Factors Affecting Freezing-and-Thawing Resistance of Chert Gravel Concrete

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A three-part investigation was made of factors affecting the freezing-and-thawing resistance of concrete containing chert gravels. Principal variables were aggregate source, particle size, curing and moisture content of concrete, and cement factor. Test results were consistent with accepted concepts of the mechanism by which concrete is damaged from freezing and thawing. The data demonstrated that those concepts have important practical significance in securing best field performance from available materials.

The tests showed that (a) reduction in the size of the chert gravel improved the resistance of concrete to freezing and thawing; (b) partial drying of the concrete before exposure greatly improved its performance; (c) once partially dried, the concrete was not easily resaturated to the point of vulnerability to freezing damage; and (d) under some combinations of saturation and exposure, increasing cement content reduced the resistance of concrete to freezing and thawing.

• DURABILITY is a prime requisite of any concrete, but it is particularly critical in highway construction where maximum return is expected from the public investment. Good performance is needed not only from standpoints of safety and utility but also because of continual exposure to the critical scrutiny of the user. Shortcomings in quality of highway construction are likely to be disconcertingly apparent.

In most areas of the country, pavements and structures must be built to resist the destructive action of freezing and thawing. Past performance in this regard has not always been good, but much improvement has been made in recent years. Air entrainment provides a high degree of protection for the cement paste and mortar phases of the concrete (4, 7) but may not overcome the effects of larger aggregate particles which undergo volume changes on freezing (11). The mechanism by which concrete is damaged by freezing has become better understood, suggesting ways by which performance can be improved (5, 7, 10, 14). The materials of concrete have been evaluated in terms of their role in durability (2, 3, 6, 8), resulting in better prediction of performance and development of methods to improve borderline materials (11, 12, 13). Finally, it is being recognized that attainment of best performance will be achieved only when environmental effects are moderated to the extent practicable by proper design and protection of the structure (8, 9). The latter approach is exemplified by proper grade alignment and subgrade drainage to eliminate excessive saturation of pavements that will be exposed to freezing.

This paper does not offer new theory on the resistance of concrete to freezing and thawing. It describes researches intended to evaluate the effects on the performance of a specific type of aggregate attainable by applying already established concepts. The aggregate was chert gravel, which is available and widely used for concrete in large areas of the middle and southern Mississippi valley. Cherts and chert gravels have been extensively studied (1, 2, 6, 10, 15). It is known that their response to freezing depends

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on their pore structure, the size of particle, the rate of freezing, their degree of saturation, and the properties of the cement matrix in which they are imbedded. The researches reported here developed information on the degree to which controllable changes in some of these factors might be expected to affect the freezing-and-thawing resistance of the concrete.

SCOPE AND OBJECTIVE

Tests were made in the Joint Research Laboratory of the National Sand and Gravel Association and National Ready Mixed Concrete Association at the University of Maryland to investigate means of developing the best performance of chert gravels in concrete exposed to freezing and thawing. The investigation involved two chert gravels from different sources and of somewhat different physical characteristics, but both with long records of successful use as concrete aggregates. Their service performance has varied somewhat, apparently depending on conditions of exposure and other factors related to the production and treatment of the concrete.

The study was conducted in three phases. The first phase provided information on the relative effects of different size fractions of the chert gravel when used to replace corresponding fractions of an aggregate composed of nearly pure quartz. In the second phase, the effects of varying degrees of drying of the concrete, with and without resaturation, were investigated. In the third phase, the effects of several combinations of factors were measured: maximum size of the chert gravel, cement factor of the concrete, and two degrees of partial drying of the test specimens.

All variables in this program have been subjects of earlier researches. The studies have involved many different investigators and, in general, have not been coordinated to permit quantitative comparisons. This investigation was intended to tie together a number of loose ends. It offers encouraging evidence that the chert gravels can yield highly durable concrete if certain relatively simple precautions are observed.

EFFECTS OF PARTICLE SIZE

Description of Tests

To evaluate the relative influence of different particle sizes on concrete durability, chert gravel lot 3701 was used as the replacement for portions of a nearly pure quartz gravel of high quality, regularly used in the laboratory as a basis for comparison. The reference concrete contained the quartz gravel graded 25 percent each of 1 to ¾ in., ¾ to ½ in., ½ to ⅜ in., and ⅜ in. to No. 4. The chert gravel was successively used to replace the 50 percent of coarse aggregate between the ½ in. and No. 4 sizes, the 50 percent between 1 and ½ in., and finally the entire quantity of coarse aggregate. As in all portions of the investigation, the coarse aggregates were saturated under vacuum and soaked for 24 hr to simulate the most adverse condition likely to be encountered in the field. Physical properties of the chert gravel are discussed in the second phase.

