TYPES AND CAUSES
OF CRACKS AND CRACKING

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1.0 INTRODUCTION

Cracking in concrete is a phenomena which is recognised world-wide. Some cracks in some situations do no harm and are entirely acceptable. In other concrete, cracks are serious defects, in that they adversely affect strength, function or appearance. There is considerable attention paid to the problems of cracking but the current reaction to cracking is often dissociated from the significance of the crack in the situation in which it occurs. This reaction ranges from the extreme of concern about the presence of a single hair crack to the blasé view that cracks are part of the nature of concrete and can be safely ignored wherever they occur and however wide they are.

2.0 CRACKS IN CONCRETE

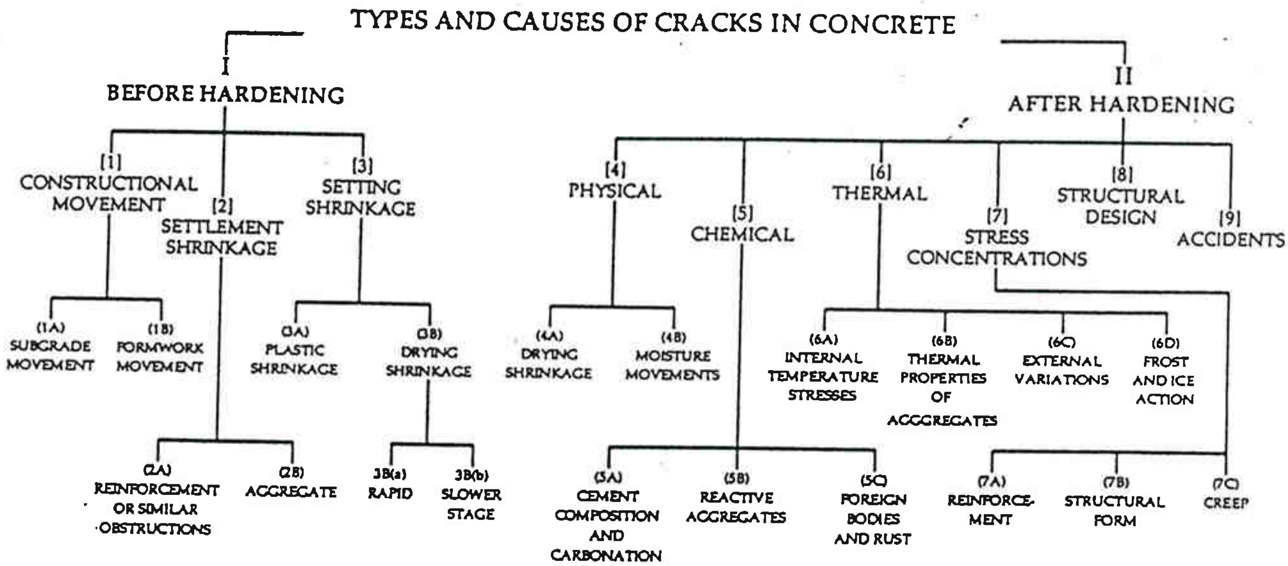

Figure 1 - Causes of Cracking in Concrete

Cracked concrete is usually a symptom rather than a fault. In the majority of cases, cracks do not result in structural failure, but they can result in definite loss of performance of the structure by causing accelerated deterioration potentially rendering the structure unserviceable. Cracks can be classified by direction, width and depth - namely longitudinal, transverse, vertical, diagonal and random. With regards to direction at the surface, there are two main kinds: map cracks or pattern cracks. These are rather uniformly distributed short cracks running in all directions roughly in hexagonal patterns; they indicate restraint of the surface layer by the inner concrete or backing. The other kind is the single continuous cracks which run in rather definite directions, often in parallel at definite intervals; they indicate restraint in the direction perpendicular to them. In most cases, cracks that appear and continue to develop after the concrete has hardened are considered active. Cracking is called dormant when it is caused by a factor that is not expected to occur again. Under this category are plastic cracks and cracks resulting from temporary overloading.

