FROST RESISTANCE AND AIR-VOID CHARACTERISTICS IN HARDENED CONCRETE

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SYNOPSIS

For many construction sites it is a problem to keep the required air-void content during transportation and handling of the concrete. Also, for many concrete structures it is a problem to meet combined requirements of high compressive strength and high air-void content based on local aggregates available. Extensive testing of the air-void system in concrete from a variety of construction sites in Norway over recent years has shown that the majority of specimens had a relatively low air-void content, and only about half of the specimens had proper air-void characteristics according to common requirements. In order to provide a better basis for evaluating the observed air-void characteristics, freeze-thaw testing for a number of the concretes was also carried out, and this testing was based on the critical degree of saturation method. The results indicate that it may be difficult to establish a direct relationship between air-void characteristics and frost resistance without also taking into account information about capillary voids and strength properties. As a basis for evaluation of the potential frost resistance of a concrete the frost resistance number is introduced. This number is based on information about compressive strength, water-cement ratio, paste fraction and amount of air-voids smaller than 300 μm.

Keywords: Air-entrainment, air-void system, frost resistance, quality control.

INTRODUCTION

For many years the relevancy of conventional freeze-thaw testing of hardened concrete has been questioned(1,2), and conventional freeze-thaw testing may also be quite time consuming. In order to obtain a relatively quick assessment of the potential frost resistance, extensive testing of air-void characteristics in hardened concrete has been carried out over recent years at the Norwegian Institute of Technology, NTH. Most of these measurements have been part of more comprehensive quality control programs carried out on contract basis for the construction industry mainly in Norway, but also in other countries.

For many of the construction sites it has been a problem to keep the required air-void content in the concrete (4-6 percent) during transportation and handling. For many of the construction sites it has been a problem also to meet combined requirements of high compressive strength and high air-void content based on local aggregates available. For these construction sites it has been crucial to find out whether a relatively low air-void content still could be acceptable for an adequate frost resistance. It is primarily the amount of smaller air-voids, i.e. below 300 m, which is related to the frost resistance(3), and proper air-void characteristics are not necessarily related to a high air-void content. According to common recommendations the specific surface and the spacing factor should preferably be above 25 mm^2/mm^3 and below 0.25 mm, respectively(4,5).

Experiences from the above testing have shown that the concrete from a majority of the construction sites had a relatively low air-void content and only about half of all the specimens tested had air-void characteristics meeting the above recommendations(6). Although higher total air contents generally improved the air-void characteristics, very good characteristics were also observed, however, for total air-void contents as low as 2.6 to 3.0 percent.

In order to provide a better basis for evaluating the observed air-void characteristics a research program was started with the objective of relating air-void characteristics and frost resistance of the concrete. As part of this program extensive field tests were carried out at one of the construction sites from which some preliminary results are reported in the present paper. The program also included some factors which may affect the stability of the air-void system both during production of the concrete and during transportation of the concrete by truck.

For a few other construction sites where testing of the frost resistance was carried out in addition to the control measurements of air-void characteristics, the test results are also included in the following. All freeze-thaw testing was based on the critical degree of saturation method(7).

EXPERIMENTAL

Test program

A view of the field tests carried out is shown in Table 1. The aggregates used were clean and inert with the fine aggregate mostly of siliceous origin and the coarse aggregate of crushed granite. The maximum aggregate size was 25 mm. An ordinary portland cement PC 30 (ASTM Type 1) was used, and in addition to an air-entraining admixture (L) a combined plasticizing and set retarding admixture (LP) was also used. The admixture L was of a vinsol resin type, while LP was mainly a sodium lignosulfonate with a small amount also of vinsol resin.

Table 1. Program for field tests.

Test Series No.	Concrete Quality				Transportatio time min.
	Cement kg/m^3	w/c - Ratio	Paste %	Air %	
1.1	300	0.65	29.2	4.3	-
1.2	375	0.58	31.1	4.9	-
1.3	450	0.49	35.5	3.7	-
2.1	375	0.54	32.4	3.9	0
2.2	"	"	"	3.3	15
2.3	"	"	"	2.9	30
2.4	"	"	"	2.9	60
2.5	"	"	"	3.3	60[1]
2.6	"	0.42	27.7	5.9	0
2.7	"	"	"	3.6	15
2.8	"	"	"	3.1	30
2.9	"	"	"	4.0	60
2.10	"	"	"	4.7	60[1]

[1] Reference concrete

For all test series efforts were made to keep the total air content in the fresh concrete at 5.0 ± 1 percent, but this was not quite sucessful. For test series 1.1 to 2.5 2 litre LP per m^3 of concrete was used and the slump was 12.5 ± 1 cm, while for test series 2.6 to 2.10 5 litre LP was used and the slump was 7.5 ± 1 cm.

