Air void measurements were made using ASTM: C 457, section 6, Linear Traverse (Rosiwal) method, with the following exceptions:

- The movable stage is driven by a variable speed DC motor, and air length is counted magnetically from a gear wheel.
- The operator, looking through the stereo-microscope, depresses a button as the cross hairs intercept the leading edge of the void, and releases the button when the cross hairs intercept the farther edge of the void.

These modifications are usually applied to the Rosiwal technique. A further modification was made in that the totalizing counter, which sums the gear tooth counts to give a single, totalized traverse length over air voids, was replaced by a specially designed system based on a Rockwell AIM-65 microprocessor. This system collects individual chord lengths and, rather than writing these on paper tape (10,11), writes them onto a digital magnetic tape. This makes the processing of the data much more convenient.

Reduction of the data is carried out using a Hewlett-Packard 9845A computer. Since the individual chord intercepts are known, rather than being previously assigned to channels (2), a variety of calculations and distribution representations can be made. One possibility would be to follow the procedures of Lord and Willis (12,13). We chose not to follow this technique, wherein expected void diameters are calculated from the chord lengths, for two reasons:

- We did not wish to introduce any assumptions into the data analysis, as required in the Lord and Willis technique.
- Previous work in our laboratory and in the literature (2) had shown that the chord length distribution is affected by superplasticizers.

Therefore, we carried out calculations and distribution analysis as outlined below.

Calculations -- Normal ASTM C 457 parameters - air content, chord length, specific surface, voids per millimetre, and spacing factor, were calculated for three conditions:

- including all voids encountered.
- including only those voids less than 1 mm in chord length.
- including only those voids less than 0.5 mm in chord length.

Table 3 presents this data for a typical air-entrained concrete. In those cases where fewer than the total voids are included, the total traverse length is not decreased. Calculations in this manner have been found useful in the case where small numbers of large voids have biased the average results. In many concretes the spacing factor calculated on the reduced void data is in fact smaller, due to the higher specific surface.

Distributions -- Two void size distributions were plotted. One represents the total voids encountered; an example is shown in Fig. 1 for the same concrete represented in Table 3. The second considers only those voids less than 0.5 mm in intercept - the "entrained" air-void system. An example of this distribution is given in Fig. 2.

The first distribution, in Fig. 1, is useful for representing the entire void system. Several points should be made:

- The size scale is logarithmic, so that all void sizes can be included.
- Data are assigned to size classes which increase in breadth logarithmically as their mean size increases. Thus, when the distribution is plotted on a log scale, the intervals are equal sized.
- The solid line represents the relative frequency of the chord intercepts, while the dotted line represents the proportion of the total air content which was measured within each size range. While this is not a true estimate of the volumetric distribution of air actually in the concrete, it is valuable because it shows the relatively high proportion of the air content measured in the relatively low number of voids above 1 millimetre in chord length.

The second distribution, in Fig. 2, treats only those voids less than 0.5 mm in chord length and is useful for representing the entrained-air system. Points to note are:

- The intervals are equally spaced at 0.01 mm, and the scale is linear.
- The solid line represents the frequency of the air void chord lengths.
- The dashed line represents a distribution function fitted to the raw data. This will be used to characterize the entrained air system.

Because of the skewed nature of the distribution of the entrained air-void chord lengths, a Gaussian distribution does not provide an adequate fit; indeed it predicts negative chord lengths. We chose to use a distribution known as the zeroth-order logarithmic distribution. This function has been found to represent populations of colloid particles satisfactorily (14). To date, our application of this technique to air-void data indicates that this function does describe the distribution of chord lengths in hardened concrete.

The zeroth-order logarithmic distribution is represented by the frequency function:

$$P_{(c)} = \frac{\exp\left[-(\ln c - \ln c_m)^2 / (2\,\sigma_0^{\,2})\right]}{\sqrt{2\pi} \cdot \sigma_0 \cdot c_m \cdot \exp(\sigma_0^{\,2}/2)}$$

Where:

- c_m is the modal (most frequent) chord length,
- σ_0 is the zeroth-order log standard deviation - a measure of the width and skewness of the distribution, and
- The expression $\sqrt{2\pi} \cdot \sigma_0 \cdot c_m \cdot \exp(\frac{\sigma_0^2}{2})$ normalizes the function.

Since this function has two unknowns c_m and σ_0, a simple solution was not obtainable. Instead, an iterative procedure was used. A series of c_m values were chosen from 70% to 130% of the most frequently encountered chord length. σ_0 values between 0.3 and 0.9 were selected, since best fits occurred in this range. The distribution function was evaluated at each combination of c_m and σ_0 within the region, and compared to the measured distribution. The function having the smallest sum-of-squares deviation was considered the best fit. This calculated frequency function was drawn on the distribution graph, Fig. 2, and the modal chord length and zeroth-order log standard deviation reported.

In interpreting these parameters, the modal chord length may be considered a measurement of the size of the entrained air voids, while the zeroth-order log standard deviation measures the spread of the air void sizes within the entrained air system.

RESULTS & DISCUSSION

Concrete Properties

Concrete properties, including compressive strengths at 14 and 28 days, are given in Table 4; strengths are shown graphically in Fig. 3. Increasing slump of mixture 1 with either water or superplasticizer had little effect on the air content of the fresh concrete, while in the higher-air-level mixture 2 the air content decreased with both superplasticizer and water additions. The much better strengths obtained with high slump concretes made using the superplasticizer are as expected.

