diameter) (mm)

and the ratio $(f_{ct}*/f_b)$ at an early age may be taken as,

= 1.00 for plain round bars
= 0.80 for Type 1 deformed bars
= 0.67 for Type 2 deformed bars

For classification of bar types see Clause 5.8.6.1 of BS 5400: Part 4: 1984.

5.4 In theory the crack spacing is an intermediate value between S_{max} and the minimum crack spacing, $S_{min} = 0.5 S_{max}$. However it is the fully developed crack width w_{max} derived from the maximum crack spacing S_{max}, that is the limiting criterion.

$w_{max} = S_{max} [R(\varepsilon_{sh} + \varepsilon_{th}) - 0.5\varepsilon_{ult}]$ .... (4)

where: w_{max} = maximum crack width
R = restraint factor
ε_{sh} = Shrinkage strain
ε_{th} = thermal strain
ε_{ult} = ultimate tensile strain capacity of concrete

5.5 The shrinkage strain ε_{sh} should be taken as the free shrinkage strain, modified by the effects of creep. For normal UK conditions the shrinkage strain is usually notvmote than 0. ε_{ult}5

5.6 The thermal strain ε_{th} is composed of two parts, the early thermal strain as the heat of hydration dissipates and the long-term strain in the mature concrete due to a seasonal fall in temperature. A factor of 0.8 is applied to the calculation of the thermal strain in immature concrete to allow for simplifications made in the design method. The value of the coefficient of thermal expansion α() may be assumed to be constant as it varies little after the first day.

Therefor e$\varepsilon_{th} = 0.8\alpha(T_1 + T_2)$ ..... (5)

where : α = coefficient of thermal expansion

T_1 = short-term fall in temperature from hydration peak to ambient

T_2 = long-term fall in ambient temperature due to seasonal variations.

5.7 As the elements which provide restraint to newly cast concrete can themselves deform, the degree of restraint provided in practice is never 100%, except in the case of infill bays. Typical values for external restraint have been determined from measurements recorded in certain structural situations and these form the basis for the values given in Table 2 of Amendment No. 1 to BD 28/87.

For internal restraint the value of R may be taken as 0.5.

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6. FORMS OF RESTRAINT

6.1 General

6.1.1 The forms of restraint fall into two categories:

(a) Internal Restraint
This is where one part of a concrete pour expands or contracts relative to another part of the same section. It occurs in thick sections as the thermal conductivity of concrete is poor and so causes a differential temperature gradient across the section. It can also occur where a high percentage of reinforcement restrains the concrete.

(b) External Restraint
This is where an external element restrains the early thermal movements of the member being cast. It can be further sub-divided into End Restraint and Continuous Edge Restraint although a given situation is often a combination of the two.

6.1.2 Usually one or other of these forms of restraint is dominant. However there are conditions under which a combination of the two can occur and this is also considered. There are also conditions in which partial or intermittent restraint can occur.

6.2 Internal Restraint due to Section Size

6.2.1 Internal restraint is caused by a temperature difference within the section such that one part of the section restrains another part of the same section during concrete setting. This only occurs in thick sections where a significant temperature gradient can be built up through the section. For example in a large base pour the surface zone will cool and contract faster than the core once the temperature peak has passed. Tension cracks can then penetrate the depth of the surface zone but due to the nature of the restraint cannot be continuous through the section. As the core cools these cracks may even close up with tensile stresses developing in the core and compressive stresses in the surface zone. In such extreme cases this can result in internal cracking.

6.2.2 Insulation by the formwork can substantially reduce the temperature gradient within a section and hence reduce the extent of cracking. However to be beneficial the formwork needs to be left in place until the temperature peak in the core has passed and the temperature gradient has reduced. Even so the effective surface zone needs to be reinforced to achieve the critical reinforcement ratio in both directions if cracking is to be controlled. The thickness of this effective surface zone can reasonably be taken as 250mm in most cases, which leads to economies in reinforcement in members thicker than 500mm.

6.3 Internal Restraint due to Reinforcement

6.3.1 Paradoxically, the provision of too much reinforcement can cause undue restraint as the surrounding concrete cools after casting. This is generally recognised in codes by, for instance, limiting the maximum steel percentage in columns, and by recommending the staggering of laps to avoid a localised double steel percentage.