The mixing plant was of a Stetter type with a 1.25 m^3 Zontoven mixer. Each batch of concrete was 1 m^3, for which the mixing time was 75 sec. For transportation a truck with a rotating container of 3 m^3 capacity was used. For these test series a volume of 3 m^3 concrete was transported from which samples were removed after 15, 30 and 60 minutes of driving along a given route. In addition a reference concrete of about 50 litre volume was kept stationary at the mixing plant.

At each testing the total air-void content was measured by use of the pressure-type air meter, and control measurements of slump were also carried out. Three 10 cm cubes were further cast, of which one was used for later determination of air-void characteristics while the remaining two were used for compressive testing at 28 days. For a number of the test series 15 cylinders of Ø 10 x 20 cm were also cast for later testing of frost resistance. Apart from Test series B.1 all specimens were cured for at least three months.

A view of the concretes tested over recent years from various construction sites is shown in Table 2. For these concretes both materials and conditions have varied within wide limits.

Table 2. Concrete from various construction sites.

Construction site	Test Series No.	Concrete Quality				Variable
		Cement kg/m^3	w/c - Ratio	Paste %	Air %	
A	A.1 A.2	425 "	0.45 "	36.6 "	3.0 1.5	Air entrainment
B	B.1	480	0.40	34.7	4.1	Early age
C	C.1	435	0.47	34.5	4.3	Dolomitic aggregate
D	D.1 D.2	457 "	0.40 "	33.0 "	7.6 2.9	Transportation

Measurements of air-void characteristics

Only with a few modifications the cutting and preparation procedures for the specimens were essentially as described in ASTM C 457$^{(8)}$. Depending on the maximum aggregate size the total section area to be examined microscopically varied from 10,000 to 15,000 mm^2. In order to obtain a statistically representative section for examination, four to five smaller sections were normally cut from different levels parallel to the top surface of the specimens.

Two different sets of equipment were employed, one for modified point-count measurements and the other for linear traverse measurements, both types essentially as described in ASTM C 457, though with automatic operation. Direct microscopic observation at magnification and light conditions as described in ASTM C 457 were used.

For all concrete specimens the air-void system was investigated by determination of the air-void content (A_C) (percent), the specific surface (α) which is the surface area of voids (mm^2) per unit volume of voids (mm^3), and the spacing factor ($\bar{L}$) which is related to the average distance of any point in the cement paste from the periphery of an air-void (mm). For most of the specimens a complete void size distribution was also determined including A_{300}, A_{200} and A_{100}, which are the space capacities for air voids with diameters below 300, 200 and 100 μm, respectively.

For further details and calculations reference is made to ASTM C 457 and a previous paper$^{(6)}$. It should be noted, however, that normally, all calculations are based on the paste content as calculated on the basis of mix proportions (p^1), while for the present measurements all calculations were based on the paste content as determined microscopically.

Measurements of frost resistance

The method used is based on the concept that a critical degree of saturation exists for which a higher moisture content will give serious damage by freezing while a lower moisture content will not give any damage even after a large number of freeze-thaw cycles. The degree of saturation is defined as

$$S = \frac{V_w}{V_p} \qquad (1)$$

where V_w is the total water volume evaporable at 105°C and V_p is the total open pore volume before freezing. The frost resistance is defined as:

$$F = S_{CR} - S_{ACT} \qquad (2)$$

where S is the critical degree of saturation, and S_{ACT} is the actual degree of saturation prevailing in the material at the time of testing.

Only with a few modifications the precedure used for determining the frost resistance was essentially as described in tentative recommendations given by Fagerlund(7).

The determination of S_{CR} was based on 10 test cylinders Ø 10x20 cm, for which the degree of saturation varied from approx. 0.8 to 1.0. The specimens were subjected to six freeze-thaw cycles to -20°C, the effect of which was evaluated by determining the dynamic modulus of elasticity before and after exposure.