The fine aggregate used throughout was a nearly pure silica bank sand from Branchville, Md., having a fineness modulus of approximately 2.7. The sand was thoroughly mixed and kept moist for 24 hr before incorporation in the concrete. Cement was a laboratory stock blend of 5 brands purchased locally.

All concrete was designed to contain 6 sacks of cement per cu yd with a slump of 3 to 4 in. and an air content of approximately 5 percent, secured by use of neutralized Vinsol resin added at the time of mixing. Aggregate proportions were selected on the basis of ACI Recommended Practice 613 to produce a degree of workability suitable for placement conditions in typical structures.

The concrete was mixed by hand in 0.25-cu ft batches. Slump was measured and air content determined gravimetrically from the unit weight measured in a 0.20-cu ft container. Two 3- by 4- by 16-in. beams were molded from each batch for the freezing-and-thawing tests. Three batches were made on different days for each of the four types of concrete.

To supplement information on the effects of degree of saturation secured in other portions of the investigation, the two specimens from each batch were subjected to different curing conditions. After remaining in the molds in the standard moist room for

TABLE 1

EFFECT OF SIZE OF CHERT GRAVEL ON FREEZING-AND-THAWING RESISTANCE OF CONCRETE

Gravel (%)		Mixing Day	Cement (sacks/ cu yd)	Water (gal/ cu yd)	Slump (in.)	Air (grav.) (%)	Unit Weight (pcf)	Freezing-and-Thawing Tests			
								Cycles to 50% E		Dur. Fac., 100 Cyl.	
Quartz	Chert							Curing A[a]	Curing B[b]	Curing A[a]	Curing B[b]
100	---	B	5.88	33.6	3.4	5.8	141.3	+500[c]	+500[c]	96	90
		C	5.90	33.6	3.5	5.6	141.5	+500[c]	+500[c]	95	91
		D	5.91	33.7	3.6	5.3	142.0	+500[c]	+500[c]	96	90
		Avg.	5.90	33.6	3.5	5.6	141.6	+500[c]	+500[c]	96	90
50[d]	50[e]	A	5.89	33.6	2.9	5.7	140.0	426	+500[c]	87	91
		B	5.96	34.6	3.0	4.2	141.9	453	+500[c]	87	90
		C	5.84	34.1	3.9	6.1	138.9	465	+500[c]	90	91
		Avg.	5.90	34.1	3.3	5.3	140.3	448	+500[c]	88	91
50[e]	50[d]	A	5.89	32.9	2.6	6.0	139.9	255	+500	75	92
		B	5.91	34.1	3.2	5.2	140.7	158	+500	63	91
		C	5.88	34.1	3.9	5.7	139.8	137	+500	58	92
		Avg.	5.89	33.7	3.2	5.6	140.1	183	+500	65	92
---	100	A	5.85	34.0	3.8	5.9	138.0	40	205	20	73
		B	5.93	33.6	3.1	4.6	139.8	50	160	25	72
		C	5.89	34.4	3.9	5.3	138.9	64	172	32	79
		Avg.	5.89	34.0	3.6	5.3	139.2	51	179	26	75

[a] 7 days in moist room and saturated limewater + 4 days in 70 F air at about 50% relative humidity + 3 days re-immersed in saturated limewater.
[b] 7 days in moist room and saturated limewater + 7 days in 70 F air at about 50% relative humidity.
[c] Specimens survived over 500 cycles before tests were discontinued to make equipment space available.
[d] 1- to ½-in. sizes.
[e] ½-in. to No. 4 sizes.

the first 24 hr, all beams were stripped and immersed in saturated limewater at 73 F to the age of 7 days. Thereafter, one from each batch was cured in air at 70 F and approximately 50 percent relative humidity for 4 days followed by re-immersion in limewater for 3 days before exposure to freezing and thawing; the second specimen from each batch was cured in the 70 F air for 7 days and exposed to freezing and thawing without resoaking.

At the age of 14 days, all specimens were subjected to freezing and thawing in accordance with ASTM Designation C 291-61T, "Tentative Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water." That exposure consisted of alternate freezing in air at 0 F and thawing in water at 40 F at the rate of approximately 7 complete cycles per day. Deterioration was evaluated by the nondestructive test for dynamic modulus of elasticity (ASTM Designation C 215). Exposure of a specimen was continued until its dynamic modulus had been reduced 50 percent or until it had been exposed to at least 500 cycles, whichever occurred first.

Results

Characteristics of the concrete and results of the freezing-and-thawing tests are given in Table 1. It is apparent that the four types of concrete were essentially the same in their basic characteristics of cement factor, water content, slump, and air content. Hence, they should provide a valid indication of the effects of substituting the different sizes of chert for the nearly nondestructible quartz gravel.