6.3.2 An example of this, which is often overlooked, occurs in staged construction of a hollow box or voided reinforced concrete deck. Although the bottom tension steel reinforcement ratio may only be 1.5% of the whole section, temporarily it can represent a very high percentage if the thin bottom slab is cast as the first stage. This form of restraint leads to a pattern of many very fine cracks in the bottom slab leading to a higher initial deflection of the deck when the falsework is removed. There is then subsequent enlargement of the cracks due to bending stresses.

6.4 External End Restraint

6.4.1 Pure end restraint would cause uniform tension to develop along the length of a section. If insufficient longitudinal reinforcement is provided in the member to achieve the critical reinforcement ratio then a single primary crack is likely to form with the steel having yielded at this point. However provision of reinforcement in excess of the critical ratio leads to a controlled pattern of cracking as shown in Figure 1.

6.4.2 Usually the first crack will occur at a construction joint as the strength of the bond between new and mature concrete is generally less than the tensile strength of the member. Such a crack is therefore less likely to be fully developed. If the overall contraction of the bay can be satisfied by fully developed cracks at one or both construction joints then the intermediate cracks shown on Figure 1 may not occur. This explains why the worst cracks are usually seen at construction joints or at changes of section which cause stress concentrations.

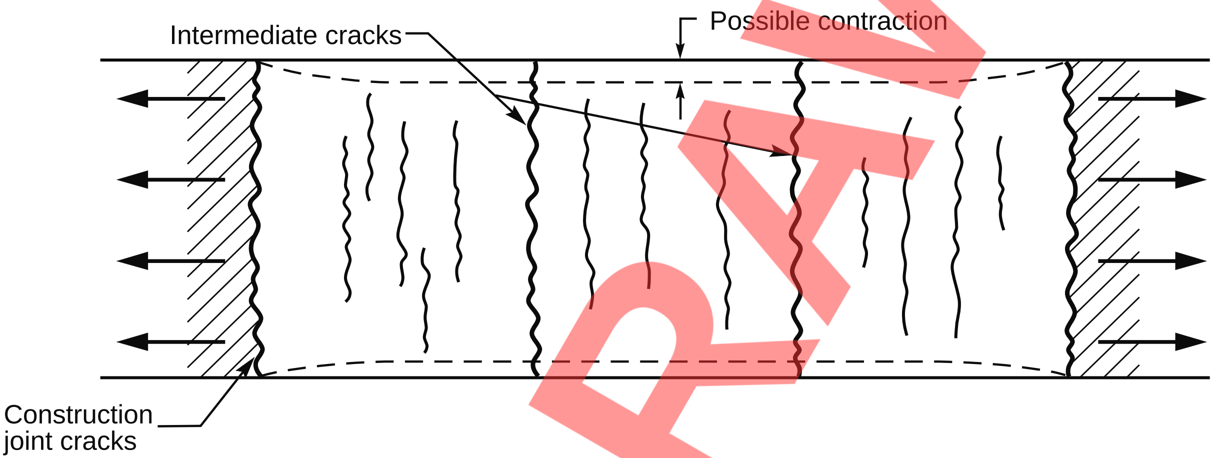

Figure 1

Cracking Due to End Restraint

6.4.3 Pure end restraint conditions can only be assumed if the restraining edges are short. Experience has shown that if the length of the restraining edge exceeds approximately 5m, the effects of edge restraint along them also need to be considered, see 6.5.

6.5 External Edge Restraint

6.5.1 A typical pattern of cracking due to edge restraint of a thin section is shown in Figure 2, assuming that the base is rigid. Without restraint the section would contract along the line of the base, and so with restraint a horizontal force develops along the construction joint. This leads to vertical cracking at midspan but splayed cracking towards the ends of the section where a vertical tensile force is required to balance the tendency of the horizontal force to warp the wall. In addition a horizontal crack may occur at the construction joint at the ends of the walls due to this warping restraint.

