

High-Performance Concretes

A State-of-Art Report (1989-1994)

4. BEHAVIOR OF HARDENED CONCRETE

The behavior of hardened concrete can be characterized in terms of its short-term (essentially instantaneous) and long-term properties. Short-term properties include strength in compression, tension, bond, and modulus of elasticity. The long-term properties include creep, shrinkage, behavior under fatigue, and durability characteristics such as porosity, permeability, freeze-thaw resistance, and abrasion resistance.

Comparatively speaking, information on the behavior of very early strength (VES) concrete and high early strength (HES) concrete is somewhat limited, whereas a substantial amount of information on the behavior of high strength concrete exists and additional information is being developed rapidly. Since high performance concretes typically have low water-cementitious materials ratios (W/CM) and high paste contents, their characteristics will, in many cases, be similar to those of high strength concrete.

A significant difference in behavior between the early strength and the high strength concretes is in the relationship of compressive strength to other mechanical properties. Typically, strength gain in compression is much faster than strength gain in aggregate-paste bond. This will lead to relative differences in elastic modulus and tensile strength of early strength concretes and high strength concretes, expressed as a function of compressive strength. Thus the relationships of mechanical properties to 28-day compressive strength of high strength concrete cannot be expected necessarily to apply to VES and HES concretes.

4.4.2: Freeze – Thaw

Damage of concrete under repeated cycles of freezing and thawing (frost attack) is a major problem of durability. In the previous state-of-the-art report [Zia et al. 1991], the mechanism with which freezing and thawing damages concrete has been discussed and some of the earlier researches have been summarized.

For the normal strength concrete, entrained air of 4 to 8% by volume of concrete provides an effective defense against frost damage and the exact amount is dependent on the maximum size of the coarse aggregate, provided that the coarse aggregate itself is frost resistant [Zia et al. 1993a]. The optimum spacing factor of the air voids should be no more than 0.2 mm (0.008 in.) and the air voids should be small with their diameter being in the range of 0.05 to 1.25 mm (0.002 to 0.05 in.) to ensure that the required spacing factor is obtained with low air contents.

By using concretes with different entrained air void systems subjected to long and short cycles of freezing and thawing in 4% sodium chloride solution, Stark [1989] found that the long freeze-thaw cycles were more severe than the short freeze-thaw cycles for same number of cycles, even where air void spacing factors were no greater than 0.2 mm (0.008 in.). His findings agree with the ice accretion theory of frost damage in concrete. However, Attiogbe et al. [1992] noted that properly air-entrained concretes containing superplasticizers can have adequate freeze-thaw resistance at calculated spacing factors greater than the ACI recommended maximum spacing factor of 0.008 in. (0.2 mm). Their test data for concretes made with or without superplasticizers showed that virtually all the concretes with adequate resistance under freeze-thaw testing had specific surface values less than the ACI recommended minimum.

Siebel [1989] found that when superplasticizers were used in a high workability air-entrained concrete, the number of pores with a diameter up to 300 μ m decreased, while the content of pores larger than 500 μ m and the bubble spacing factor increased. Small pores coalesced and formed larger pores. Although the air content of the fresh concrete was sufficient, the superplasticized concrete sometimes had a spacing factor above 0.20 mm. For this reason, concrete with superplasticizers did not always have

adequate freezing and thawing resistance. The de-airing agents contained in the superplasticizers were found to have a considerable effect.

At the present time, there is no clear direction as to whether all high-strength concrete will require air-entrainment and the necessary air-void parameters. Some argue that with low W/CM ratio and mineral admixtures, the amount of freezable water in high-strength concrete would be low and its pore size would be decreased to the extent that water in the pore cannot freeze. However, in their study of high performance concretes, Zia et al. [1993c, 1993d, 1993e] found that 5% entrained air was required to achieve a higher level of frost resistance than that required by the ASTM C 666, Procedure A (i.e., a durability factor of 80% versus 60%).