For specimens partially dried but resoaked before exposure, the 50 percent substitution of chert for the 1- to ½-in. sizes of quartz reduced freezing-and-thawing resistance much more than did substitution for the ½ in. to No. 4 sizes. With chert used for the smaller size, the concrete performed excellently, withstanding an average of 448 cycles of freezing and thawing. When the larger, 1- to ½-in. sizes of chert were substituted, resistance was reduced to 183 cycles, a poorer but still creditable performance. In these resaturated concretes, use of the chert gravel as the entire coarse

aggregate resulted in the concrete's withstanding only 51 cycles under the severe conditions of aggregate treatment and exposure employed.

When the concrete was allowed to air dry for a full 7 days and was not resoaked immediately before freezing, good performance was secured from all combinations. Specimens in which chert comprised 50 percent of the coarse aggregate in either the smaller or larger size range withstood over 500 cycles of exposure. The concrete with 100 percent chert gravel survived an average of 179 cycles.

The data from this portion of the investigation provide two clear-cut indications. First, the smaller sizes of chert gravel are much less susceptible to the disruptive effects of freezing than are larger sizes. Second, resistance of the concrete is greatly enhanced if it has an opportunity to dry partially before being frozen. Both of these findings are consistent with, and merely confirm, accepted concepts (5, 7, 14).

EFFECTS OF CONCRETE MOISTURE CONDITION

Description of Tests

To study in more detail the magnitude of moisture effects, comparative tests were made using two chert gravels: lot 3701, the same as in the first series, and lot 3691 from a second source. General procedures for grading and treatment of the aggregates and proportioning of the concrete were the same as in the first phase with limited exceptions. Instead of being mixed by hand, the concrete was mixed for 6 min in 1.1-cu ft batches in a small tilting mixer. Slump was measured and air content determined gravimetrically using a 0.50-cu ft container. Nine 3- by 4- by 16-in. beams were molded from each batch to be subjected to 9 different sequences of curing, partial drying, and resaturation. Two batches were mixed on different days with each of the two sources of chert gravel.

All specimens remained in the molds in the standard moist room for the first 24 hr, after which they were stripped and immersed in limewater at 73 F to the age of 28 days. They were then placed in an atmosphere of 70 F air at approximately 50 percent relative humidity and treated as follows before exposure to freezing and thawing: air dried for four different periods—3, 7, 14, and 28 days—and then immediately subjected to freezing and thawing; air dried for 28 days and then resoaked for five different periods in 73 F limewater—3, 7, 14, 28, and 91 days—before exposure. The treatment combinations can be more clearly visualized from Table 2.

Results

Characteristics of the fresh concrete are given in Table 3. The two batches made with each aggregate were very similar in basic characteristics but, for purposes of the present discussion, that is not critical because the principal comparisons are among pre-exposure curing treatments represented within each batch. The freezing-and-thawing test data are given in Table 2, and pertinent relationships bearing on their significance are shown in Figures 1 through 5.

Figures 1 and 2 show specific gravity and absorption characteristics of the two chert gravels. The curves in Figure 1 indicate rate of absorption in terms of both percentage by weight of the gravel and percentage of the amount of water absorbed under vacuum saturation. Absorption of lot 3691 chert was considerably higher than that of lot 3701. However, the difference appeared to consist of the larger pores which filled with water quickly. After about the first hour, the rate of absorption was essentially the same for the two materials. Also, as shown by the upper curves in Figure 1, the relative absorption (roughly corresponding to the degree of saturation) was similarly related to time for both aggregates.

Figure 2 shows the specific gravity distribution of the two cherts, based on sink-float separations of the vacuum-saturated aggregates in heavy liquids of varying density. Lot 3701 had considerably fewer particles in the low specific gravity range than lot 3691. For example, the latter contained approximately 35 percent of particles lighter than 2.4, as compared with only about 5 percent for the former. These relationships are consistent with the bulk specific gravity and absorption data shown in Figure 1.

TABLE 2

FREEZING-AND-THAWING TESTS OF CONCRETE

Subsequent Treatment[a] (days)		Age at Start of F-T (days)	Coarse Aggregate Lot 3691							Coarse Aggregate Lot 3701							
			Weight Loss[b] (g)			Saturation at F-T Start (%)	Cycles of F-T to 50% E	Durability Factor		Weight Loss[b] (g)			Saturation at F-T Start (%)	Cycles of F-T to 50% E	Durability Factor	
At +70 F, 50% Rel. Hum.	At +70 F, in Limewater		From 28 Days to F-T Start	From F-T Start to Oven Dry	Total			At 100 Cycles	At 200 Cycles	From 28 Days to F-T Start	From F-T Start to Oven Dry	Total			At 100 Cycles	At 200 Cycles
3	0	31	114	488	602	81	6	3	2	105	420	525	80	21	10	5
7	0	35	164	429	592	72	12	6	3	147	370	517	72	110	52	28
14	0	42	215	362	577	63	22	98	57	182	316	498	64	343	101	84
28	0	56	262	324	586	55	+700[c]	102	101	218	296	514	58	578	100	95
	3	59	139	448	587	76	+700[c]	100	100	92	424	516	82	612	98	94
	7	63	116	462	578	80	+700[c]	100	99	76	424	500	85	466	94	85
	14	70	107	481	588	82	647	98	99	68	436	504	87	348	92	74
	28	84	92	488	580	84	385	94	74	60	444	504	88	262	78	58
	91	147	68	514	582	88	50	25	13	42	459	501	92	176	60	44

[a] After all specimens (3- by 4- by 16-in. beams) cured 28 days in saturated limewater.
[b] Average difference between weight of beams (having approximately 3, 150-cc volume) at 28 days and at indicated condition.
[c] Specimens survived more than 700 cycles.

