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Durability of Concrete Under Winter Conditions

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Please note

Concrete is a versatile and widely used construction material. Its excellent record of durability is remarkable when one considers the variety of severe exposures to which it is subjected. There are, however, processes that can produce considerable damage if well known precautions are not taken. One of these is deterioration due to frost action.

The critical factor in frost damage, as in most potentially destructive processes involving concrete, is the moisture condition of the material. Only concrete elements subjected to continuous or frequent wetting are susceptible to damage by freeze-thaw cycling. In recent years the frost damage problem has been aggravated by the wide use of de-icing salts. The severest exposures are horizontal areas or any surfaces on or near ground level subjected to both freeze-thaw cycling and de-icing salts while wet.

It is now well established, in the laboratory and in the field, that ordinary concrete can be made highly resistant to winter conditions with little or no extra complication or cost. This has been possible through improved understanding of the nature of the freeze-thaw process in concrete - understanding that has led to procedures that minimize frost damage.

Evidence of Frost Damage

Most processes that can cause deterioration in concrete produce an ultimate excessive expansion and cracking. This is true of sulphate attack and alkali-aggregate reaction. It is also true of frost damage, and it is therefore not always evident from visual observation which destructive process is responsible in any given case. though in most instances the conditions prevailing give a good indication.

Difficulties often occur on horizontal surfaces; vertical surfaces are usually not vulnerable except at corners and edges where moisture take-up is high, or near ground level where there may be frequent splashing. Trouble spots may develop where run-off is delayed, water is trapped, or snow accumulation extended.

Surface scaling is perhaps the most easily recognized result of frost damage; it occurs mainly on pavements, sidewalks and other horizontal surfaces, and is most severe if de-icing salts have been used. Scaling occurs to depths of an inch or more and is progressive. It is to be distinguished from peeling of the thin skin of laitance that forms on surfaces that have been made with concrete of excessively high slump or subjected to excessive compaction or trowelling.

Pattern- or map-cracking is caused by differential dimensional movement between concrete near the surface and concrete at greater depths. It can therefore result from frost damage as well as from other destructive processes. Its alligatoring appearance may be seen on such structures as platforms and piers. Map-cracking from frost damage occurs to some depth and is to be distinguished from crazing, where cracks are hair-thin and penetrate usually only the laitance layer. Drying and carbonation shrinkage are the common causes of crazing.

Frost action sometimes produces D-line cracking, in which cracks run parallel to and near the edges and corners of such elements as sidewalks and pavement slabs. This can usually be associated with stresses due to a particular configuration and to the vulnerability of the corners and edges to wetting.

Crumbling or powdering is evidence of advanced destruction from other processes as well as from frost action. It is often seen where concrete was frozen in the plastic or green state, or where it had been of very poor quality. This type of crumbling in depth is to be distinguished from surface dusting, which is caused by a weak laitance material or by carbonation from stove-heated enclosures in winter construction.

Microstructure of Concrete and Its Moisture Condition

Hardened cement paste, like sand and stone aggregates, is a porous solid and will absorb water. Whereas maximum strength and dimensional stability are achieved by the lowest possible voids content, maximum resistance to freeze-thaw damage depends upon the size and distribution of pores and capillaries, and the degree of saturation.

Sand and stone particles, which are acceptable as aggregates in dense concrete, have pore systems that have already withstood exposure for geological ages. They are, therefore, frost resistant, provided the degree of saturation does not exceed a critical limit.

When portland cement is mixed with water, the chemical reactions of hydration begin rather slowly to produce new compounds. These reactions proceed at the most favourable rate when temperatures are moderate, tending to be slow at low temperatures and accelerated at high temperatures.

The products of hydration are greater in total volume than the original cement grains, so that as hydration proceeds voids existing in the initial mixture of aggregate and cement are gradually reduced. Water is a reactant in the hydration process and there is a gradual depletion of the original mix water. The reaction products bond with each other to produce the familiar high compressive strength of hardened cement paste and bond quite compatibly with stone and sand particles.

The bond between aggregate and paste may be weakened in the plastic stage by a strong movement of water from aggregate to paste (producing an excessively high water-cement ratio in the bond region), or from paste to aggregate (leaving inadequate water for hydration in the bond area). This is the reason why aggregates used in making concrete should not be too dry or too wet.

In the curing, or maturing, of concrete there is a gradual decrease in the number and size of voids, an increase in strength, and a decrease in moisture content. In general, these factors are favourable to resistance of frost damage and it follows that the maturity of the concrete at the time of exposure to frost is critical to durability.

Excess mix water is undesirable because spaces filled with water in the original mix become voids when the water not used in hydration is lost by evaporation. For reasons of good workability of the plastic mix, however, the total mix water is normally much greater than that needed for hydration. Thus, a considerable voids system is present even under the most favourable conditions.