Galeota et al. [1991] studied the freeze-thaw resistance of both non-air-entrained and air-entrained cylindrical specimens (38 specimens of each kind). Half of each kind contained 20% silica fume by weight of cement. After every 50 cycles of freezing and thawing, the dynamic modulus of the specimen was measured and compared with that of the control specimen to determine the durability factor until the durability factor was reduced to 40 per cent. Each cycle of freezing and thawing lasted 12 hours during which the specimens were cooled from $50\text{C} \pm 20\text{C}$ to $-250\text{C} \pm 20\text{C}$ in air and then warmed to $50\text{C} \pm 20\text{C}$ in water. They found that the specimens with silica fume, both non-air-entrained and air-entrained, performed very poorly with their durability factors being reduced to less than 40% in 50 and 100 cycles of freezing and thawing respectively. After 250 cycles of freezing and thawing, the non-air-entrained specimens without silica fume achieved an average durability factor of 60%, but the air-entrained specimens without silica fume showed no deterioration at all. It was concluded that the very poor performance of the specimens was probably due to the high void spacing factor because of very high silica fume content, even though the air-entrained specimens had 5% air in the fresh state.

The freeze-thaw resistance of both air-entrained and non-air-entrained concretes was also investigated by Kashi and Weyers [1989]. They tested specimens from 27 batches of high-strength concrete containing silica fume with W/CM ratios of 0.25 and 0.32, and with and without entrained air. The tests were conducted in accordance with ASTM C 666, Procedure A. Another set of similar specimens were moist cured for 28 days instead of 14 days to determine the effect of curing time. The results showed that non-air-entrained high-strength concrete with W/CM ratio of less than 0.30 was frost resistant regardless of the length of curing time. Non-air-entrained high strength concrete with W/CM ratio of 0.32 was durable if silica fume was not used.

Li et al. [1994] investigated the freezing and thawing (F/T) durability of non-air-entrained cement pastes, mortars, and concrete. The test specimens (with four different W/C ratios of 0.24, 0.27, 0.30, 0.33) were cured in $95 \pm 3\%$ relative humidity and a temperature of $230\text{C} \pm 10\text{C}$ until testing at 14, 28, or 90 days. Freezing and thawing was performed according to ASTM C 666, Procedure A. The F/T durability of non-air-entrained pastes and mortars was evaluated by measuring the decrease in compressive strength, but the F/T durability of non-air-entrained concrete was determined by the method of ASTM C 666, Procedure A. For comparison purposes, the relative dynamic modulus of the mortar was also measured. At the W/C ratio of 0.24, both the paste and mortar showed excellent F/T resistance at 0, 5, and 10% silica fume levels. When the W/C ratio was higher than 0.24, the paste and mortar durability was significantly reduced. Similarly, at the W/C ratio of 0.24, the non-air-entrained concretes were F/T durable regardless of the silica fume and total cementitious content but the durability was decreased for concretes with higher W/C ratios. The results indicated that factors other than the W/C ratio had little influence on the F/T durability and the critical W/C value was 0.24. The damage in the paste was characterized by surface scaling while in the mortar and concrete a few large cracks led to final failure. [Authors' Note: The research described by Li et al. covers only non-air-entrained pastes, mortars, and concretes, in spite of the misleading title of their publication.]

The F/T durability of non-air-entrained high-strength concrete with a constant W/CM ratio (0.35) and a fixed amount of silica fume (10 % by weight of cement) was investigated by Cohen et al. [1992] to evaluate the effects of the duration of curing in saturated lime-water for 7, 14, 21, and 56 days prior to the freezing and thawing cycles. The aggregates used in the investigation were frost resistant. Therefore, the failure of the non-air-entrained concrete specimens could be attributed only to cracking of the paste. It was found that silica fume modified the frost resistance mechanism of the paste in the concrete. All

specimens failed when tested according to the ASTM C 666, Procedure A, using 60% relative dynamic modulus as the failure criterion. The test data suggested the possible existence of a critical curing period of 14 to 21-day in saturated lime-water, which was associated with the largest gains in length and mass, the largest drops in bulk density and compressive strength, and the lowest number of cycles to failure (or lowest durability factor). There were some improvements to the frost resistance properties when the duration of curing was decreased to 7 days or increased to 56 days, but the improvements were insufficient for the concrete to meet the standard test requirements. An interesting observation was made in that the induced damage to the concrete after 300 cycles of freezing and thawing was indicated primarily by a significant drop in the dynamic modulus (from 6.5-million psi to 300,000 psi) rather than a major reduction in compressive strength (with highest compressive strength of 11,000 psi at 0 cycle and lowest strength of 8,000 psi after 300 cycles). The researchers concluded that while an explanation for this phenomenon requires further study of the microstructure, it appears clear that the concrete deterioration process during the freezing and thawing cycles had reached a stage that the normal relationship between the compressive strength and the modulus could no longer hold true.