TABLE 3

CHARACTERISTICS OF FRESH CONCRETE

Lot No. C.A.	Mixing Day	Cement (sacks/ cu yd)	Water (gal/ cu yd)	Slump (in.)	Air (grav.) (%)	Sand (% tot. agg.)	b/bo	Unit Weight (pcf)
3691	C	6.01	33.7	2.6	4.0	36.9	0.687	138.8
	D	5.96	34.6	2.8	4.2	36.9	0.681	138.0
	Avg.	5.98	34.2	2.7	4.1	36.9	0.684	138.4
3701	C	5.91	34.6	5.0	5.3	36.5	0.681	138.7
	D	6.00	34.5	3.2	4.2	36.5	0.691	140.5
	Avg.	5.96	34.6	4.1	4.8	36.5	0.686	139.6

Figures 1 and 2 show that the lot 3691 chert has a higher capacity for absorbing water and might be expected, therefore, to be more vulnerable than lot 3701 to freezing under highly saturated conditions. The evidence also suggests, however, that water might be expected to move more readily into and out of the pores of the former. Under certain circumstances, this might benefit the resistance to freezing for either or both of two reasons (10, 14):

1. By permitting water to escape from the aggregate, and hence reduce its degree of saturation whenever the concrete has an opportunity to dry; and
2. By facilitating the movement of water through the aggregate pores during freezing, thus reducing the likelihood of disruptive pressures developing.

Principal indications from the freezing-and-thawing tests of concrete can be seen directly from the test results in Table 3. Effects of the various drying and resaturation treatments were similar for the two gravels. When the concrete, which had been kept saturated for 28 days, was allowed to dry for only 3 days, and hence could be expected to remain highly saturated on the interior, it was destroyed in a very few cycles of freezing and thawing. As the drying period was increased, resistance improved until, after 28 days of drying, the concretes were highly durable. Resoaking for 3 days after the 28-day air-drying was not harmful, but continuation of soaking thereafter progressively reduced freezing-and-thawing resistance. However, even after 28 days of reimmersion the concretes remained highly durable, withstanding 385 cycles in the case of lot 3691, and 262 cycles for lot 3701. After 91 days of resoaking, the concrete with lot 3691 withstood only 50 cycles of freezing and thawing, but that with lot 3701 was still capable of withstanding 176 cycles, a commendable performance.

Careful records were kept of the weight changes of all specimens during curing and testing. When freezing and thawing were terminated on any specimen, it was oven dried to constant weight at approximately 225 F to provide a reasonably fixed reference for moisture conditions at other stages. The first line in each portion of Table 3 indicates the amount of water lost from a specimen between 28 days, when it was at its most highly saturated condition, and the beginning of freezing and thawing. The second line shows weight loss between the start of freezing and thawing and the oven dry condition after exposure. Thus, for the first curing condition of concrete with lot 3691, the average weight of specimens at the start of freezing and thawing was 114 g less than the 28-day weight and 488 g more than the oven dry weight. The total weight difference between 28 days and the oven dry condition was 114 plus 488 or 602 g. This sum remains reasonably constant for either gravel regardless of curing treatment of the concrete. Further, the average difference between these sums for the two gravels (77 g) is only slightly less than the difference between the vacuum-saturated absorptions of the two gravels in the amount contained in a test specimen.

Figures 3, 4, and 5 show some of the factors involved in freezing resistance of the chert gravel concretes. Figure 3 shows moisture changes of concretes during the vari-

