CONCRETE CASE STUDY No. 20

DELAYED EXPANSION OF CONCRETE DELIVERED BY PUMPING THROUGH ALUMINUM PIPELINE

by

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VIRGINIA HIGHWAY RESEARCH COUNCIL

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(A Cooperative Organization Sponsored Jointly by the Virginia
Department of Highways and the University of Virginia)

Charlottesville, Virginia

October 1969

Revised and Reprinted March 1970

CAUTION

This report documents a detrimental reaction between concrete and an aluminum pipeline through which it was pumped. This should not be construed in any way as suggesting that a similar reaction occurs when concrete is pumped through conduits of other materials, nor should it be extrapolated to suggest detrimental behavior of aluminum when used either attached to or embedded in concrete.

ACKNOWLEDGEMENTS

The nature of this study required the cooperation of numerous individuals, both within and outside of the Department. The data were analyzed, interpreted and a report prepared by the Research Council. The Construction Division arranged and coordinated the special demonstration and Materials personnel from both the Central Office and Field conducted much of the testing.

The Ready Mixed Concrete supplier, a cement company, and the pumping contractor donated materials, equipment, and/or labor for the special demonstration.

The cooperation of all participants is gratefully acknowledged.

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PURPOSE

On May 9, 1969 the Virginia Department of Highways modified its specifications to allow the delivery of concrete by pumping with the following restriction:

> Pumping of concrete may be approved provided the concrete is pumped through a conduit system other than aluminum.

The purpose of this report is to present the experiences upon which this restriction was based to serve as a caution to others contemplating use of this method of delivery. While local variations in conditions and materials may influence the degree of adverse reaction, the experiences and observations presented here suggest that these variations are subordinate to the main phenomenon; namely, the reaction of the freshly mixed concrete with the aluminum pipeline.

BACKGROUND

The delivery of concrete by pumping through pipelines began in the United States with the issuance of a patent for a pump in 1913 (Weber — 1963). The process has undergone a cyclic development since that time, and there was a comparatively rapid advance in the late fifties with an increased appreciation of the factors affecting the "pumpability" of mixes. Pumping now has come to be more widely used as a result of the development of equipment that can deliver relatively stiff mixes at acceptable rates.

Since its inception, pumping has been used with 5 - 6 inch lines in mass concrete work. The sixties saw widespread acceptance of 4 inch lines, particularly for structural concrete. Trade and technical publications indicate that the technology for pumping normal weight concrete with dense aggregate is established. Thus in recent years research and development has focused on delivery of lightweight concrete, which presents different and more troublesome problems (Wilson — 1967).

Until recently, pumping was used very infrequently in the construction of highway structures. While there was no single reason for this infrequent use, the following factors exercised at least some retarding influence:

1. Most structures included pours of modest size that were readily accessible to conventional modes of delivery.
2. Hand screeding and finishing techniques discouraged use of equipment with high delivery rates.
3. The requirements for low slump mixtures with low sand contents and modest cement contents also discouraged pumping.

However, new developments in placing bridge deck concrete, such as machine screeding and larger continuous pours, coupled with more daring designs with longer, higher and generally less accessible spans, place a premium on rapid delivery and have kindled interest in use of rapid delivery equipment such as pumps and conveyors. The Virginia Department of Highways specifications for bridge decks require machine screeding, which in turn demands high delivery rates. Thus the request from a contractor that he be allowed to deliver concrete by pumpline on two interstate bridges containing 22 spans varying in length between 87 and 136 feet was well received. An additional consideration prompting his request was the anticipated speedup of construction that would result from the ability to deliver by pumpline across previously placed slabs at an earlier time than would be governed by strength development in those slabs sufficient to support trucks, cranes, or other types of placing equipment.

Because this was the first significant use of pumping by the Department, tests were conducted on the concrete before and after pumping. During placement, a delayed expansion occurred that severely reduced strength. The cause was ultimately shown to be a reaction between the concrete and the aluminum delivery line.

This report presents the results of observations and tests made on the deck concrete, along with those from a subsequent special field trial using both aluminum and steel lines to deliver several mixtures of widely varying materials and properties that confirmed the role of the aluminum in the detrimental expansion. Data obtained during the deck placement are given separately from those derived from the special demonstration. Both sets of observations serve as the basis for discussion of the implications of the findings.