Pigeon et al. [1991] also attempted to determine the influence of various parameters on the limiting value of W/CM ratio below which air entrainment is no longer required for good freezing and thawing resistance. Seventeen high-strength concretes were made using portland cement with and without silica fume, and tested for frost resistance according to ASTM C 666, Procedure A. The parameters included the type of cement, the type of aggregate, and the length of the curing period. The test results, along with previously published data, indicated that the limiting value of W/CM ratio could be higher than 0.30 in certain cases, but equal to or less than 0.25 in others, depending particularly on the characteristics of cement. They suggested that more research is needed before the values can be used as guidelines, since field exposure conditions differ substantially from laboratory testing conditions, and because the air void spacing factor of non-air-entrained field concretes could be significantly higher than that of laboratory made concretes. It is interesting to note that Burg and Ost [1992] tested five commercially available non-air-entrained high-strength concretes for their freeze-thaw resistance. The W/CM ratios of the five concrete mixes ranged from 0.22 to 0.29, their 28-day compressive strengths of moist cured 150 x 300 mm (6 x 12 in.) cylinders ranged from 11,400 psi (80 MPa) to 17,250 psi (121 MPa), and their silica fume contents ranged from 0 to 16%. Out of the five concretes, only the one with the highest strength, the lowest W/CM ratio, and the largest amount of silica fume sustained the freezing-thawing test without deterioration for over 1,400 cycles. The other four concretes all failed to meet the requirements of ASTM C 666, Procedure A.

In lieu of silica fume, high-reactivity metakaolin has been found as an effective mineral admixture to produce high-strength concrete with good freeze-thaw resistance [Caldarone et al. 1994]. In the past several years, there has been an increasing interest in using large quantities of fly ash or GGBS to produce high performance concrete. The durability of such concrete becomes an important issue since these mineral admixtures are often used to replace a major portion of the portland cement in the concrete. A series of recent studies reported in Canada [Langley et al. 1989; Malhotra 1989; Malhotra and Painter 1989; Malhotra 1990; Bilideau et al. 1994; Bilodeau and Malhotra 1994] showed that air-entrained high-volume fly ash concrete exhibited excellent frost resistance based on the ASTM C 666, Procedure A test. The performance of the concrete was also very good against chloride-ion penetration based on the AASHTO T 277 test. The only exception was the deicing salt-scaling test (ASTM C 672) in which the performance of the concretes investigated was less than satisfactory. The concrete mixes contained class F fly ash (about 56% of the total cementitious materials and W/CM of 0.30) or GGBS (up to 50% of the total cementitious materials and W/CM of not more than 0.55) with roughly 4 to 6% entrained air and a large dosage of superplasticizer for good workability. On the other hand, using class C fly ash, Nasser and Lai [1993] found that the use of high percentage of fly ash in concrete (35 to 50%) reduced its resistance to freezing and thawing even though it contained about 6% air and was cured in water for 80 days. However, concrete containing 20% fly ash gave satisfactory performance if its air content and strength were comparable to control concrete which contained no fly ash.

Several recent studies on the freeze-thaw durability of air-entrained concrete for marine and arctic construction have been conducted. Moukwa et al. [1989] tested concrete with W/C = 0.44 and 4% air in both fresh and seawater. Two laboratory procedures were used, one simulating the field freeze-thaw conditions the concrete undergoes in the tidal zone and the other similar to ASTM C 666, Procedure A.