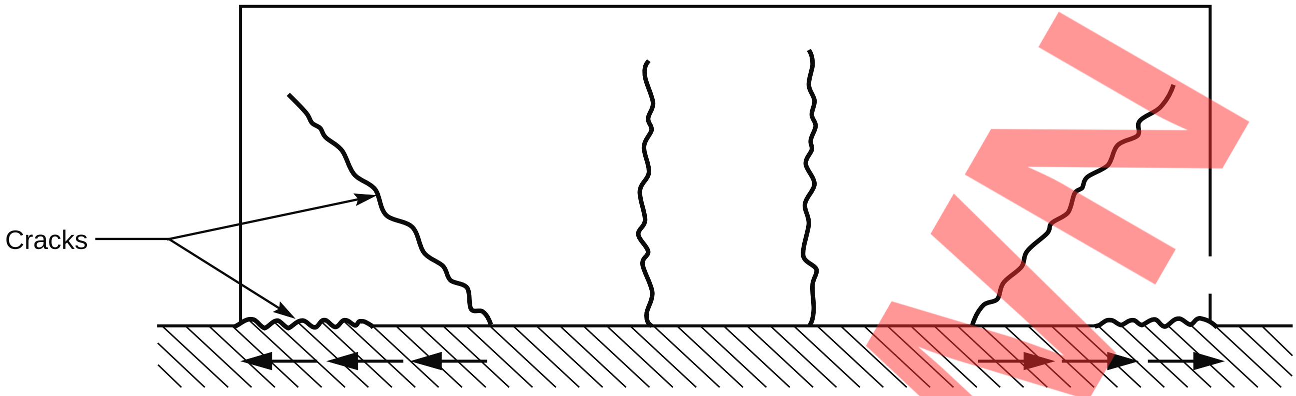

Figure 2

Cracking Due to Edge Restraint

6.5.2 This basic pattern of cracking is independent of the amount of reinforcement provided. When sufficient reinforcement is provided to achieve the critical reinforcement ratio the widths of these primary cracks are controlled, although secondary cracks may be induced. The extent and size of cracking will then depend on the amount and distribution of reinforcement provided.

6.5.3 In practice the pattern of cracking can be modified. Typically the base may not be sufficiently rigid for the full warping restraint at the ends to occur. This leads to the cracks being less splayed at the ends and reduces the possibility of a horizontal crack at the construction joint. Other factors that may modify the crack pattern are planes of weakness such as joints, and stress concentrations such as at weepholes and box-outs.

6.5.4 Often it is satisfactory to assume that full restraint occurs throughout a section and to provide an area of reinforcement to control crack widths. However, in the case of a wall with continuous base restraint only, this is unduly conservative as the degrees of restraint reduces with increasing height. At the free ends the restraint reduces to zero over the height but there is insufficient information to predict intermediate values. Also vertical restraint due to warping is only significant over a short length at the end of the wall.

6.6 Combined End and Edge Restraint

6.6.1 This occurs when there is alternate bay construction of a thin section. The edge restraint provided by the base only serves to modify the crack pattern as shown in Figure 3.

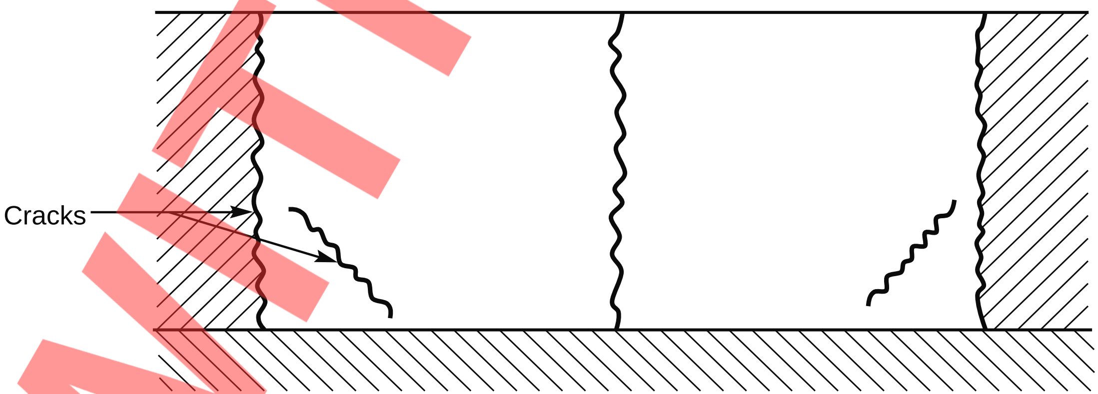

Figure 3

Cracking in an Infill Bay

6.6.2 As cracking is caused by the restraint of movement, reducing or removing the restraint can alleviate some of the problems. One way of reducing the restraint is to adopt sequential bay construction which results in the crack pattern as shown in Figure 4. However, sequential bay construction tends to produce a wider crack at the base.