DECK PLACEMENT

Even though an eighty-seven foot end slab was the first span to be placed, the contractor elected to pump over a distance of approximately 400 feet in order to demonstrate the feasibility of placement in the most remote span. Several minor difficulties developed during the start-up, and they resulted in the accumulation of several trucks on the job. One load was rejected for excessive mixing time, and rather than risk further rejection the contractor elected to place concrete from five trucks by crane buckets. The pumpline was shortened to 200 feet and the remaining 72 cubic yards (9 trucks) were satisfactorily pumped. Thus about one-third of the deck was placed from buckets, while the remaining two-thirds were pumped. A general view of the construction area and equipment is shown in Figure 1.

The pump was a modern high volume piston pump rated to delivery 60 to 80 cy./hr. A 4 inch aluminum line (subsequently identified as alloy 6061 — Schedule 40) was used in 10 twenty-foot sections.

Figure 1. General view of construction area and quipment.

Slump, air content, and mixture temperature were determined for each of four truckloads before and after pumping. At the truck and at the discharge end of the pipeline, two cylinders were made for each batch for compressive strength determinations. Approximately 45 minutes after the first cylinders were fabricated, expansion was observed as shown in Figure 2. Expansion was simultaneously evident in the deck, which was being screeded with a longitudinal mechanical screed. This expansion is shown in Figure 3. As it became apparent that all of the concrete in the deck and cylinders was expanding, various explanations were suggested and it was ultimately concluded that a reaction with the aluminum line was the most plausible explanation.

Figure 2. Cylinders approximately 45 minutes after pumping through aluminum pipe. Expansion is approximately .4 inch.

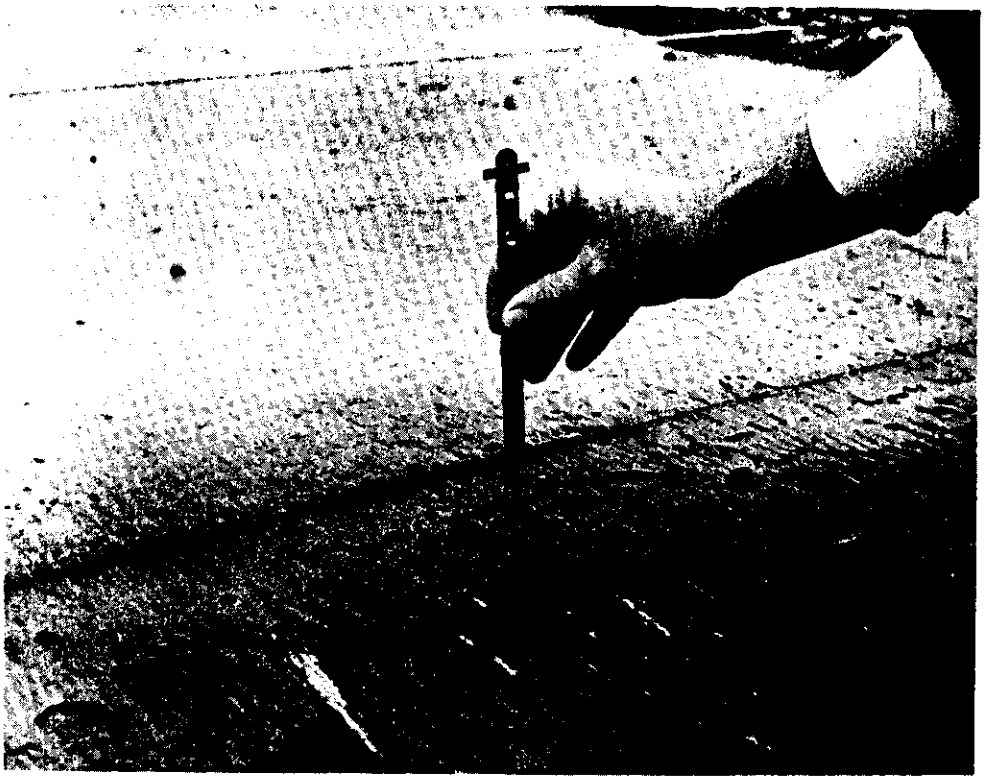


Figure 3. Evidence of expansion at end of deck slab.

Test Results

Concrete Properties

The significant characteristics of the freshly mixed concrete are given in Table I, along with the compressive strength data.

The significant observations are: (1) the reduction in strengths of approximately 50%, (2) the modest increase in air content that occurred during pumping, and (3) the increase of slump in loads three and four.

When it was evident that the cylinder strengths of the pumped concrete were low, eight cores were removed from the slab; four from areas into which concrete had been pumped and four from those placed with the crane bucket. One core from the pumped concrete and one from that placed by bucket were examined petrographically and the remaining six were tested for compressive strength at an age of 41 days. These strength results, along with those previously given for the cylinders cast during construction, are given in Table II.