The results of the study suggested that surface effects would probably play an important role in the deterioration of concrete under arctic conditions. Whiting and Burg [1991] tested high-strength lightweight concretes produced from two different lightweight aggregate sources subjected to a variety of freezing and thawing test procedures and conditioning methods. The concrete strengths ranged from 54 to 73 MPa (7,700 to 10,400 psi) and their unit weight varied from 1,920 to 2080 kg/m³ (120 to 130 lbs/ft³). Silica fume, fly ash, and GGBS were used in the different mixtures. The high-strength lightweight concretes exhibited excellent performance with virtually no degradation during the standard freeze-thaw testing. Prolonged exposure was needed to cause significant damage under simulated arctic offshore conditions. Durability was found to be a strong function of cumulative freezing and thawing cycles and moisture content, with saturation of aggregates prior to test leading to premature failure.

In a separate study, Tamura and Tazawa [1991] developed a new mixing procedure in which the lightweight coarse aggregate and 50% of the cement (plus fly ash or silica fume) were mixed first for one half of a minute with 50% of superplasticizer plus a portion of the water to make the W/CM = 0.15. The remaining half of the cementitious materials was then added and mixed for another half of a minute. The fine aggregate (sand) was then added to the mixer at the one minute mark and mixing continued for another half of a minute. At the 1-1/2 minute mark, all the remaining water and superplasticizer were added to the mixer and mixing continued until it was complete at the 3-minute mark. This mixing procedure allowed the lightweight coarse aggregate to be enveloped first with relatively soft cement paste and then the second addition of cement absorbed the water from the first cement paste coating to ensure a stronger enveloping action. The proposed mixing procedure proved to be most effective in enhancing the freeze-thaw resistance of high-strength lightweight concrete studied. In addition, they study also indicated that there was a close relationship between the water content in the lightweight aggregate before mixing and the resistance to freezing and thawing. For the high-strength lightweight concrete containing fly ash with its air content of 7 to 8%, it was desirable to adjust the water content in the lightweight aggregate to no more than 8%. For the concrete with silica fume, adequate freeze-thaw resistance was obtained even with a water content of 14% in the lightweight aggregate.

To better control water absorption into the lightweight aggregate under high pumping pressure, Asai et al. [1994] developed a new lightweight coarse aggregate with its surface being coated by a high molecular paraffin. The coated aggregate made it possible to produce lightweight concrete with high durability against freezing-thawing, abrasion, and fire.

4.4.3: Scaling

Scaling is another problem of durability. It is caused by repeated application of deicing salts. Concrete surface damaged by salt scaling becomes roughened and pitted as a result of spalling and flaking of small pieces of mortar near the surface. Even high-quality concrete with adequate air entrainment can still suffer scaling by deicing chemicals.

The exact cause of scaling is not well understood but it is recognized that when deicing chemicals are applied to melt ice, the heat consumption causes a rapid drop in the temperature of the concrete just below the surface resulting in damages from the effects of rapid freezing or differential thermal strains. Furthermore, deicing chemicals can accumulate in the surface layer of the concrete, forming relatively concentrated solutions. When water stays on the concrete surface, it flows towards the concentrated chemical solution causing an osmotic action accompanied by hydraulic pressures. These pressures may, in turn, cause salt scaling.

Scaling is most likely to occur where there is a weak layer of paste or mortar at or near the concrete surface. The best prevention of scaling is to eliminate the weak layer of material by proper mix design and good construction practice in placing, finishing, and curing. Over vibration, too much trowelling, and excessive bleeding should all be avoided. Well cured concrete pavements, allowed to dry for a period before deicing salts are applied, generally will have good scaling resistance.

Earlier studies on the scaling resistance of concrete containing silica fume and using Pyrament blended cement have been summarized in the previous state-of-the-art report [Zia et al. 1991]. It was concluded that based on the available research results curing history and moisture condition are important factors to

field performance which can not be accounted for by the standard ASTM test procedures. Thus a need exists for new test procedures that will take into account these factors.