The determination of S_{ACT} was based on five slices of concrete Ø 10 x 2.5 cm cut from two test cylinders, for which the rate of water uptake by capillary action was measured over a period of about one month. By putting:

$$S_{ACT} = S_{CAP} \qquad (3)$$

where the rate of water uptake S_{CAP} is a function of time, eq. 2 can be written as:

$$F = a - b \log t \qquad (4)$$

where

$$a = S_{CR} - c \qquad (5)$$

and b and c are constants which can be obtained by linear regression or graphically.

In the following the frost-resistance of the concrete is expressed by the frost-resistance period which is defined as the time necessary in hours or years for F to become zero, $t_{F<0}$.

Although the experiences by interpreting the frost resistance based on the frost-resistance period $t_{F<0}$ is rather limited at the time being, preliminary experiences indicate that a period of 5 to 10 years should reflect an adequate frost resistance. For several of the construction sites S_{ACT} was also roughly estimated by evaluating the actual exposure conditions for various parts of the concrete structure at the time of possible freezing.

RESULTS AND DISCUSSION

Effect of concrete quality

An overall view of the observed frost resistance for the various concrete qualities investigated is shown in Table 3. Of all concretes from the field tests (test series 1.1 to 2.9) only two had an adequate frost resistance (2.6 and 2.9), while the others

Table 3. Effect of concrete quality.

Test Series No.	Cement kg/m^3	w/c-Ratio	Compressive Strength MPa	Air %	Air-Void characteristics						Frost Resistance				
					A_c %	A_{300} %	A_{200} %	A_{100} %	α mm^2/mm^3	$\bar{L}$ mm	S_{CR}	Period ($t_{F\leq 0}$)		Number	
												hrs.	years	N	N'
1.1	300	0.65	28.8	4.3	4.9	1.4	0.59	0.13	14	0.35	0.83	45	0.0	327	495
1.2	375	0.58	39.6	4.9	4.5	1.5	0.71	0.26	21	0.25	0.80	11	0.0	568	935
1.3	450	0.49	44.6	3.7	4.5	1.1	0.68	0.36	18	0.31	0.84	11	0.0	576	1120
2.1	375	0.54	33.5	3.9	3.6	1.1	0.65	0.20	18	0.32	0.90	2500	0.3	389	690
2.4	375	0.54	31.3	2.9	3.5	0.81	0.45	0.15	17	0.35	0.88	13	0.0	268	467
2.6	375	0.42	50.0	5.9	6.1	2.1	1.1	0.42	21	0.21	0.94	10^6	114	2149	3704
2.9	375	0.42	52.9	4.0	3.9	1.4	0.90	0.37	26	0.22	0.93	$2x10^5$	23	1516	2891
A.1	425	0.45	-	3.0	3.8	-	-	-	27	0.23	0.85	25.000	2.9	-	-
A.2	425	0.45	-	1.5	1.8	-	-	-	17	0.51	0.90	1.000	0.1	-	-
B.1	480	0.40	-	4.1	2.8	-	-	-	41	0.17	0.91	100	0.0	-	-
C.1	435	0.47	46.0	4.3	3.4	-	-	-	38	0.17	0.87	4.000	0.5	-	-
D.2	457	0.40	50.6	2.9	4.8	1.5	0.85	0.40	25	0.21	0.92	40.000	4.5	1438	2636

did hardly have any frost resistance. Increasing cement contents to as much as 450 kg per m^3 and decreasing water-cement ratios to as low as 0.49 did not improve the frost resistance.

For concrete 2.6 and 2.9 the frost-resistance period was 114 and 23 years, respectively, which indicates a very good frost resistance. For these two concretes the air-void characteristics α and $\bar{L}$ did meet fairly well current requirements of being above 25 mm^2/mm^3 and below 0.25 mm, respectively. For the concretes A.1, B.1, C.1 and partly also 1.2, however, α and $\bar{L}$ did also meet the above reguirements, while the frost-resistance period was almost zero. Although A_c, α and $\bar{L}$ give valuable information about the air-void systemm the above results indicate that it may be difficult to establish a direct relationship between these air-void characteristics and the observed frost resistance.