Three width ranges are commonly referred to: Fine - generally less than 1mm in width; Medium - between 1 and 2mm; Wide - over 2mm. Cracks up to 0.3mm wide are generally aesthetically acceptable. However, an acceptable crack width depends on the exposure to which the member is subjected. The following values are recognised: for the most severe exposure (industrial or marine environment where watertightness is essential), 0.1mm; for normal external exposures, or internal exposure of structural members in a humid or aggressive atmosphere, 0.2mm; for internal and protected members 0.3mm.

Figure 1 shows a family tree of crack types. The cracks are classified into two broad categories including those that occur before hardening and those observed after hardening. Subtypes in the before-hardening category are due to constructional movement, settlement shrinkage, and setting shrinkage. These are caused by the subgrade settlement, movement of formwork by swelling of timber, or lack of robustness of the form and plastic shrinkage of concrete by the rapid evaporation of moisture from the concrete surfaces. After hardening, cracks are classified under six headings: physical, chemical, thermal, stress concentrations, structural design, and accidental overload.

After-hardening cracks are caused by the later stages of drying shrinkage as well as those which are environmentally induced. Some of the phenomena which bring about environmentally induced cracking are: expansion due to the use of unsound cement, the alkali-aggregate reaction, sulfate attack, corrosion of embedded steel, freezing and thawing, thermal cycling, and mechanical loading. Figure 2 gives an idealised illustration of the various crack types that can occur in a hypothetical structure in typical situations. In all of these phenomena, environmentally induced moisture movement is the primary factor that may cause cracking. Table 1 summarises the characteristics of these cracks and lists the time periods in which these types of cracks appear.