More recently, the deicer salt scaling resistance of high-strength concretes made with different cement was studied by Gagne et al. [1991]. Seventeen concrete mixtures were prepared with W/CM = 0.26 and 0.30, which produced high-strength concretes with a 28-day strength in the range of 60 to 90 MPa (8,600 to 12,860 psi). For W/CM = 0.26, Type I cement plus 6% silica fume was used. For W/CM = 0.30, two types of cement and a silica fume were used (Type III, Type III + 6% silica fume, Type I + 6% silica fume). Using sodium chloride as a deicer, all specimens were subjected to 150 daily cycles of freezing and thawing in accordance with ASTM C 672. After 50 cycles, the weight loss for all concretes was lower than 0.75 kg/m² and after 150 cycles the weight loss was under 2 kg/m². No clear relationship was found between the scaling resistance and the spacing factor. The test results, along with others, indicated that non-air-entrained high-strength concretes with good deicer salt scaling resistance could be produced with a portland cement plus silica fume and good quality coarse aggregate by using a W/CM of 0.30, even after only 24 hours of curing. With certain Type III cement, it is also possible to produce scaling resistant concrete with air entrainment and silica fume. In their study of non-air-entrained concretes, Li et al. [1994] also found no salt scaling, after 50 cycles of testing, for concretes with W/CM of either 0.24 or 0.27, but some scaling was observed for the specimens with W/CM = 0.30 and the specimens with W/CM = 0.33 suffered severe scaling. After 100 cycles of testing, the specimens with W/CM = 0.27 showed some scaling while those with W/CM = 0.24 still showed no sign of scaling.

In lieu of silica fume, high-reactivity metakaolin has also been used as an effective mineral admixture for high-strength concrete which proved to have satisfactory performance in scaling resistance [Caldarone et al. 1994].

The effect of curing and drying on salt scaling resistance of fly ash concrete was investigated by Bilodeau et al. [1991]. Concretes with 20 and 30% fly ash as cement replacement were produced with two types of aggregate, using W/CM of 0.35, 0.45, and 0.55. The test results showed that, with few exceptions, concrete with up to 30% fly ash performed well under the scaling test. Extended moist-curing or dry periods did not seem to affect significantly the scaling performance of the reference concrete as well as the fly ash concrete. However, when higher volume of fly ash (55 to 60%) was used in air-entrained concrete, the scaling performance of the concrete was less than satisfactory [Bilodeau et al. 1994].

4.4.4: Abrasion

Abrasion is wearing due to repeated rubbing and friction. For pavements, abrasion results from traffic wear. Adequate abrasion resistance is important for pavements and bridge decks from the standpoint of safety. Excessive abrasion leads to an increase in accidents as the pavement becomes polished reducing its skid resistance.

There is no generally accepted criterion for evaluating the abrasion resistance of conventional concrete. The lack of an abrasion resistance criteria is due to the fact that surface wear normally is not a controlling factor in pavement performance. If the pavement surface is provided an adequate texture depth during construction, its design is dictated by other requirements. An exception is in areas where the use of studded tires is permitted.

Abrasion resistance of concrete is a direct function of its strength, and thus its water-cement ratio and constituent materials. High quality paste and strong aggregates are essential to produce an abrasion resistant concrete.

The superior performance in abrasion resistance of concretes made with Pyrament blended cement was summarized in the previous state-of-the-art report [Zia et al. 1991]. Unfortunately, Pyrament cement is no longer being produced and not available to the construction industry.

The use of silica fume high-strength concrete with low W/C ratio for the repairs of abrasion-erosion damage of in the stilling basin at Kinzua Dam and in the concrete lining of the low-flow channel, Los

Angeles River was described by McDonald [1989]. It was shown that silica fume offers potential for improving many properties of concrete which are particularly beneficial in repair of hydraulic structures. The experimental work on the abrasion resistance of concrete pavements subjected to heavy traffic from studded tires was discussed in a paper by Gjorv et al. [1990]. Their test results indicated that if the concrete strength were increased from 50 MPa (7,200 psi) to 100 MPa (14,400 psi), the abrasion of the concrete would be reduced roughly by 50%. At 150 MPa (21,600 psi), the abrasion of the concrete was comparable to that of high quality massive granite. When compared with a high quality asphalt pavement, the abrasion resistance of the very high-strength concrete represents an increase in the service life of the pavement by a factor of nearly ten.

