Durability Factor (DF)	Rating
75 - 100	Excellent
50 - 75	Good
25 - 50	Fair
0 - 25	Poor

It has been suggested (7) that the Corps of Engineers rating system is too lenient. Indeed, some authorities consider a durability factor of less than 80 as unsatisfactory. The Corps of Engineers rating system does, however, take into account the severity of the ASTM C666 Procedure A test. Ultimately it requires engineering judgement to assess whether a given durability factor is acceptable for a specific application. For example, a shotcrete which displays a durability factor of say 60 after 300 freeze-thaw cycles may exhibit significant scaling and loss of surface mortar. This may be acceptable for some shotcrete applications, but not for others.

PARAMETERS OF THE AIR VOID SYSTEM

Assuming the use of durable aggregates, the vulnerability of fibre reinforced shotcrete to freezing and thawing is a function of the pore structure of the cementing materials paste phase and the moisture condition of the shotcrete at the time it is exposed to freezing. The pioneering work in understanding the influence of pore structure on freeze-thaw durability was undertaken by T.C. Powers and his co-workers at the Portland Cement Association in the 1940's and 1950's. Recently Philleo (3) has presented an excellent overview summarizing the principal findings of Powers and explaining the mechanism by which air entrainment imparts freeze-thaw durability to concrete.

The ASTM C457 Standard Practice for "Microscopical Determination of Air-Void System in Hardened Concrete" provides a means for determining the important characteristics of the pore structure of hardened concrete (or shotcrete). Values measured include the air-void content, specific surface, spacing factor and air-paste ratio. The air-void content includes both intentionally entrained air-voids and entrapped air-voids, based on the size and shape of the air-voids. The entrained air-voids generally range in size from about 0.05 to 1.25 mm (0.002 to 0.05 in.) and are spherical in shape; entrapped air-voids are generally larger than 1.25 mm (0.05 in.) and irregular in shape. In dry-mix shotcretes this distinction tends to blur, as it is possible to develop a pore structure from the pneumatic application process which provides tiny air-voids (albeit irregular) similar in size and spacing to those in air-entrained wet-mix shotcrete or concrete (8).

Perhaps even more important than the air-void content, is the air-void spacing factor (L), an index related to the maximum distance of any point in the cement paste from the periphery of an air-void, measured in inches or mm. Authorities such as the Canadian Standards Association Concrete Materials and Methods of Concrete Construction Committee A23.1, have recommended a maximum spacing factor of 0.23 mm (0.009 in.) for freeze-thaw durable concrete. Recent work by Pigeon (9), and a review by Philleo (3), however, indicate that with modern high strength, low water-cement ratio materials, freeze-thaw durability can be obtained at spacing factors greater than 0.23 mm (0.009 in.).

The next air void parameter of interest is the specific surface; the surface area of the air voids in hardened concrete (or shotcrete) expressed in mm^2/mm^3 (or $in.^2/in.^3$). This parameter is related to the air content and spacing factor. Neville (11) reports that:

> "For air entrained concrete of satisfactory quality the specific surface of voids is in the range of approximately 16 to 25 mm^{-1} (400 to 600 $in.^{-1}$) but sometimes as high as 32 mm^{-1} (800 $in.^{-1}$). By contrast the specific surface of accidental air is less than 12 mm^{-1} (300 $in.^{-1}$)".

An appreciation of how the specific surface changes with changes in air content and spacing factor is well demonstrated in the paper by Pigeon (9).

Finally, the question is sometimes asked as to how the air content of the plastic shotcrete (or concrete) as measured by the ASTM C231 pressure method compares to the air-void content of the hardened shotcrete (or concrete), as measured by the ASTM C457 procedure. There is unfortunately no simple answer to this question. The correlation between the two depends in part on the relative effectiveness of consolidating the shotcrete or concrete for the different tests. A review of the literature (10), indicates that for concrete or shotcrete air entrained in the range of about 4 to 8 percent, the air content in the plastic and hardened samples generally agrees within about ±1.5 percent. Variations outside of this spread can, however, be found. At air contents below 4 percent variations tend to be less.

STEEL FIBRE SHOTCRETE DURABILITY

In 1987 Morgan et al (12) published the results of a detailed evaluation of the performance of both wet and dry-mix shotcretes made both with and without additions of steel fibre and silica fume. This study was conducted to evaluate the influence of these additions on a variety of plastic and hardened properties of these types of shotcrete. The results of the freeze-thaw durability studies were published separately in 1988 (13).