For legend see Table 1

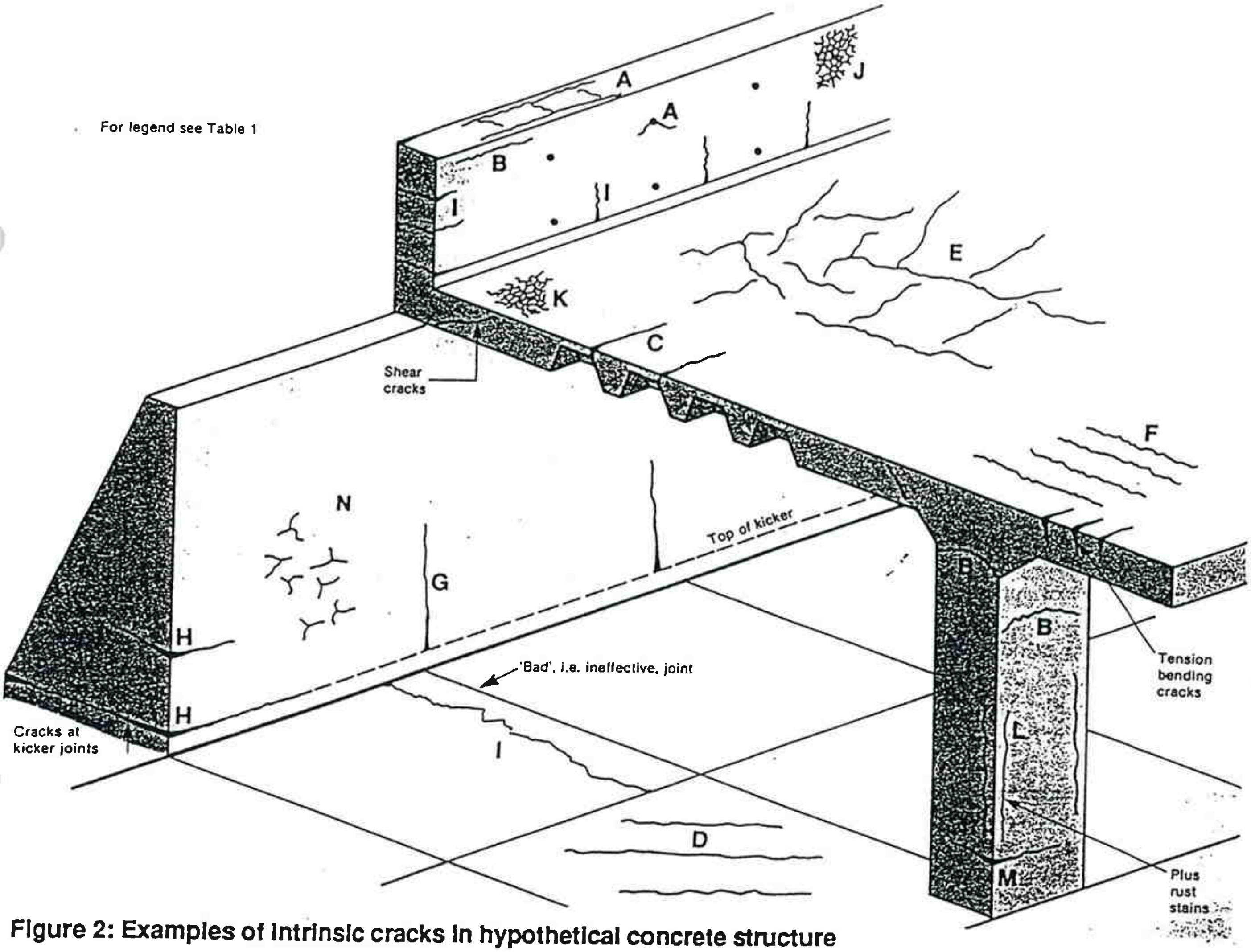

Figure 2: Examples of intrinsic cracks in hypothetical concrete structure

Table 1 - Classification of Intrinsic Cracks

Type of Cracking	Letter (See Figure 2)	Subdivision	Most Common Location	Primary Cause (Excluding Restraint)	Secondary Causes/Factors	Remedy (Assuming Basic Redesign is Impossible) In All Cases Reduce Restraint	Time of Appearance
Plastic settlement	A	Over reinforcement	Deep Sections	Excess bleeding	Rapid early drying conditions	Reduce bleeding (air entrainment) or revibrate	Ten minutes to three hours
	B	Arching	Top of columns				
	C	Change of depth	Trough and waffle slabs				
Plastic shrinkage	D	Diagonal	Roads and slabs	Rapid early drying	Low rate of bleeding	Improve early curing	Thirty minutes to six hours
	E	Random	Reinforced concrete slabs				
	F	Over reinforcement	Reinforced concrete slabs	Ditto plus steel near surface			
Early thermal contraction	G	External restraint	Thick walls	Excess heat generation	Rapid cooling	Reduce heat and/or insulate	One day to two or three weeks
	H	Internal restraint	Thick slabs	Excess temperature gradients			
Long-term drying shrinkage	I		Thin slabs (and walls)	Inefficient joints	Excess shrinkage Inefficient curing	Reduce water content Improve curing	Several weeks or months
Crazing	J	Against formwork	'Fair faced' concrete	Impermeable formwork	Rich mixes Poor curing	Improve curing and finishing	One to seven days, sometimes much later
	K	Floated concrete	Slabs	Over-trowelling			
Corrosion of reinforcement	L	Natural	Columns and beams	Lack of cover	Poor quality concrete	eliminate causes listed	More than two years
	M	Calcium chloride	Precast concrete	Excess calcium chloride			
Alkali-silica reaction	N		(Damp locations)	Reactive aggregate plus high-alkali cement		Eliminate causes listed	More than five years

In summary, a list of some factors causing cracking are as follows:

- Poor quality of concrete - too high a water content and use of excessively high cement contents.
- Poor structural design.
- The development of differential thermal stresses due to high heat of hydration.
- The tensile stresses developed due to restrained thermal expansion and contraction from temperature changes, and ensuing dimensional changes as a result of diurnal and seasonal temperature cycles.
- Dimensional expansion and contraction caused by cycles of wetting and drying.
- Errors, negligence, or bad workmanship.
- Corrosion of steel by chloride ions or carbonation of concrete.
- Rapid evaporation of moisture due to dry, hot and windy conditions prevailing at the time of placing.
- Structural adjustment due to foundation movement by settlement or due to expansive soils.
- Chemical attack of concrete both internally (alkali-aggregate) and externally (sulfate attack).
- Improper use or altered use of a structure.
- Ageing and weathering.
- Plastic settlement and heavy loading.

3.0 STRUCTURAL CRACKS

The tensile strength of concrete is small and tensile forces in concrete structures are generally carried by steel reinforcement. The purpose of this reinforcement is not to prevent cracking of the concrete, the tensile strain capacity of the concrete is small compared with the usual working strains in the steel and cracking is thus inevitable. However, it is necessary to limit the widths of the cracks so that aesthetic requirements are not violated and also so that the embedded steel does not corrode as a result of penetration of water into the cracks.