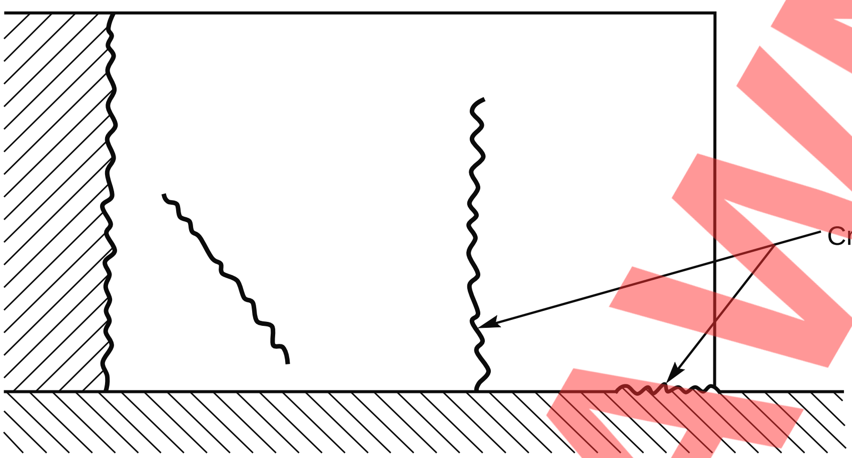

Figure 4

Cracking in an End Bay

6.7 Combined Internal and External Restraint

6.7.1 A typical case of combined internal and external restraint is in alternate bay construction of a thick wall such as an abutment. The appearance of cracking in a thick section is similar to that for a thin section. However the slower cooling rate of the interior of the section initially provides an additional restraint on the surface layer. Cracking is therefore limited to the surface layers at first, and the cracking can be controlled by providing reinforcement based on the effective surface zone. Later, as the interior itself cools, the already established crack pattern of the surface extends into the core of the concrete. As the internal temperature generated is greater than for thin sections, the temperature fall T, used to calculate the reinforcement requirements, should be at about 10° greater than the values used for thicknesses up to 500mm.

7. MINIMISING EARLY THERMAL MOVEMENT

7.1 General

7.1.1 In order to minimise the early thermal movement it is necessary to either reduce the temperature rise or to reduce the coefficient of thermal expansion. Unless specific measures are taken the coefficient of thermal expansion should be taken as $12 \times 10^{-6}/°C$. The only practical means of reducing this is to use an aggregate with a low coefficient such as some limestones, although this in itself can cause problems with differential thermal strains. Unless such aggregates are known to be available at a competitive cost the design and specification should not be based on their use.

7.1.2 The variables that affect the temperature rise and the temperature difference between sections are considered in detail in the CIRIA Report 91 (3). Basically they are:

- (a) Section thickness
- (b) Cement type
- (c) Concrete mix proportions
- (d) Formwork and Insulation
- (e) Ambient conditions and placing temperature

7.2 Section Thickness

7.2.1 The thicker the section, the greater will be the temperature rise. However, when the section thickness becomes greater than 1.5 to 2m the additional increase in temperature becomes so small as to be negligible. As discussed in Section 6.2 economies in design can be effected when the section thickness exceeds 500mm by considering only an effective surface zone. This results from concrete being a poor thermal conductor making the temperature gradient across the section more important than the peak temperature rise when the section exceeds 500mm.

7.3 Cement Type

7.3.1 Cement type is important as both the rate of heat liberation and total heat generated are dependent on the characteristics of the cement used. Although the heat evolution characteristics of cements of the same nominal type can be vastly different some general guidance can be given.

7.3.2 The typical temperature rise due to sulphate resisting Portland cement (SRPC) is 20 to 30 per cent lower than that in an equivalent strength mix using ordinary Portland cement (OPC).