Results of Tests For Resistance to Freezing and Thawing

Table 5 gives the average results of frost-resistance testing on duplicate prisms. All specimens met the ASTM: C 494 requirement of 80% relative durability factor at 300 cycles, and in no case did the relative dynamic modulus of elasticity, (RDME), drop below 80%. In all mixtures except 1C, no significant difference in RDME occurred after the first 36 cycles. In 1C, which contained the superplasticizer at the lower air content, a small decrease was noted, but no failure. All specimens exhibited moderate scaling.

Linear - Traverse Results

Table 6 summarizes the computed air-void system parameters, including the spacing factors for voids less than 1 mm and less than 0.5 mm in chord length, as well as the modal chord length and zeroth-order log standard deviation from the fitted frequency function. Fig. 4 through Fig. 9 give the graphical distribution information for mixture 1 specimens, Fig. 10 through Fig. 15 do so for mixture 2 specimens. Several conclusions can be drawn from Table 6 and Fig. 4 through Fig. 15:

- Hardened air contents measure somewhat higher than the air contents of the fresh concrete.
- Lower air contents with the superplasticizer are confirmed.
- Spacing factors for the concretes not containing the superplasticizer generally meet the 0.2 mm criterion for resistance to freezing and thawing; those for the superplasticized concretes do not. Mixture 2B is marginally high at 0.216 mm.
- Spacing factors of the system of voids 0.5 mm in chord length decrease for the superplasticized concrete, relative to the total void spacing factor. Those for the non-superplasticized concrete show no trend, increasing or decreasing slightly.
- The modal chord length of the higher air content reference concrete, mixture 2A, is significantly greater than that of mixture 1A.
- The modal chord length of the void system is increased by an increase in slump, as follows:
  Mixture 1: 0.098 mm to 0.121 mm by water addition.
  0.098 mm to 0.121 mm by superplasticizer addition.
  Mixture 2: 0.144 mm to 0.161 mm by water addition.
  0.144 mm to 0.174 mm by superplasticizer addition.
- Although the modal chord lengths increase slightly in the high-slump non-superplasticized concretes, the proportion of the total air measured in the large void sizes decreases. Note the differences between the dotted line curves for mixture 1A in Fig. 4 and mixture 1B in Fig. 6. This occurs because the low-slump concrete, 1A, has a greater number of large voids.
- Modal chord lengths in concretes containing the superplasticizer are not significantly higher than in the high-slump reference concretes. The difference occurs in the zeroth-order log standard deviation, which increases significantly. This indicates a much broader distribution of air void sizes in the superplasticized concrete, but the most frequently occurring chord lengths remain nearly the same.

CONCLUSIONS

Since all the concretes tested in this work were frost resistant, including those containing the superplasticizer, our ability to draw firm conclusions from the air-void distribution data is limited. Work is continuing along these lines in other mixture proportions, to gain a better understanding of the relationship between modal chord length, air content, and durability. However, from this work we may conclude:

1. The superplasticizer did increase Power's spacing factor to the range where previous experience would predict poor resistance to frost.

2. Superplasticized concretes were found to be frost resistant.

3. We were able to show, using the fitted distribution functions, that one parameter of the air-void system is similar in the superplasticized and non-superplasticized concretes. This is the modal chord length. Lacking a failed specimen for comparison, we cannot say that this factor is a predictor of performance. We will be testing this hypothesis in future work.

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TABLE 1

Sieve Analysis of Fine Aggregate

Sieve Size	Individual % Retained	Cumulative % Retained
4.75 mm	1	1
2.36 mm	10	11
1.18 mm	15	26
600 μm	20	46
300 μm	30	76
150 μm	22	98
Pan	2	
Fineness Modulus		2.58

TABLE 2

Type I Cement Composition Information

Chemical Analysis*	%
Silicon Dioxide (SiO_2)	21.4
Aluminum Oxide (Al_2O_3)	3.97
Ferric Oxide (Fe_2O_3)	2.10
Calcium Oxide (CaO)	64.7
Magnesium Oxide (MgO)	2.12
Sulfur Trioxide (SO_3)	3.03
Alkali as Na_2O	0.61
Loss on Ignition	1.12
Insoluble Residue	0.11
Potential Compounds	**%**
Tricalcium Silicate (C_3S)	62
Dicalcium Silicate (C_2S)	15
Tricalcium Aluminate (C_3A)	7
Tetracalcium Aluminoferrite (C_4AF)	6

* Manufacturer's Data

TABLE 3

Example Air-Void System Characteristics

Calculated Paste Volume	26.6%
Total Length Traversed	2120 mm

	Voids<0.5 mm	Voids<1.0 mm	All Voids
Number	611	642	649
Percent of Total Number	94.14	98.92	100.0
Length Air Traveled (mm)	96.00	117.02	128.42
Percent of Total Air Traversed	74.8	91.1	100.0
Percent Hardened Air	4.53	5.52	6.05
Average Chord Length (mm)	0.1571	0.1823	0.1979
Paste/Air Ratio	5.87	4.82	4.39
Specific Surface (1/mm)	25.5	21.9	20.2
Voids/mm	0.288	0.303	0.306
Spacing Factor (mm)	0.1958	0.2075	0.2159