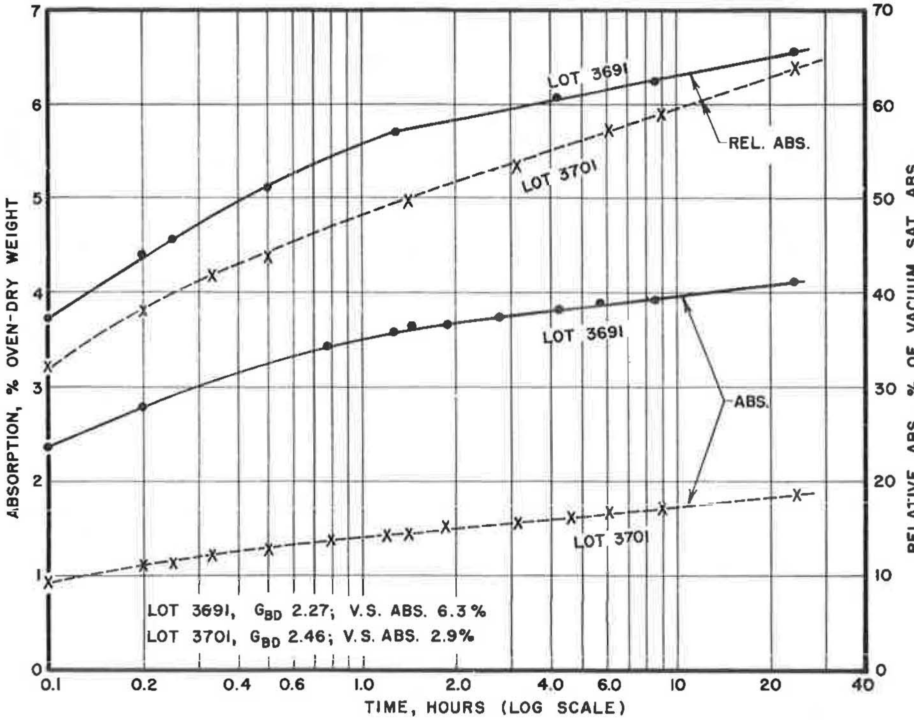

Figure 1. Absorption characteristics of chert gravels.

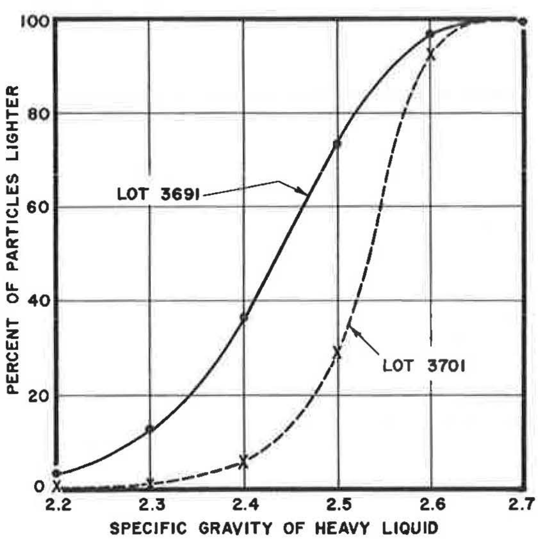

Figure 2. Specific gravity distribution of chert gravels.

ous curing treatments. As already mentioned, until the end of the initial 28-day immersion period, the difference in moisture content between concretes with the two gravels was about equal to the difference in water absorbed by the aggregates. As the concrete was dried after 28 days, more water was lost from the concrete with lot 3691 as evidenced by the reducea difference in weight. On resoaking, even after 3 months, the differential in aggregate water content was never completely restored. Without regard to what this might mean in terms of comparisons between the two gravels, it strongly suggests that the cherts are not easily resaturated once they have an opportunity to dry out reasonably well.

Support for the latter hypothesis, as well as evidence of its potential significance, is shown in Figure 4. Here, the moisture change data have been plotted in relation to the 28-day weights, when the concretes were most completely saturated. The number of cycles of freezing and thawing withstood by the various specimens has been shown at points on the curve corresponding to the times when they were removed from curing to be subjected to freezing and thawing.

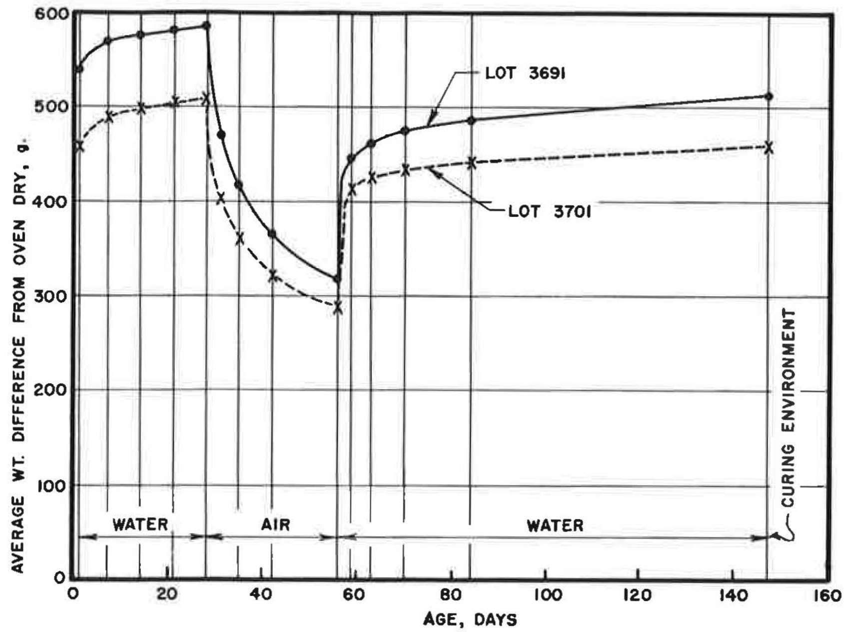

Figure 3. Moisture changes during curing of concretes with chert gravels.