A unique piece of equipment, called TEREDO, for in-situ assessment of abrasion resistance of concrete has been developed by researchers at University of Belfast, Northern Ireland [Montgomery et al. 1989]. It is designed for accelerated abrasion test by using rotating wheels. Three sets of spiked steel dressing wheels are mounted on radial arms around a central spindle rotating at a constant speed of 50 rpm by a small DC motor with a variable speed control. The central shaft is attached to a center-hole jack allowing a force to be applied to the spindle through the jack, thus enabling the rotating wheels to abrade the surface. The machine is so designed that the dressing wheels will follow the contours of the test surface, including any peaks and troughs formed by its abrading action. The depth to which the test surface has been abraded is measured at 8 points along the abraded annular path after 15 minutes of operation. This recorded depth is used as a measure of the abrasion resistance of the surface. The investigation into the sensitivity of the apparatus to the variables of concrete mixes indicated that TEREDO produces test results which relate to the strength of the concrete. Therefore, correlations can be established between the measured abrasion depth and water/cement ratio, curing regime, and the method of surface finish. Laplante et al. [1991] conducted an experimental program using the ASTM C 779 test method to determine the abrasion resistance of concrete with silica fume addition, W/CM ratio, and coarse aggregate type as variables. They found that coarse aggregate was the most important factor, followed by W/CM ratio in rank, affecting the abrasion resistance of concrete. The abrasion resistance of concrete is strongly influenced by the relative abrasion resistance of its mortar and coarse aggregate. When the coarse aggregate and mortar have nearly the same abrasion resistance, the surface wear of the concrete would be fairly uniform and the concrete can present serious skidding and slipping problems when wet. When the W/CM is very low, it can make the concrete almost as abrasion resistant as high-performance rocks.

Also using the ASTM C 779 test method, Dhir et al. [1993] conducted a study to investigate the abrasion resistance of concrete as affected by the curing method (water vs air), length of curing, variable workability, and variable maximum aggregate size. By measuring also the initial surface absorption (ISAT) at the 10-minute mark, a linear correlation was established between the abrasion of concrete and its initial surface absorption at 10 minutes, see [Fig. 4.20](#).

Abrasion resistance of high-strength concretes containing chemical and mineral admixtures was investigated by de Almeida [1994]. Ten concrete mixtures were evaluated for their abrasion resistance according to a Portuguese Standard, which is similar to the Brazilian Standard and the German Standard DIN 52108, using the Dorry apparatus, [Fig. 4.21](#). The compressive strength of the concrete varied from 60 to 110 MPa (8,700 to 15,950 psi) at 28 days, and the W/CM varied from 0.24 to 0.42. The concrete mixtures contained silica fume, fly ash or natural pozzolan, with or without a superplasticizer, with workability being kept constant, [Fig. 4.22](#). From the test results, it was concluded that the abrasion resistance of concrete generally varies inversely with the W/CM ratio (see [Fig. 4.23](#)), the porosity, and the cement paste volume in the concrete. Therefore, by using superplasticizer to reduce substantially the W/CM ratio, the abrasion resistance of concrete would be improved considerably. Introducing mineral admixture without using superplasticizer would reduce the abrasion resistance of concrete since more water would be needed to maintain a constant workability. It is noted that the results of the study should be applied to high-strength concrete mixtures only. However, even the least abrasion resistant concrete produced in the study resulted in surface wear that was only 17% of ordinary concrete.

It is worth noting that Fwa [1989] developed a laboratory test procedure for cyclic wetting and drying to simulate the weathering effects of Singapore's climate on the wearing resistance of concrete pavements. Tests were conducted with a rotating drum on plain cement mortar specimens with and without

weathering treatment. While no direct correlations were established between his test data and the field performance of in-service pavements, the test results did suggest that the test procedure could be useful for evaluation of the relative surface wear resistance of concrete pavement.

Abrasion resistance of concrete including rather high volumes of Class C fly ash (50% and 70% replacements of cement) was investigated by Naik et al. [1994]. A reference portland cement concrete was proportioned to produce 28-day strength of 41 MPa (5,950 psi). Abrasion tests were conducted by using the rotating cutter method of ASTM C 944. All the specimens made either with or without fly ash passed the abrasion resistance requirements of ASTM C 779, Procedure B. An accelerated test method, using the rotary cutter device having dressing wheels equipped with smaller size washers, was developed. A measured amount of standard Ottawa sand was added to the surface being abraded at one minute intervals. The results of the accelerated test showed lower abrasion resistance for high-volume fly ash concrete systems relative to no-fly ash concrete.