Tests were conducted according to the ASTM C666, Procedure A, rapid freezing and thawing in water to 300 cycles. The tests followed the ASTM procedure, except that the dry-mix shotcrete was allowed to moist cure for 99 days and the wet-mix shotcrete for 56 days before being subjected to freeze-thaw cycling. The shotcrete mixture proportions used are summarized in Table 1. Properties of both the plastic and hardened shotcrete are summarized in Table 2. A 10 mm (3/8 in.) maximum size aggregate, conforming to the gradation requirements of ACI 506R-85, Table 2.1 (14) was used.

In these studies the compressive strength of the shotcretes was high and the water/cementing materials ratio low. The compressive strength of the dry mix shotcretes varied from 41.9 Mpa (6,080 psi) in the accelerated steel fibre reinforced shotcrete mix (9D) to 51.8 MPa (7,510 psi) in the silica fume shotcrete (2D). The compressive strength of the wet-mix shotcretes ranged from 55.8 MPa (8,090 psi) for the plain mix (1W) to 65.7 MPa (9,530 psi) for the silica fume mix

(2W). All of the shotcretes displayed durability factors at 300 cycles in excess of 95 percent.

No attempt was made to entrain any air in the dry-mix shotcrete. (This is viewed by the writer as being a rather dubious exercise). The wet-mix shotcrete, by contrast, was air-entrained. The as-batched wet-mix shotcrete was air-entrained to 8±1% before shooting. Plastic air content was determined by two procedures.

a) shotcrete was applied directly into the base of an ASTM C231 air pressure meter;

b) shotcrete was applied to a vertical wall, the shotcrete removed by scoop and reconsolidated in an air pressure meter base by rodding.

Both procedures were found to produce very similar values for plastic air content. From examination of the data in Table 2 it is apparent that, for this study, approximately one-half of the as-batched plastic air content was lost in the pumping and shooting process. Measurements indicated that generally less than 1.5% air content was lost in the actual pumping process; the remainder was lost in the shooting process. The air content in the hardened shotcrete was, however, on average about 1.5% higher than that measured in the plastic shotcrete.

Perhaps of more significance than the air content alone are the other parameters of the air void system i.e. spacing factor and specific surface. The specific surface values, with the exception of Mix 9D, are in the range of 16 to 32 mm^{-1} (400 to 800 $in.^{-1}$) suggested by Neville (11) as being indicative of concrete with suitable air entrainment for freeze-thaw durability.

There is good correspondence between the spacing factor in both the wet and dry-mix shotcretes. With the exception of the plain wet-mix (1W), these vary between 0.28 and 0.31 mm (0.011 and 0.012 in.). These values are in excess of the maximum of 0.23 mm (0.009 in.) suggested by CSA/CAN3-A23.1-M90 as being required for freeze-thaw durable concrete. However, if the data is evaluated against the suggestions of Pigeon et al (7) for a critical spacing factor (L crit), for freeze-thaw durable high strength, silica fume concrete, then the shotcretes would be indicated as being durable. This is consistent with the results of the freeze-thaw durability study to ASTM C666 Procedure A to 300 cycles.

It was noted that the quality of the hardened shotcrete was excellent in all test panels, with no indications of sand lenses, excessive voids, laminations or other defects. On completion of freeze-thaw cycling test specimens were observed to still be in excellent condition with no significant scaling or surface deterioration; saw cut edges were still sharp.

In summary, it is clear that it is possible to produce freeze-thaw durable wet and dry process shotcretes, made with and without additions of steel fibre, accelerators and silica fume, provided:

- the shotcrete is properly proportioned, using freeze-thaw durable aggregates;

- the water/cementing materials ratio is kept sufficiently low;

- for wet-mix shotcretes, adequate air entrainment must be provided; this will generally require as-batched air contents of about 8 to 10 percent, or possibly even higher, in order to produce satisfactory parameters of the air voids system in the hardened wet-mix shotcrete.

- the shotcrete is properly batched, mixed, supplied and applied i.e. the in-place shotcrete must be free of excessive voids, dry patches, sand lenses, laminations, fibre balls, etc.