With either aggregate, as already discussed, resistance increased greatly as the specimens were progressively dried for longer periods. The important indication, however, is that this improvement in performance was not forfeited by resaturation even when total saturation exceeded levels at which resistance had been very poor for specimens never previously dried. For example, specimens with lot 3701 chert, resoaked for 14 days after drying, had been restored to within less than 55 g of their 28-day weight but withstood 348 cycles of freezing and thawing. Less saturated companion specimens, which had been dried to a point more than 90 g below their 28-day weight, withstood only 21 cycles. The differences are even more remarkable with lot 3691, for which the resistance of partially dried specimens was poorer. As already pointed out, even after 3 months of resoaking when the concrete had been restored to a high degree of overall saturation, the lot 3701 concrete gave a good account of itself, withstanding 176 cycles of freezing and thawing.

The relationships just discussed are shown in somewhat different form in Figure 5. Here, saturation has been expressed as a percentage of the maximum moisture content (at 28 days), and resistance to freezing and thawing in terms of durability factor as defined in ASTM Designation C 291. The progress of drying and resoaking is indicated by arrowheads on the curves. The considerable displacement of the resoaking portion of the curve toward the higher percentages of saturation demonstrates the lasting benefit of the drying period. At anything above about 65 percent of saturation, the concretes that had not been previously dried performed poorly. On resaturation after drying, the concrete could tolerate 80 percent saturation or more and still give good performance. It appears that, during the initial drying, water tends to remain in the aggregate particles where it causes disruptive expansion, on freezing. Once dried, however, the particles reabsorb water reluctantly. In the resoaked concrete, a greater proportion of the total absorbed water is in the cement paste where it is prevented by the entrained air from causing damage.

In summary, this phase of the investigation illustrates a simple but most important requirement for the assurance of successful performance from the chert gravel concretes. If opportunity is provided for the concrete to lose excess moisture before being frozen, supplemented by reasonable efforts to prevent excessive resaturation disruption from freezing can almost certainly be avoided.

TABLE 4

EFFECTS OF SIZE, SOURCE OF CHERT, CEMENT FACTOR, AND CURING ON CONCRETE DURABILITY

Lot No.	Max. Size (in.)	Cement Factor (sacks)	Sand (%)	b/bo	Batch Ref. No.	Cement (sacks/ cu yd)	Water (gal/ cu yd)	Slump (in.)	Air (grav.) (%)	Unit Weight (pcf)	Freezing-and-Thawing Tests: Cycles to 50% E, Curing A[a]	Freezing-and-Thawing Tests: Cycles to 50% E, Curing B[b]	Freezing-and-Thawing Tests: Dur. Fac., 100 Cyl., Curing A[a]	Freezing-and-Thawing Tests: Dur. Fac., 100 Cyl., Curing B[b]
3691	1	5.0	38.9	0.686	1C5	5.10	31.2	3.0	5.0	137.5	27	251	14	97
					1D5	5.12	31.2	2.6	4.5	138.2	18	420	9	92
					Avg.	5.11	31.2	2.8	4.8	137.8	22	336	11	94
		7.0	35.1	0.682	1C7	7.11	34.7	3.3	4.0	138.6	8	121	4	63
					1D7	7.10	34.9	3.1	3.9	138.6	17	41	8	20
					Avg.	7.10	34.8	3.2	4.0	138.6	12	81	6	42
	½	5.0	54.3	0.500	2C5	4.99	38.8	3.9	5.8	133.9	83	865[c]	42	89
					2D5	5.00	38.5	4.3	5.6	134.3	130	+1,200[c]	55	99
					Avg.	5.00	38.6	4.1	5.7	134.1	106	+1,030[c]	48	94
		7.0	51.4	0.507	2C7	7.09	39.3	3.2	4.9	136.4	77	+1,200[c]	39	94
					2D7	7.09	39.5	4.1	4.7	136.6	42	590[c]	21	101
					Avg.	7.09	39.4	3.6	4.8	136.5	60	+900[c]	30	98
3701	1	5.0	39.4	0.674	3C5	5.01	32.9	2.7	5.4	138.9	58	163	29	70
					3D5	5.03	33.1	4.0	5.1	139.2	76	420	38	87
					Avg.	5.02	33.0	3.4	5.2	139.0	67	292	34	78
		7.0	35.5	0.668	3C7	6.97	35.8	3.6	5.0	139.1	61	178	30	82
					3D7	6.97	36.9	4.3	5.1	139.1	64	174	32	73
					Avg.	6.97	36.4	4.0	5.0	139.1	62	176	31	78
	½	5.0	54.4	0.500	4C5	5.00	38.8	2.8	5.1	136.9	745[c]	1,200[c]	78	89
					4D5	4.99	39.8	3.1	5.2	136.7	625[c]	900[c]	77	91
					Avg.	5.00	39.3	3.0	5.2	136.8	+685[c]	1,050[c]	78	90
		7.0	51.2	0.502	4B7	7.03	40.4	3.6	4.7	137.9	207	940[c]	77	95
					4C7	7.00	40.0	4.2	5.2	137.3	244	530[c]	70	93
					Avg.	7.02	40.2	3.9	5.0	137.6	226	735[c]	74	94