Normal drying of dense concrete following the curing period is often vital to resistance to frost damage. Once the original water in the concrete has been largely used by hydration and the bulk of the remainder lost by evaporation, the process of reabsorption through normal re-wetting is very slow. Fortunately, it is difficult to achieve near-saturation of a "dry" slab of concrete by subsequent exposures to periodic wetting by rain or snow. This is true of lightweight aggregate concretes also. They have a much higher total absorption capacity than dense concretes, but it is the fraction of complete saturation that is critical in freezing conditions.

Another fortunate situation is that not all the water left in hardened cement paste will freeze under normal maturing conditions. That part of the water adsorbed directly on the surfaces of the voids is quite unlike ordinary water in some properties. This adsorbed water will, depending on its proximity to the solid surfaces, not convert to ice until temperatures drop to 50, 60 or more F degrees below the freezing point. Because the total surface area in matured cement paste is very high, the proportion of such water is quite large.

Mechanisms of Frost Damage and the Role of Entrained Air

There are several recognized mechanisms that explain different forms of frost damage to concrete. They can operate singly or together, depending on the condition of the concrete and type of freezing environment. If the degree of saturation exceeds about 91 per cent, ice formation with consequent increase in volume of about 9 per cent will produce rupture in one or two freezings. Such situations are rare. They may occur with very young concretes that still have very large voids and are still nearly saturated, or they may occur in continuously soaked concretes of poor quality.

Concretes with moisture contents well below the "critical saturation" value (about 91 per cent) can be damaged by freeze-thaw cycling over a period of time. Two phenomena are responsible: migration of moisture, and build-up of pressures in the paste. Both can be observed and measured. One long-standing explanation is based on the concept that ice will form from water in the larger pores and that the ice crystals will grow by drawing water from the walls of the voids. This partial desiccation will then cause water to be drawn from the smallest pores until eventually, as the ice crystals grow, the pressure build-up in dense pastes will result in rupture.

The Division of Building Research has for many years been engaged in studies of the freezing of water in porous materials. It appears that there are other possible explanations of the destructive action.

According to any of these concepts, the incorporation in the cement paste of unfilled, well-distributed voids tends to prevent excessive pressures from developing and thus reduces disruptive damage. This accounts for the remarkable effect of air-entrainment in improving the frost resistance of concrete.

An air-entraining agent is an organic material which, added as an admixture to concrete in very small dosages (about 1 per cent or less by weight of the cement), will generate air bubbles through a foaming action during mixing. Under optimum conditions the bubbles are spaced about 0.01 in. or less apart and are of about the same order of magnitude in maximum diameter. In the average concrete the total entrained air should be about 5 to 7 per cent by volume.

Ice-lensing, as found in the frost heaving of soils, is not a primary mechanism of destruction in normal, dense concrete. It does occur as a directional effect in some cases where cement paste has already deteriorated badly through other processes, including freeze-thaw cycling. It is thus an end result rather than a primary cause of destruction.

The reason for the added severity of freeze-thaw action in the presence of de-icing salts is not yet clear. The salts usually used on sidewalks, pavements and other surfaces are calcium chloride and sodium chloride. It is interesting that such chemically unrelated substances as glycol, alcohol and urea aggravate concrete scaling in a similar manner under the same conditions of freeze-thaw cycling.

Freezing of concrete in the plastic state usually results in permanent damage, even with a single cycle. Ice-lensing can occur in such cases. The volume change accompanying freezing tends to increase separation between particles of cement and aggregate so that later bridging by hydration products can be only partly achieved. Such concretes, when hard, have sharply reduced strengths and much higher porosity.

Methods of Evaluating Frost Resistance

Rate and degree of absorption have been used for many years as a means of predicting durability of concrete to frost damage. The tests are simple and inexpensive but, unfortunately, they yield very poor correlation with field performance. The generally accepted method of test is the freeze-thaw cycling of concrete specimens. This is essentially a simulation of natural cycling, except that it is more rapid and gives results in reasonable time. Rate of deterioration is usually determined by measuring resonant frequencies from which the dynamic modulus can be calculated. Weight loss is another but less reliable measure.

The freeze-thaw cycling test gives results that permit reasonably good assessment of the field performance that can be expected of a particular concrete mix. It has, however, several drawbacks. Equipment is fairly expensive and there are not many Canadian agencies with such facilities. It has not been possible to standardize such factors as rate of cycling, minimum freezing temperatures, reference materials, and whether freezing should take place in air or in water. The test takes a month or more.

Resistance to de-icing salts is measured by freeze-thaw cycling of concrete slab sections with salt solutions on the upper surfaces. Deterioration is measured by degree of scaling and judgement is based on comparison with reference concretes of known performance.