7.3.3 The use of rapid hardening Portland cement (RHPC) should be avoided where possible as the heat is evolved very quickly giving a high temperature rise. However, if a RHPC mix is placed in cold weather the temperature rise may not exceed that of an equivalent OPC mix used at normal temperatures. Some modern OPCs have rapid hardening properties similar to RHPC and their use should be avoided where possible.

7.3.4 One method of reducing the temperature gradient within a thick base is to use a cement replacement material with a low reactivity such as pulverised fuel ash (PFA) or ground granulated blast furnace slag (GGBFS). PFA/OPC concrete and concrete mixes containing a GGBFS replacement material can be expected to have a lower temperature rise than an equivalent OPC concrete. Guidance on calculating the temperature rise where a cement replacement material is used is given in CIRIA Report 91 (3).

7.4 Concrete Mix Proportions

7.4.1 The effective cement content has a significant effect on the temperature rise. An increase in cement causes a greater evolution of heat per unit volume and hence a higher temperature rise. Therefore consideration should be given to specifying a reduced maximum cement content for sections which are likely to be affected by early thermal cracking.

7.4.2 The use of water reducing admixtures can reduce the temperature rise because they allow a lower cement content than in an ordinary mix with the same grade and workability. It is the lower cement content and not the admixture which is beneficial. An admixture that acts as a retarder has little effect on the temperature rise as it only delays the onset of the hydration process. The use of an admixture that acts as an accelerator can cause problems as it speeds up the rate of heat liberation. If an accelerator is used in cold weather, the increase in temperature rise may not exceed the design value based on placing in normal weather conditions.

7.5 Ambient Conditions and Placing Temperature

7.5.1 In assessing early thermal movement and the subsequent seasonal movement it is necessary to predict the mean daily temperature during the period of construction. Often the period of construction is not known at the time of design and therefore it is normal to assume that the concrete is placed during the summer months. The highest monthly average mean daily temperature in the UK is 17°C but obviously there are periods in which the mean daily temperature exceeds this value.

7.5.2 Although ambient temperature is not controllable it is possible to restrict the concrete placing temperature. This can be beneficial as the higher the temperature the faster is the rate of heat liberation. Generally the temperature of concrete as placed in the UK is up to 5°C higher than the mean daily temperature but it can be 10°C higher in hot weather with long haul distances. This assumes that no precautions have been taken to reduce the concrete placing temperature. Despite the face that a number of relatively simple precautions can limit the placing temperature, imposing further restrictions on the contractor is not usually cost effective.

7.6 Formwork and Insulation

7.6.1 Formwork and insulation have a significant effect on the temperature peak and temperature gradient across a section. The higher the insulation value of formwork, the higher is the temperature peak as heat is retained longer, and the lower the temperature gradient as there is less difference between sections. If restraint is external and the section is less than 500mm thick formwork with a high conductivity can be beneficial. However in thick sections internal restraint is caused by changes in temperature gradient and insulating the concrete minimises the temperature gradient.

7.6.2 Although contractors generally remove their formwork as soon as possible after concreting for economic reasons, this cannot be assumed at the design stage. Removing formwork the morning after casting tends to reduce the peak temperature rise but increases the temperature gradient. However, if formwork with a high thermal conductivity is being used, such as steel or glass-reinforced plastic, removal after 18 hours makes little difference. Restrictions on striking times based on thermal requirements are therefore not justified for sections up to 500mm thick. Where a section is more than 500mm thick benefit may be gained by firstly, insulating to reduce the thermal gradient and secondly, restricting the striking time until the thermal gradient has reduced to an acceptable level. An assessment of striking times considering the implications of factors other than early thermal effects is given in CIRIA Report 73 (4).

8. REDUCING THE MOVEMENT RESTRAINT

8.1 General

8.1.1 Since it is restraint of early thermal movement that causes cracking, a most effective way of limiting cracking is to reduce or remove the restraint. In some forms of construction the restraint is inherent in the system and necessary to its function. Examples of this are composite steel/concrete decks and precast prestressed concrete beams with an insitu concrete deck slab. In such cases the restraint cannot be reduced and the full early thermal strains must be allowed for.