[a] 7 days in moist room and saturated limewater + 4 days in 70 F air at about 50% relative humidity + 3 days re-immersed in saturated limewater.
[b] 7 days in moist room and saturated limewater + 7 days in 70 F air at about 50% relative humidity.
[c] Extrapolated values; specimens removed after surviving 500 cycles.

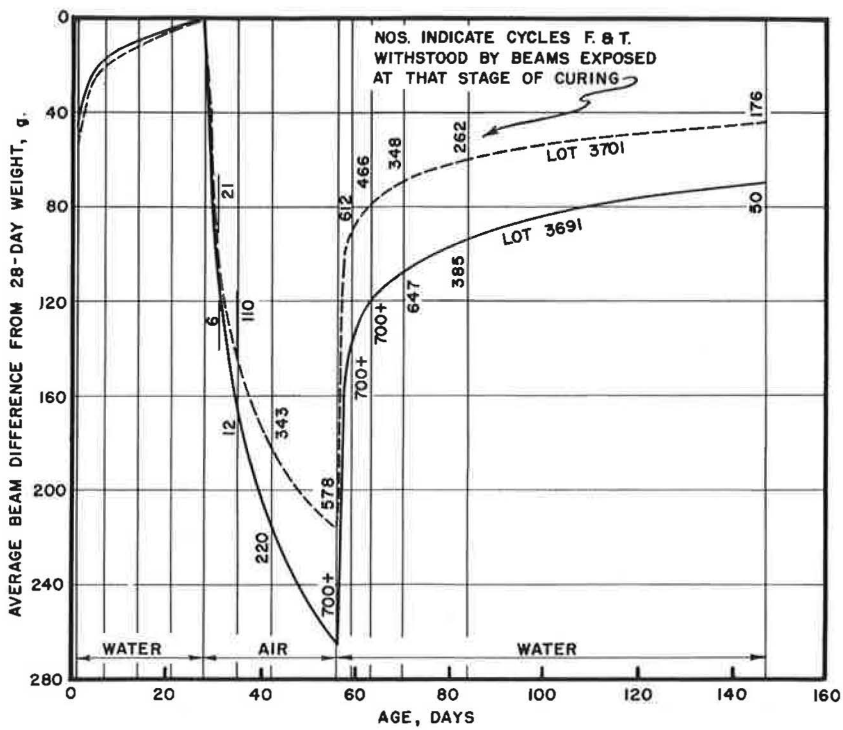

Figure 4. Relation of durability of concrete to moisture content.

EFFECTS OF MAXIMUM AGGREGATE SIZE AND CEMENT FACTOR

Description of Tests

To develop more quantitative information on the improvement in durability caused by using smaller sizes of the chert gravel, comparisons were made between concretes containing the two chert gravels graded to both 1- and ½-in. maximum sizes. For each combination of size and source, cement factors of 5 and 7 sacks per cu yd were employed, making a total of 8 conditions.

Two batches of each kind of concrete were mixed by hand on different days, and beams were molded for freezing-and-thawing exposure after two sequences of curing:

1. To age 7 days immersed in 73 F limewater, followed by 4 days in air at 70 F and approximately 50 percent relative humidity, and 3 days re-immersed in limewater; and
2. To age 7 days in limewater, followed by 7 days in the 70 F air without re-immersion.

These curing conditions, as well as other procedures for preparation of the aggregates, and mixing, molding and testing of concrete, were the same as described for the first group of tests.

Results

Results of the tests are given in Table 4. With one exception, comparability of concrete characteristics among the several conditions was closely maintained. The exception was the 7-sack mixture with the 1-in. maximum size of lot 3691, in which the air content dropped to only about 4 percent compared with 5 percent or slightly higher for the other conditions. This may account for the poor performance of this combination, which is somewhat out of line with the others.