POLYPROPYLENE FIBRE SHOTCRETE DURABILITY

In 1989 Hardy BBT Limited conducted tests on the freeze-thaw durability of wet-mix shotcrete made with high volume additions of collated fibrillated polypropylene fibre (CFPF). Previous studies (1) have shown that such shotcrete can provide a viable alternative to mesh or steel-fibre reinforced shotcrete with respect to physical performance parameters such as toughness and pseudo-ductility. In this 1989 freeze-thaw durability study, the CFPF was added at an addition rate of 5.7 kg/m^3 [9.6 lb/cu.y.d] (0.62 percent by volume). Details of the actual batch proportions are given in Table 3. Properties of the plastic and hardened shotcrete are provided in Table 4. While the parameters of the air void system were not determined in this particular study, the freeze-thaw durability tests (durability factor of 98.6) indicate that this shotcrete had excellent freeze-thaw resistance. It also appears that continuing hydration (and pozzolanic reactions with the fly ash) occurred during the thaw cycles, as evidenced by the increase in strength recorded in the shotcrete subjected to 300 cycles of freezing and thawing in water.

Extensive testing was conducted in 1989 into the freeze-thaw durability of high volume fly ash, high volume polypropylene fibre reinforced wet-mix shotcretes by Hardy BBT Limited. Five different shotcrete mixtures were evaluated; two mixtures at a nominal total cementing materials content of 420 kg/m^3 (708 lb/cu. yd.) and three mixtures at a nominal total cementing materials content of 480 kg/m^3 (810 lb/cu. yd). Details of the as-batched mixture proportions are given in Table 5. The key differences between these mixtures and conventional wet-mix fly ash shotcretes are the low portland cement content, high fly ash content, high superplasticizer dosage rate and low water demand of the high volume fly ash system. Polypropylene fibre addition rates varied between 0 and 6.5 kg/m^3 [11.0 lb/cu. yd] (0.71 percent by volume).

Results of plastic property tests and air void parameters tests are given in Table 6. Results of hardened properties tests are given in Table 7. ASTM C666 Procedure A freeze-thaw durability testing was commenced after 28 days of continuous moist curing in a lime saturated water bath maintained at 23°C. It can be seen that all mixtures provided excellent freeze-thaw durability, with durability factors ranging from 91.6 to 98.5. There was some light surface scaling and mass loss varied from 1.6 to 3.0 percent. The excellent freeze-thaw durability recorded is consistent with predictions based on the measured parameters of the air void system (air content, spacing factor and specific surface).

In summary, it appears feasible to produce freeze-thaw durable high volume fly ash wet-mix shotcrete, with or without high volume polypropylene fibre reinforcement, provided the mixtures are properly proportioned and applied. These conclusions are supported by the results of freeze-thaw durability tests conducted on similar mixtures by CANMET (2) and the early age performance of shotcrete field trials conducted on such systems at Halifax airport in Nova Scotia and in Burnaby, British Columbia.

CASE HISTORIES

Steel Fibre Shotcrete

Steel fibre reinforced shotcrete has been used in external freeze-thaw exposure environments in Canada since the early 1980's (15). Examples of such projects include:

- portal areas in rail tunnels in the Rocky mountains in central B.C., constructed in 1982-1983;
- various rock-slope stabilization projects on the Coquihalla highway and Horseshoe Bay to Squamish highway, B.C., 1984-1986;
- rock slope stabilization of railway cuts in the Fraser Canyon, B.C. 1984;
- artificial West Coast rockscape at the Vancouver Public Aquarium killer whale pool, 1985-1986;
- creek stabilization, using boulders embedded in steel fibre reinforced shotcrete, Lions Bay, B.C., 1986-1987;
- creek channelization to protect bridge abutments; Hope-Princeton Highway, B.C., 1986;
- rehabilitation of upstream face of an old Amberson buttress dam at Jordon River on Vancouver Island, B.C., 1988-1989;
- rehabilitation of deteriorated wharf faces at the Port of Saint John, New Brunswick, 1986-1990.

In many of these projects the shotcrete is subjected to freezing and thawing in a potentially critically saturated condition. Some structures, such as the berth faces at the Port of Saint John, New Brunswick are subjected to particularly severe freezing and thawing conditions (16). The earliest shotcrete repair work on these wharf structures (1986) has now undergone approximately 1000 freeze-thaw cycles and is in still excellent condition. Such performance was predicted, based on preconstruction freeze-thaw durability testing and quality control testing for plastic air content and parameters of the air void system in the hardened shotcrete (16). In summary, there is extensive field evidence (albeit still fairly short term) to support the laboratory predictions that properly designed, batched, mixed, supplied and applied steel fibre reinforced shotcrete (both wet and dry-mix) should be freeze-thaw durable.