A valuable test, known as the linear traverse method, consists of determining by optical microscope the air bubble content and spacing in hardened cement paste or concrete. This test readily discovers whether the entrained air will provide adequate protection. Again, equipment is quite costly and few agencies have the facilities. The simple air-meter measurement of air content on plastic concrete indicates whether or not enough air has been added, but it does not indicate the size and distribution of bubbles in the set concrete.

Despite these obstacles to evaluation, it is possible to ensure adequate frost resistance to exposed concretes by following recommended practices.

Preventive Measures and Good Practice

The moisture content of concrete is the most critical factor of frost damage for those elements subject to freeze-thaw cycling. Adequate drainage to provide rapid water run-off is thus a most important design feature.

Prior test evidence of resistance to frost action should be provided for concrete elements exposed to continuous or frequent wetting, especially if they are to be exposed to de-icing salts. This should apply to precast as well as to in-situ concretes, whether air-entrainment is used in the manufacturing process or not. Less severe exposures such as wall panels would normally be required to meet less restrictive specifications. Air-entrainment should, however, be a requirement for all exposed concretes except where the manufacturing processes are such as to provide other safeguards against frost damage, e.g., high density, low porosity elements.

It is notable that air-entrainment is achieved only in a limited range of plastic consistency of the concrete (slump). Very wet or very dry mixes do not entrain air in proper size and distribution. Over-vibration and excessive trowelling also affect the entrained air adversely.

Recommended practice for producing concrete highly resistant to the severest exposures of frost and de-icing salts is well established and generally adopted by construction engineers. The practices that follow are intended to be used with discretion and judgement.

1. The components of concrete, aggregates, cement, water and admixtures, are required to meet normal specification limits for average use. Mix proportions are also required to meet normal good practice.
2. Air-entrained concrete for severe exposures should be of the 3500- to 4500-psi class. Water-cement ratio should not exceed 0.45, and slump should not exceed 3-½ in.
3. Compaction must be given special attention. Tamping or vibration should achieve a homogeneous, dense product, but must not be overdone because of the danger of segregation. High slump mixes are especially vulnerable.
4. Finishing is critical in that excessive laitance is vulnerable to frost action, especially in the presence of de-icing salts. Screeding, or levelling, should be followed by a few passes with a wood trowel or by such methods as do not bring water and fines to the surface. Steel trowelling should be avoided for normal slump concretes in horizontal sections that must later withstand severe exposure. Steel trowelling can be tolerated on very low- or zero-slump concretes, but these are not normally used in outside exposures because of added cost of placement and compaction, and because of difficulty of entraining air.
5. Good curing practice is required to obtain adequate maturity. The longer the period of optimum hydration, the more resistant the concrete will be to frost damage, quite apart from the important role played by entrained air. Depending on severity of exposure, minimum wet curing at moderate temperatures should range from 1 to 10 days. Maturity can be accelerated by the use of high early strength cements (a costly method), or by an accelerating admixture.
6. Air-drying of concrete after curing is essential where exposure to de-icing salts is probable. Slab-on-ground concretes should be placed well in advance of below-freezing weather to permit an adequate drying period as well as to achieve maturity.
7. A final step, which is usually reserved for severe de-icing salt exposure such as on garage floors, is the application of a thin, penetrating water repellent such as boiled linseed oil. Some change in colour can be expected after such treatment.

Sea-water exposures are severe in Canada because of the combination of freezing conditions and high moisture content at and near the waterline. In addition to air-entrainment, durability requires high density and low porosity. In hydraulic structures those sections that are subject to freezing and thawing require similar precautions.

It is of interest that certain light-weight aggregate concretes. in spite of high absorption coefficients, can be made highly resistant to frost action and even to de-icing salts, if they are air-entrained. On the other hand, there are concretes manufactured by special precast processes without entrained air that appear to have high resistance to the severest exposures.

Concluding Comments

A ready-mix concrete producer will generally supply air-entrained concrete for exposed structures whether entrained air is specified or not. He prefers to limit the number of mixes, and use of an air-entraining agent provides the extra benefit of workability, lower water requirement, less bleeding, and often better yield. The producer is also conscious of his responsibility to provide concrete that will perform satisfactorily. If a purchaser does not want air-entrained concrete, as is sometimes the case for the best finishing qualities of an inside floor, he would be well advised to say so.

The use of entrained air in concrete does not itself guarantee resistance to frost damage. The other steps outlined in good practices must also be followed. Bell-compacted, dense concrete made with low water-cement ratio can achieve high resistance to winter exposures.

All the evidence of extensive field and laboratory performance shows the importance of adequate drainage and run-off features in the design of concrete elements and structures.