3.1 Flexural Cracking

In reinforced concrete flexural members, the small tensile strain capacity of the concrete and the relatively large working strains in the steel reinforcement combine to make flexural cracking inevitable in the tensile zone. The width and spacing of flexural cracks are controlled primarily by geometric factors (the neutral axis height and the cover to the reinforcement) and are relatively insensitive to the quality of bond between the steel and concrete. These natural control factors usually ensure that flexural cracks are numerous and of acceptably small width.

3.2 Shear Cracking

In reinforced concrete, shear cracking is usually better described as diagonal tension cracking. That is to say, it occurs as a result of the inclined principle tensile stress caused by combined bending and shear. Cracking caused by a pure shearing action is rare in concrete structures.

3.3 Internal Micro Cracking

Two quite different forms of micro-cracking occur. In situations such as end blocks of prestressed beams, and elsewhere where complex tri-axial stress zones occur, a principle tensile stress may cause very local micro-cracking long before visible cracking occurs. The second form of micro-cracking results from compressive loading, such as in the standard cylinder test. This micro-cracking occurs parallel to the compressive stress and accompanies the lateral dilation that characterises compression failure of concrete. As collapse is approached, the micro-cracks join up and become visible warning of impending failure.

4.0 NON-STRUCTURAL CRACKS

Non-structural cracks are the result of the intrinsic properties of concrete and its constituent materials. They are not caused by any external forces or other factors, although they will of course be influenced by matters such as ambient temperature and humidity. These factors are not as consistent or predictable as cracking from most structural loads. Intrinsic cracks are much less common than structural cracks, they can usually be limited, or controlled but there are some circumstances when they cannot be avoided altogether.

When an element of concrete dries or cools, it tries to shrink or contract respectively and, provided it is free to do so, it will not crack. However, if it is restrained, then stresses will be developed which are to some extent reduced by the mechanism of creep. If at any time the net stress exceeds the tensile strength of the concrete, cracks will form. Restraint may be external, as is usually the case when one element of concrete is cast against another which is older and hardened. External restraint can be reduced or even eliminated by the correct provision of movement joints. Restraint can be internal and occurs when one part of a concrete element is subject to different conditions from the rest. This is most common when the surface of a thick section dries and/or cools more rapidly than the core of the section. This phenomenon can be reduced by efficient curing of the concrete, both in the thermal and non-drying sense of the word.

If strains or restraint cannot be eliminated, the cracks can be controlled (as opposed to eliminated) by the provision of specially designed reinforcement often provided in slabs in the form of welded wire fabric or mesh.

4.1 Prehardening Cracks

Plastic cracks which form before concrete has fully hardened usually occur between 10 minutes and six hours after placement. There are three main types:

(a) Plastic Shrinkage Cracks
(b) Plastic Settlement Cracks
(c) Cracks caused by formwork movement

All occur as a result of construction conditions and practices and are usually preventable by the adoption of good construction procedures.

4.1.1 Plastic Shrinkage Cracks

Plastic shrinkage cracking is primarily caused by rapid drying of the surface. After concrete is placed and compacted, the solids settle and a film or layer of water usually forms on the surface. This is known as bleeding.

Under conditions of rapid drying this bleed water often evaporates before the concrete hardens. The surface of the concrete is left dry. Water within the concrete will be drawn to the surface and then evaporates. When this happens, the concrete near the surface shrinks and may crack in much the same way as clay soils do when they dry out, even though at this time the concrete may not have hardened. Strong winds, high temperatures, and low humidity alone or together are likely to cause cracking because they promote evaporation.

They usually form one of three patterns:

(a) Diagonal cracks at about 300mm to 1m centres, most common in unreinforced and lightly reinforced slabs.
(b) A very large map pattern, usually when the slabs are structurally reinforced.
(c) A pattern which corresponds to a restraint, such as steel near the top surface, or a change of depth.

Plastic shrinkage cracking will be minimised by any procedure which reduces evaporation of water from the surface of the concrete immediately after screeding.

Suggested procedures listed below are in the order they may be carried out. No one alone is the answer to all situations, nor would it be feasible to employ all of them in one occasion.