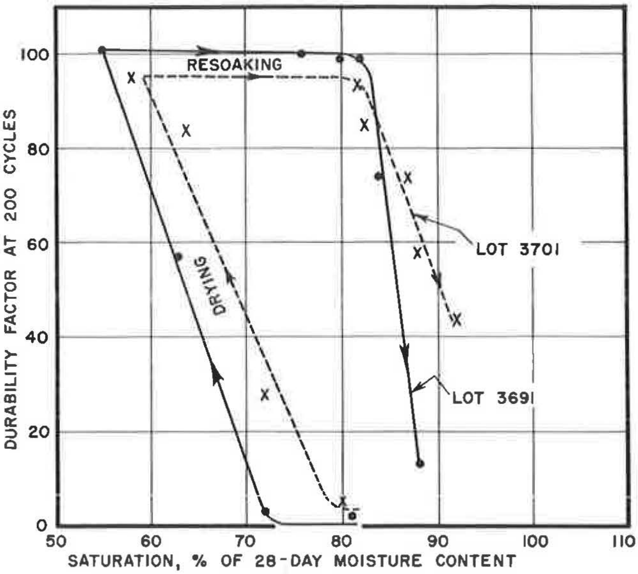

Figure 5. Effects of drying and resaturation on durability of chert gravel concrete.

The data permit several comparisons among the different test conditions. As in other portions of the study, increasing the period of drying before exposure greatly improved the concrete's resistance to freezing and thawing. In fact, except for the low-air-content concrete previously mentioned, all specimens air dried for 7 days before freezing gave a satisfactory to excellent account of themselves.

For otherwise comparable conditions, without exception, concrete with the ½-in. maximum size gravel was much more durable than that with 1-in. maximum. This was true regardless of gravel source, cement factor or curing treatment. In most cases, the number of cycles which the concrete withstood was multiplied several times by lowering the maximum size to ½ in.

The data indicate the 5-sack concretes to have been more durable than the 7-sack, although the difference may not actually be as pronounced as the numbers in the table suggest. There was a slight tendency for the richer mixtures to contain less air but, even though this could account for some of the difference in durability, it appears too small to be a major factor. The data suggest other probable explanations for the seemingly anomalous behavior. First, Table 4 shows that mixing water requirements for the richer concretes were consistently higher than for the leaner mixtures. Although this additional water would tend to be immobilized by reaction with the greater quantity of cement over a long period, it seems probable that, for the relatively short curing used in these tests, there may have been more freezable water in the richer mixes at the time exposure was started.

At least one additional factor probably contributed to the lower durability of the rich mixes. Their lower water-cement ratio would produce a less permeable mortar, tending to retard the loss of freezable water during the interludes of drying. That this actually occurred can be demonstrated from weight measurements made during the curing treatment. For comparable concretes, the net loss of water between 7 days, when the concretes were at their highest saturation, and the beginning of freezing and thawing was always less for the rich than for the lean mixtures. Thus, when exposure to freezing and thawing was started, the richer concretes contained more total water and almost surely more freezable water than the leaner ones. This higher water content coupled with the higher resistance to movement of the water in the richer, less permeable paste, would result in higher disruptive stresses, on freezing.

Comparative performance of the two chert gravels appears reasonably consistent

with indications from other portions of the investigation. For specimens resoaked before exposure, the lot 3701 chert produced better resistance than lot 3691. With more thorough drying of the concrete, the performance of both gravels was greatly improved and about equal.

SUMMARY

These investigations provided quantitative information verifying a number of concepts concerning the freezing-and-thawing resistance of concretes made with chert gravel:

1. The relative performance of the chert gravels in relation to other aggregates is likely to be distorted by laboratory tests made on highly saturated concretes containing highly saturated aggregate. The pore structure of the cherts is such that they are highly vulnerable under these conditions. Because concrete in actual practice will almost never be so highly saturated when exposed to freezing, laboratory treatment should logically include a realistic respite from continuous saturation.
2. A moderate amount of drying of the concrete before exposure to freezing and thawing greatly enhances the performance of the chert gravels.
3. Once the concrete has had a reasonable opportunity to dry, its immunity to freezing damage is retained in large measure even after extended resoaking. In these tests, the concrete could tolerate much higher total moisture contents induced by resoaking than were sufficient to cause rapid failure before the concrete had had an opportunity ever to lose the original water.
4. Reducing the maximum size of the chert gravel improves resistance of the concrete to freezing and thawing.
5. Rich concretes will not necessarily be more resistant to freezing and thawing than leaner ones, but relative performance will almost certainly be affected by curing condition and age. The richer cement paste tends to require more mixing water, retard the loss of freezable water due to evaporation, and, by resisting movement of water, increase the stresses developed by freezing. All these factors reduce durability but tend to be offset or overcome by the increased strength of the richer paste or immobilization of the water by chemical combination with the extra cement during long periods of hydration.

Considered in the light of the established service records of many chert gravels, these studies provide encouraging evidence that, for most exposures and with judicious application of normal precautions in removing and excluding water from the concrete, these gravels can be expected to perform well in concrete exposed to freezing and thawing.

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