Polypropylene Fibre Shotcrete

The use of polypropylene fibre reinforced shotcrete is more recent than for steel fibre reinforced shotcrete and field experience of freeze-thaw durability performance is thus still fairly limited. The following are, however, examples of where such shotcrete has been used in external freeze-thaw exposure conditions, with a potential for critical saturation of the shotcrete at the time of freezing.

- Oldman River Dam, Southern Alberta; portal areas in drainage tunnels and shotcrete cover of exposed bedrock at dam spillway section, 1989;
- municipal incinerator fly ash disposal site, Coquitlam, B.C.; capping and sealing compacted ash, 1988-1990;
- Hell's Gate, Fraser Canyon Highway, B.C.; rock slope stabilization, 1989;
- Hope-Princeton Highway, B.C.; rehabilitation of several freeze-thaw and scour deteriorated bridge abutments and piers, 1988-1989;
- field exposed restrained shrinkage test panels in CANMET study, Burnaby, B.C., 1988-1990;
- capping and sealing pyritic slate against surface water entry at Halifax Airport, Nova Scotia, 1989-1990;
- construction of 5 mile long drainage canal around tailings dam, Lead, South Dakota, 1988-1989.

Laboratory tests conducted on shotcrete mixtures used in these projects predict excellent long term freeze-thaw durability. Early age feed-back from the field for these projects is good; these projects will continue to be monitored for long-term field performance.

CONCLUSIONS AND RECOMMENDATIONS

It is possible to produce freeze-thaw durable wet and dry-mix fibre reinforced shotcretes provided the following guidelines are adhered to:

1. The shotcrete should be properly proportioned, using proven freeze-thaw durable aggregates.

2. The water/cementing materials ratio should be kept sufficiently low; the general recommendations provided in CAN/CSA-A23.1-M90, Tables 7 and 8 should be followed.

3. For wet-mix shotcretes adequate air entrainment must be provided; this will generally require as-batched air contents of about 8 to 10 percent, or possibly even higher, in order to produce satisfactory parameters of the air void system in hardened wet-mix shotcrete. (For guidance on air voids systems see Reference 10).
4. The shotcrete must be properly batched, mixed, supplied and applied; i.e. the in-place shotcrete must be free of excessive voids, dry patches, sand lenses, fibre balls, laminations, etc.

5. The shotcrete should be properly cured and then preferably be allowed to dry before being subjected to freezing (i.e. avoid freezing while critically saturated if possible).

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Table 1 - Study by Morgan et al, 1988 (10) Wet and Dry-Mix Shotcrete Proportions

Mix No.	Shotcrete Process	Cement Content Before Shooting		Silica Fume Content		Water/ Cementitious Ratio	Steel Fibre Content	
		lbs./cu.yd	kg/m^3	lbs./cu.yd	kg/m^3		lbs./cu.yd	kg/m^3
1D	Dry	696	413	-	-	0.29	-	-
2D	Dry	609	361	88	52	0.29	-	-
9D *	Dry	608	361	88	52	0.29	101	60
1W	Wet	784	465	-	-	0.35	-	-
2W	Wet	681	404	103	61	0.35	-	-
3W	Wet	681	404	103	61	0.35	101	60

* contained 3% by mass of cement shotcrete accelerator.

Table 2 - Study by Morgan et al, 1988 (10) Wet and Dry-Mix Shotcrete Properties

Mix No.	28 Day Compressive Strength		Plastic Air Content %	Hardened Air Content %	Air-Void Spacing Factor		Specific Surface		Durability Factor at 300 Cycles	Durability Rating
	psi	MPa			in.	mm	$in.^{-1}$	mm^{-1}		
1D	7,190	49.6	-	5.39	0.011	0.27	467	18.4	97.3	Excellent
2D	7,510	51.8	-	6.00	0.011	0.29	422	16.6	99.2	Excellent
9D	6,080	41.9	-	6.51	0.012	0.31	376	14.8	97.4	Excellent
1W	8,090	55.8	3.8	5.57	0.007	0.17	693	27.3	101.6	Excellent
2W	9,530	65.7	3.7	4.54	0.011	0.28	452	17.8	99.1	Excellent
3W	9,430	65.0	3.8	5.15	0.011	0.27	470	18.5	96.9	Excellent