- Erect wind breaks to reduce the wind speed over the concrete surface.

- Dampen the subgrade or forms before placing concrete to avoid loss of water from below. Any excess water must be removed prior to concreting.

- Protect the fresh concrete surface by spraying from a fog spray nozzle.

- The surface can be effectively protected for a period with a spray of aliphatic alcohol. This is not a curing compound.

- Cover the fresh concrete surface with an impervious sheeting such as polythene, and making quite sure the sheeting stays in place particularly in high winds.

- Well timed wood floating and power steel trowelling often closes up cracks in the initial stage of their development. Plastic shrinkage cracking is more likely to develop unnoticed in screed or broom finished surfaces because everyone has left the site, and no trowelling, let along re-trowelling has been done. When rapid drying conditions prevail, all surfaces should be inspected periodically until the concrete is quite hard. This will allow any cracks to be closed by wood float or power trowel as they occur prior to hardening. Such trowelling has to be vigorous enough to close the crack for its full depth. Drawing a thin layer of mortar over the top of the crack will achieve nothing.

4.1.2 Plastic Settlement Cracks

Plastic settlement cracking over reinforcement of steps in formwork, such as in a waffle floor, is a different mechanism. These cracks are formed after placing and compaction if the concrete continues to settle over reinforcement bars, ducts, or steps in formwork. If the mass of the concrete is restrained from settling evenly by a reinforcing bar or a formwork step, the stiffening mass may crack open over the restraint, possibly leaving a void under a reinforcing bar, as the concrete settles on each side of the obstruction. Plastic settlement cracking is not due to rapid drying, and often occurs under a film of surface water. It typically occurs in thick sections.

Plastic settlement cracks occur only when there is a high amount of bleeding and settlement, and there is some form of restraint to the settlement. These cracks occur as follows:

(a) Cracks directly over formwork tie bolts or reinforcement which is fixed near the top of a section.
(b) Cracks in narrow columns and walls where settlement is restrained either by simple wedging or arching of concrete or by a mushroom head to a column.
(c) Cracks at change of depth of section, particularly in trough or waffle floors.

There are a few ways of dealing with plastic settlement cracks:

(a) Reduce the bleeding and settlement.
(b) Reduce the restraint.
(c) Adopt the techniques of revibration.

These methods can be effected by using different construction procedures as detailed below:

- With deep sections, place the concrete in layers compacting each before placing the next layer. Vibration of subsequent layers should penetrate the previous layer.

- With ribbed floor slabs, the ribs should first be filled to the underside of the slab, and allowed to settle before the slab concrete is placed over the ribs. Of course the delay cannot be so long as to jeopardise the bonding of ribs and slab.

- Elements likely to develop settlement cracking should be kept under observation until the concrete has hardened. A person should be left behind to continually inspect the work, and if plastic settlement develops the affected areas can be revibrated. Generally, late vibration has been found to improve strength. In special cases such as high energy external form vibration, the quality of the concrete could be impaired. If any doubt exists, the engineer should be consulted.

Delayed use of a float and power trowel can be used as an additional or an alternative procedure to revibration, particularly with ribbed slabs. Care must be taken to eliminate any cavity which may have developed under reinforcement bars and to close the cracks for their full depth.

Other procedures which may help reduce plastic settlement cracking include:

(a) using lower slump mixes;
(b) using more cohesive mixes;
(c) using an air entrainer to improve cohesiveness and reduce bleeding; and
(d) increasing cover to top bars.

4.1.3 Cracks Caused by Formwork Movement

If there is movement of the formwork, whether deliberate or unintentional, after the concrete has started to stiffen but before it has gained enough strength to support its own weight, cracks may form. Such cracks have no set pattern.

To avoid cracking from this cause, formwork must be:

- sufficiently strong and rigid to support the weight of the concrete without excessive deflections; and

- left in place until the concrete has gained sufficient strength to support itself.

4.2 Cracks in Hardened Concrete

Cracks occur in hardened concrete for two principal reasons:

(a) Volume changes in the concrete; and
(b) Chemical reactions within the body of the concrete which cause expansion and subsequent cracking of the concrete.

Volumetric movement in concrete cannot be prevented. It occurs whenever concrete gains or loses moisture (drying shrinkage) or whenever its temperature changes (thermal movement). If such movements are excessive, or if adequate measures have not been taken to control their effects, the concrete will crack.