8.2 Provision of Construction Joints

8.2.1 Every construction joint in a reinforced concrete deck introduces restraint and increases the risk of early thermal cracking. Typically reinforced concrete voided or hollow box type deck construction involves staged construction with a joint at the bottom slab to web connection. The subsequently cast section is then restrained by the previously cast section and reinforcement should be provided to limit the cracking. In assessing the early thermal movement, there is only differential shrinkage to be considered and not the full long term shrinkage. Also the thermal movement due to seasonal variations does not have to be accommodated.

8.2.2 Another typical problem occurs with bridge parapet beams which are often case separately to the main insitu deck concrete. If the parapet beams are cast integrally with the deck there is no restraint to be considered. However, integral casting can cause an unsatisfactory finished parapet line in longer spans unless adequate precamber information is given for formwork setting. Some form of movement joint may be provided over supports on continuous decks to avoid live load bending stresses tending to open up early thermal cracks.

8.2.3 Restraint of post-tensioned concrete members at an early age can cause a problem as they are only lightly reinforced and not prestressed at that stage. In addition they are generally subject to larger early thermal movements as stronger concrete requires higher cement contents. Prior to prestressing they should therefore be treated as reinforced concrete members.

8.2.4 Staged construction of a post-tensioned member has its own particular problems because of the effect on prestress. Any restraint cracking in the webs of a box girder, or indeed the top flange if three stages are used, will be locked-in by the adjacent stage. This can interfere with the designed distribution of prestress. For cracked webs, this could mean transfer of prestress from webs to flanges and, in a severe case, no crack closure resulting in no web prestress. In such circumstances it could prove necessary to grout cracks prior to prestressing. Ideally, staging should be avoided wherever possible but, when it is used, adequate reinforcement should be provided to limit the early thermal cracking. Early partial prestressing is occasionally used to minimise early thermal cracking due to staged construction, but this is not normally economically viable.

8.3 Construction Sequence

8.3.1 Reduction of restraint can also be achieved in some instances by altering the construction sequence. This applies particularly to continuous wall construction where sequential casting of bays causes less restraint than alternate bay construction. A similar condition occurs in the construction of a long continuous deck slab cast in a number of separate pours and also in the construction of parapet plinths.

8.3.2 The timing of the construction sequence can also affect the restraint. When constructing large sections, such as bridge piers or columns, in a series of vertical lifts it is best to minimise the time between lifts. If the previous lift is still hot it offers little restraint as both lifts are contracting, although at slightly different rates. With slipform construction the time between successive lifts is minimised and external restraint is negligible. A greater time difference will induce some restraint but with a well insulated section cracking can be reduced by casting the next lift within a few days.

8.4 Movement Joints

8.4.1 An alternative method of reducing restraint is to provide movement joints. This applies to sections in which there is external longitudinal restraint of early thermal movement. Both expansion joints and full contraction joints reduce the restraint that occurs and hence reduce cracking. Where possible the provision of full movement joints at a maximum of 15m spacings means that the thermal movement due to seasonal variations can be accommodated at the joints.

8.4.2 The position and spacing of movement joints is considered in detail elsewhere (2). At one extreme, control of cracking is exercised by providing movement joints at close spacing with no reinforcement and at the other, no movement joints are provided and the cracking is controlled totally by the provision of adequate reinforcement. Intermediate solutions between the two extremes can also be practical and the optimum solution is often a matter of economics.

9. REINFORCEMENT AND PRESTRESSING

As discussed in Section 3, cracking can be controlled by the provision of an appropriate area of distribution reinforcement. The design rules for this are the subject of the associated Departmental Standard BD 28/87 (5). Crack control by means of partial prestressing is an expensive operation only generally used in special circumstances and is outside the scope of this Advice Note.

10. REFERENCES

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3. Harrison, T A. Early Age Thermal Crack Control in Concrete. CIRIA Report 91. 1981.

4. Harrison, T A. Formwork Striking Times - Methods of Assessment. CIRIA Report 73, 1977.

5. Departmental Standard BD 28/87. Early Thermal Cracking of Concrete.

11. ENQUIRIES

Technical enquiries arising from the application of this document to a particular design should be addressed to the appropriate Technical Approval Authority.

All other technical enquiries or comments should be addressed to:-

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