The mechanism of deterioration due to freezing and thawing is very complex with a number of factors influencing the frost resistance. As a fairly simple basis for evaluation, however, Schäfer(3) introduced the frost-resistance number:

$$W_b = \frac{L_{300} \cdot B}{K} \cdot 100 \qquad (6)$$

where

L_{300} = space capacity of air voids below 300 μm
B = flexural strength
K = space capacity of capillary voids

In this expression information about the strength and the capillary system is also included. The flexural strength represents the ability of the material to withstand the tensile stresses developing during freezing, while the space capacity of capillary voids indicates the total pore volume which can be filled with freezable water. Although L_{300} only makes up a smaller part of the total air-void content, it comprises as much as about 99 percent of all air voids and thus represents the efficient part of the void system.

In order to evaluate the data from the present field tests a similar expression to eq.6 was used:

$$N = \left(\frac{A_{300}}{P^1/100}\right) \cdot \left(\frac{1}{w/c}\right)^2 \cdot f_c' \qquad (7)$$

where

A_{300} = space capacity of air voids below 300 μm (percent)
p^1 = paste content (percent)
w/c = water-cement ratio

f_c' = compressive strength (MPa)

Since A_{300} refers to the volume of concrete for which the paste fraction varied within wide limits, the space capacity of voids relative to the paste fraction is introduced. For lack of information about B and K in eq. 6, the compressive strength and the water-cement ratio are introduced, assuming a square function between K and the water-cement ratio.

The calculated frost-resistance numbers (N) are shown in both Table 3 and Fig. 1. Although the number of data is very limited Fig. 1 indicates an adequate frost resistance for values of N above a certain threshold level (approx. 1500).

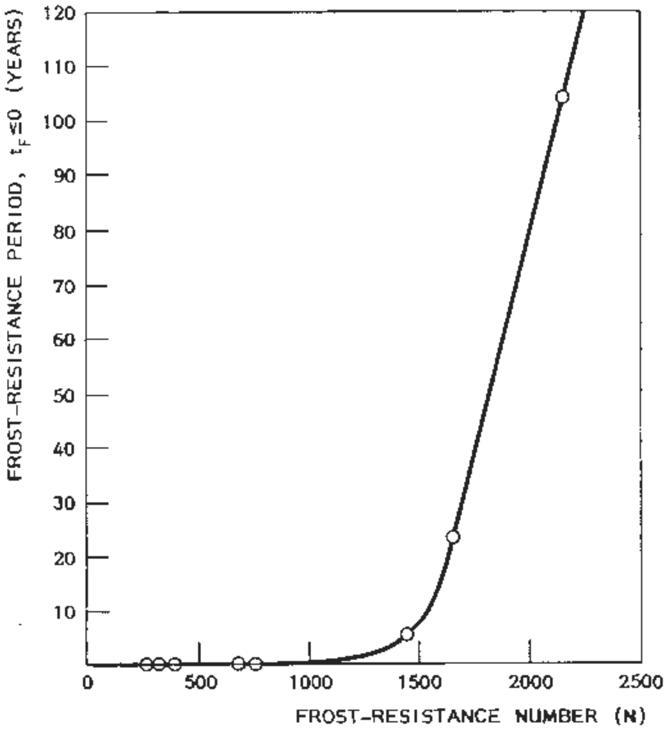

Fig. 1 Relationship between the frost resistance number and the observed frost resistance.

Although A_{300} appears to be an appropriate characteristic of the most interesting part of the air-void system it can be seen from Table 3, however, that the corresponding space capacites for voids below 200 and 100 µm also vary within wide limits. In order to include these variations a further expression was used:

$$N' = \left(\frac{A_{300} + A_{200} + A_{100}}{p^{1}/100} \right) \cdot \left(\frac{1}{w/c} \right)^{2} \cdot f_c' \qquad (8)$$

If the frost resistance number is calculated on the basis of eq. (8), Table 3 indicates that this number (N') should at least be higher than about 2500 in order to reflect an acceptable frost resistance. Instead of ($A_{300} + A_{200} + A_{100}$) in eq. 8 the whole integrated area below the void-distribution curve up to 300 μm would probably be an even better characteristic of the air-void system.

For concrete A.1 to C.1 from various construction sites sufficient data for calculating the frost-resistance number was not available. For the construction siste A, however, the only difference between the two concretes A.1 and A.2 was an air entrainment to the former. Although this air entrainment was not quite sufficient, a distinct difference in frost resistance was observed.