Chemical reactions within the body of the concrete, which can cause it to expand and crack, include reinforcement corrosion and sulphate attach and alkali-aggregate reaction. Provided adequate care is taken in the selection of materials and good quality concrete is properly placed, compacted and cured, these reactions should not occur except in extreme environmental conditions.

4.2.1 **Crazing**

Crazing describes the very fine cracks which appear on the surface of concrete after it has been exposed to the atmosphere for some time. The cracks are so shallow that they do not affect the structural integrity of the concrete and in themselves, should not lead to subsequent deterioration of the concrete.

It occurs in the floated or trowelled surface layers of concrete slabs. It occurs as the concrete surface expands and shrinks during alternate cycles of wetting and drying, or as it carbonates and shrinks during long exposure to the air. The use of cement-rich mixes on the surface of the concrete and overworking can increase the problem.

To avoid the crazing on trowelled surfaces, the following can be done:

(a) Avoid very wet mixes.
(b) Do not use driers.
(c) Do not overwork the concrete.
(d) Do not attempt finishing whilst bleed water is present.
(e) Do not steel trowel until the water sheen has gone.
(f) Commence continuous curing promptly.
(g) Do not subject the surface to wetting and drying cycles.

On formed surfaces, very wet and over-rich mixes should be avoided and curing should be continuous. The concrete should not be subjected to wetting and drying cycles.

4.2.2 Drying Shrinkage Cracks

Hardened concrete shrinks, i.e. it reduces in volume as it loses moisture due to:

(a) the hydration of the cement; and
(b) evaporation.

The shrinkage caused by moisture loss is not a problem if the concrete is completely free to move. However, if it is restrained in any way, then a tensile stress will develop. If that stress exceeds the ability of the concrete to carry it, the concrete will crack.

A number of factors influence the shrinkage of concrete, in particular the total water content. Others include:

(a) the content, size and physical properties of the aggregate;
(b) the relative humidity;
(c) admixtures, especially those containing calcium chloride; and
(d) the curing conditions.

The cement content of concrete influences shrinkage drying almost only to the extent that it influences the amount of water used in a mix.

In order to reduce the total shrinkage of concrete:

(a) The water content should be minimised (consistent with the requirement for placing and finishing);
(b) The amount of fine material should be minimised;
(c) The highest aggregate content should be used;
(d) The largest possible maximum aggregate size should be used; and
(e) Good curing practices should be adopted.

However, simply reducing the shrinkage of a concrete will not necessarily reduce cracking since this is also influenced by the restraint, detailing, geometry, construction practice, etc.

The control of shrinkage will be detailed in the next paper and therefore no details on preventing cracking due to drying shrinkage will be detailed in this section.

4.2.3 Thermal Movement Cracks

Thermal movement occurs when the temperature of concrete changes, due either to environmental changes or to the heat generated when the cement first hydrates. If an element of concrete is big enough and is insulated by adjacent materials including formwork, then the rate of heat development in the first 24 hours is likely to exceed the rate of heat loss to the atmosphere, and the concrete temperature will rise.

After a few days, the rate of heat development falls below the rate of heat loss and the concrete will cool. As with nearly all materials, this cooling will cause contraction of the element. Theoretically there will be no cracking if this contraction is unrestrained. In practice, however, there is bound to be some restraint and this can be considered as being divided into two components:

(a) External restraint. If the concrete is cast onto a previously hardened base, or if it is cast adjacent to or between similar elements, without the provision of a movement joint, then it will be externally restrained. External restraint can be reduced between vertical lifts so that the temperature history of adjacent pours is not too dissimilar.

(b) Internal restraint. The surface of an element of concrete is bound to cool quicker than the core; it will also respond to daily temperature variations more than the core. Therefore there will be differential strains across the section and, where this differential is large, such as in thick sections, cracks may develop at the surface at least. This internal restraint cannot be avoided but the risk of cracking can be reduced, as discussed later.

In practice, the balance of these components will depend upon several factors, the most important being the geometry of the element, the nature of the formwork and its striking time.