For concrete B.1 having a cement content of 480 kg, a water-cement ratio of 0.40 and a successful air entrainment, it may be noted that adequate frost resistance was still not observed. For this concrete it should be noted, however, that the degree of hydration at the time of testing was very low. Due to urgent circumstances at the construction site all tests had to be completed and the results reported within a period of 36 days from the time of casting of the specimens.

Also for concrete C.1 it may be noted that a high quality concrete with very good air-void characteristics did show very poor frost resistance. For this concrete a crushed dolomitic limestone was used as aggregate, for which previous experiences indicate a high susceptibility to frost damage.

Although several factors are influencing the frost resistance the above results clearly demonstrate that entrainment of air is essential in providing adequate frost resistance even for a concrete with a compressive strength of 40-50 MPa. By use of air entrainment A_{300} may increase from typically 0.20 up to 1.5 or 2.0, and thus increase the frost-resistance number (N) by a factor of 7.5 to 10, while a further increase of compressive strength from for example 50 up to 70 MPa only increases the frost-resistance number by a factor of 1.4. Although the effect of air content, compressive strength and water-cement ratio in eq. 8 are all interrelated, the above results clearly demonstrate the importance of a proper air-void system even for concrete with a compressive strength of up to 50 MPa. In the field, however, handling and transportation of the concrete may destroy an established air-void system.

Effect of transportation

The observed effects of transportation by truck are shown in Table 4 and graphically demonstrated in Figs. 2 and 3. For the first transportation (2.1 to 2.4) the total air content in the fresh concrete successively dropped from 3.9 to 2.9 percent during the first half hour, but the air-void characteristics did not show much difference after one hour of transportation. The observed loss of air was evenly distributed over the whole range of void diametres (Fig. 2). From Table 4 it can be seen that the reference concrete 2.5 had approximately the same void characteristics after one hour as before the start of transportation (2.1), only with a small reduction in A_{300}. During transportation it can further be seen from Table 4 that both slump and compressive strength had increased somewhat during the first half hour, but then decreased again.

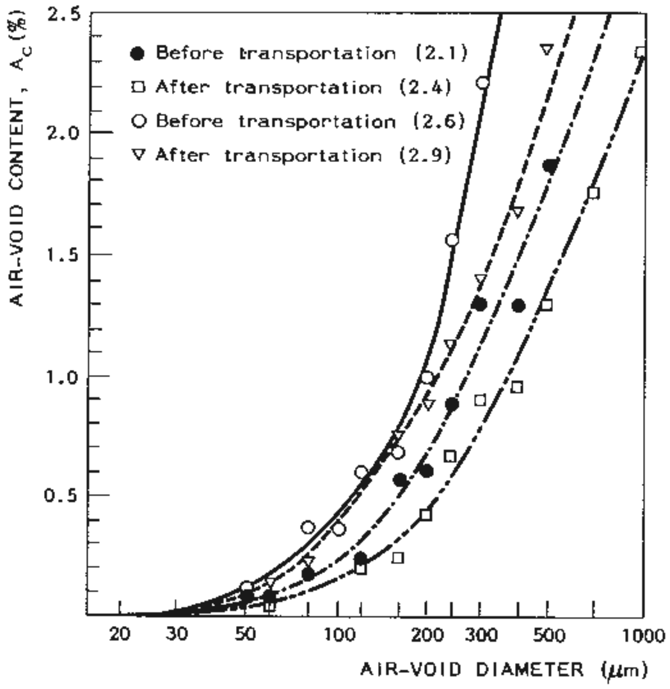

Fig. 2. Effect of transportation on the distribution of air voids.