One of the most important factors which assist in diagnosing whether the crack is due to early thermal contraction as opposed to long-term drying shrinkage is a knowledge of when the crack first forms. A crack which forms in the first week is unlikely to be drying shrinkage unless the element is a thin slab subjected to extreme drying conditions. Conversely, cracks which form after a period of several weeks or months cannot be early thermal contraction cracks.

The factors affecting temperature rise in a concrete section include the following:

(a) Initial temperature of materials.
(b) Ambient temperature.
(c) Dimensions.
(d) Curing.
(e) Formwork striking time.
(f) Type of formwork.
(g) Admixtures.
(h) Cement content and type.

There are no simple recommendations for minimising early thermal contraction cracks because they can be controlled only by carefully co-ordinated planning by both the designer and the contractor.

The fundamental factors which have to be considered and specified are:

(a) Design and specification
- (i) Restraint (size of pour, spacing of movement joints)
- (ii) Distribution steel (designed in relation to all other factors, particularly restraint)
- (iii) Heat development (section thickness, cement type and content)
- (iv) Aggregate type

(b) Construction
- (i) Restraint (sequence and timing of pours, additional movement joints)
- (ii) Heat development (choice of concrete materials and formwork type)
- (iii) Cooling (striking of formwork, curing, insulation)

4.2.4 Other Types of Cracks

(a) Corrosion of Reinforcement

When reinforcing steel is embedded in concrete, it does not normally corrode because, in the inherently alkaline environment, a protective passive layer forms on its surface. However, if the depth of cover is insufficient or the concrete is permeable, then the concrete may carbonate as deep as the reinforcement and the protective layer may be at risk.

The passive layer will also be broken down in the presence of excessive amounts of chloride ions. The chlorides can originate from sodium chloride (common salt) in marine locations, from de-icing applications, or from the use of the admixture calcium chloride.

When the protective passive layer breaks down, the steel is liable to rust or corrode and, as this is an expansive process, it can cause the concrete to crack and spall. Cracking and spalling are particularly noticeable at corners of beams and columns over the main steel, although the pattern of links and stirrups can often be seen also. Such cracks will usually show signs of rust stains on vertical faces and soffits.

(b) Alkali-Silica Reaction Cracks

Alkali-silica reaction is known to have caused cracking and expansion in concrete structures. The parts of structures affected are of high alkali content and have been subject to ground-water, rain or heavy condensation.

To minimise the risk of cracking due to ASR, the following approach should be used in new structures:

(a) Use an aggregate with a long history of satisfactory performance.
(b) Test the aggregate for reactive silica.
(c) Test the cement aggregate combination for reactive silica.
(d) Place an alkali limit on the concrete or the cement.
(e) Use a blended cement.

5.0 CONCLUSION

Most engineers involved in design and construction in concrete will agree that the harder you look for cracks the more you find. In considering the acceptability of cracks, it can be concluded that there will in all cases be a minimum width below which the crack is aesthetically acceptable. The acceptance of cracks will depend on whether the cracks will lead to the following conditions:

(a) Failure of the structure.
(b) Corrosion of the reinforcement.
(c) Malfunction of the structure.
(d) Aesthetic acceptance.

Cracking of concrete can be minimised by good design detailing, proper construction procedures, suitable use of the concrete structure and continual maintenance for the environmental conditions in which it has been placed.

6.0 REFERENCES

6.1 The Reduction of Cracking in Concrete, The University of Sydney, School of Civil Engineering Notes, May, 1979.

6.2 Design of Concrete Structures for Serviceability, Cement and Concrete Association of Australia Notes, October, 1978.

6.3 Thermal and Shrinkage Cracking in Reinforced Concrete, G.D. Base and M.H. Murray, January, 1978.

6.4 Cracks in Concrete Due to Plastic Shrinkage and Plastic Settlement - NRMCA Technical Bulletin 90/2.

6.5 Repair and Protection of Concrete Structures - N.P. Mailvaganam - CRC Press, 1992.

6.6 Non-Structural Cracks in Concrete - Concrete Society Technical Report No. 22 - 3rd edition 1992.

6.7 Guide to Concrete Construction - Cement and Concrete Association of Aust. and Standards Australia - 1994.

6.8 Non-Structural Cracking of Concrete - The effects of polypropylene fibres - C.D. Turton - Concrete 95 Towards Better Concrete Structures Conference - Sept., 1995.