For the second transportation (2.6 to 2.9) the total air content in the fresh concrete successively dropped from 5.9 to 3.1 percent during the first half hour, but then the air content slightly increased again. After one hour of transportation the air-void distribution was distinctly changed indicating that mostly larger voids had disappeared, but also a part of the smaller voids (Fig. 2). A_{300} was reduced from 2.1 to 1.4 percent. From Table 4 it can also be seen, however, that about

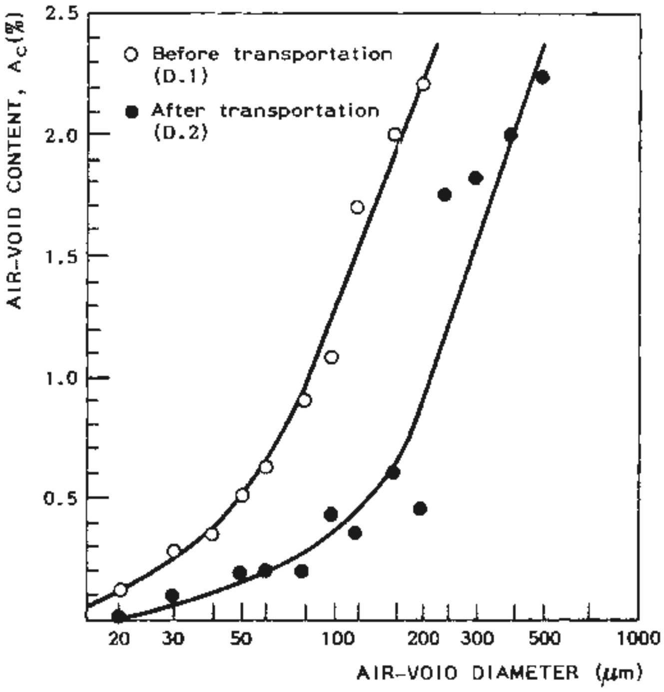

Fig. 3. Effect of transportation on the distribution of air-voids.

the same change in void distribution was observed in reference concrete 2.10. During transportation it can further be seen from Table 4 that the slump had successively decreased from 5.5 to 2.5 cm, while the compressive strength increased form 50 up to 62.8 MPa after half an hour, but then decreased to 52.9 MPa.

By comparing the two types of concrete transported it was the concrete with the highest air content which was affected mainly. For the former concrete with an air content of 3.9 percent the void system was insufficient to provide a frost resistance in any way, but the frost-resistance number (N) was reduced from 389 to 268. For the latter concrete with an air content of 6.1 percent the frost-resistance number was reduced from 2149 to 1516, while the frost-resistance period was reduced from 114 to 23 years.

For the concrete from the construction site D the air content was even higher and the effect of transportation was even more significant. During 25 minutes of transportation which was also carried out by truck with a rotating container, the total air content dropped from 7.6 to 2.9 percent, and the observed air-void characteristics indicate that both larger and smaller voids had disappeared (Fig. 3). During this transportation the frost-resistance number (N) was reduced from 2577 to 1438, while the

Table 4. Effect of transportation.

Test Series No.	Transportation Time min.	Slump cm	Compressive Strehgth MPa	Air %	Air-Void Characteristics					
					A_c %	A_{300} %	A_{200} %	A_{100} %	α mm^2/mm^3	$\bar{L}$ mm
2.1	0	13.5	33.5	3.9	3,8	1,1	0,65	0,20	18	0,32
2.2	15	14.0	34.5	3.3	–	–	–	–	–	–
2,3	30	17.0	35.4	2.9	–	–	–	–	–	–
2.4	60	14.0	31.3	2.9	3.5	0,81	0.45	0.15	17	0.35
2.5	60[1)]	11.0	30.0	3.3	4.0	0,94	0.60	0.18	16	0.36
2.6	0	5.5	50.0	5.9	6.1	2.1	1.1	0.42	21	0.21
2.7	15	3.5	57.0	3.6	–	–	–	–	–	–
2.8	30	3.5	62.6	3.1	–	–	–	–	–	–
2.9	60	2.5	52.9	4.0	3.9	1.4	0.90	0.37	26	0.22
2.10	60[1)]	2.5	51.0	4.7	3.4	1.4	0.90	0.37	27	0.21
D.1	0	15	43.9	7.6	9.6	3.1	2.2	1,2	26	0.12
D.2	25	9	50.6	2.9	4.8	1.5	0,85	0.40	25	0.21

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1) Reference concrete

characteristics showed that both larger and smaller voids disappeared.

(5) Depending on time of transportation, air entrainment and properties of the concrete a loss of air may not necessarily represent a problem. After 25 to 30 min. of transportation increased compressive strength of up to about 25 percent was observed, while the frost resistance was still adequate. For air-entrained concrete subjected to extensive handling and transportation, however, measurements of air-void characteristics should be an important part of the quality control program.

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