The agreement between the results from cores and those from cylinders is excellent. Another significant point from these data is the reduction in unit weight of approximately 5%, which is consistent with the strength reductions.

TABLE I

SLUMP, AIR CONTENT, MIX TEMPERATURE AND COMPRESSIVE STRENGTH BEFORE AND AFTER PUMPING OF BATCHES USED IN DECK PLACEMENT

Load	Slump, inches		Air Content, %		Mix Temperature, °F		14-Day Compressive Strength, psi		Reduction %
	Before	After	Before	After	Before	After	Before	After	
(6)	4	2-3/4	6.4	6.6	72	72	4775	1700	-64.5
(7)	3-3/4	3-1/4	6.4	7.8	73	73	3997	2120	-47.0
(11)	3	5	5.8	7.2	75	75	3943	2280	-42.2
(14)	4	5-5/8	6.4	8.0	70	70	4279	2110	-50.7
Specified	(3 ± 1)		(6.5 ± 1.5)		90		3400*		

*Based upon 85% of anticipated 28-day strength for 4000 psi.

TABLE II

CORE STRENGTHS AND UNIT WEIGHTS FROM PUMPED AND PLACED AREAS OF DECK SLAB

Mode of Placement	Cast Cylinders	Cores	
	Compressive Strength, psi 14 Days	Compressive Strength, psi 41 Days	Unit Weight pcf
Crane Bucket	4780	3820	147.3
	3940	4440	146.6
	4280	4500	151.6
Avg.	4333	4253	148.5
Pumped	1700	2050	140.4
	2280	2060	139.8
	2110	2910	141.6
Avg.	2030	2340	140.6

Petrographic Features

The major objective of the petrographic examination was the determination of the characteristics of the void system in accordance with ASTM C 457. Determinations were made on horizontal surfaces taken from the upper, middle, and lower portions of the specimens. The average void contents from these measurements are given in Table III-a, along with strengths and unit weights. The detailed data are given in Table III-b. Photographs of concrete surfaces showing typical void systems are shown in Figure 4.

TABLE III

AIR VOID CHARACTERISTICS, STRENGTHS AND UNIT WEIGHTS FROM PUMPED AND PLACED AREAS OF DECK SLAB

(a) Summary

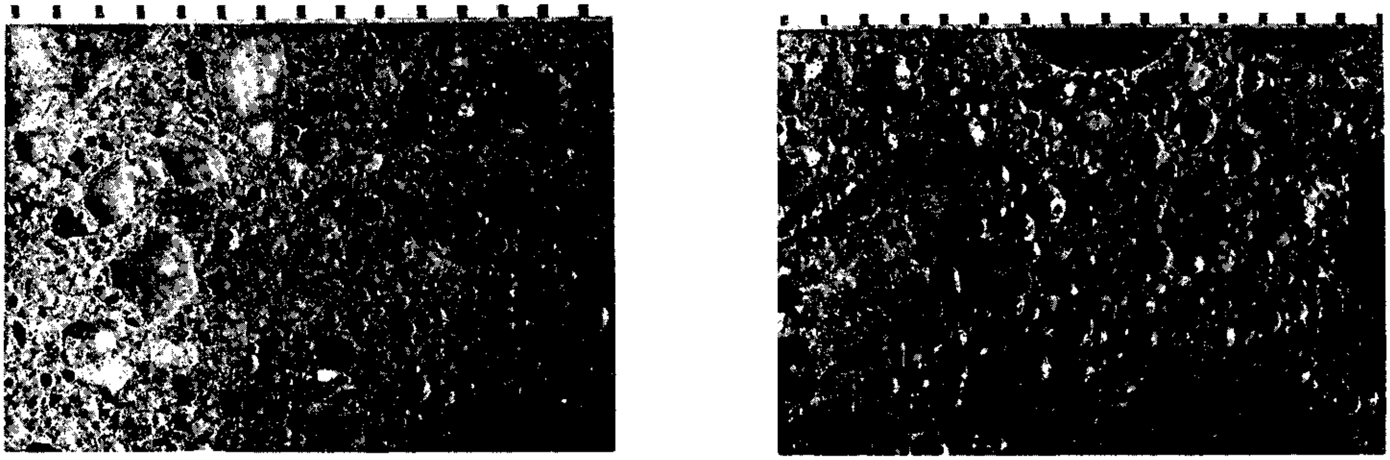
Sample	14 Day Compressive Strength, psi	Total Void Content, %	Unit Weight, pcf
Cylinders:			
Pumped	2052	11.6	--
Truck	4249	7.7	--
Cores:			
Pumped	2340	14.7	140.6
Placed	4253	6.4	148.5

TABLE III (Continued)

(b) Detailed Data

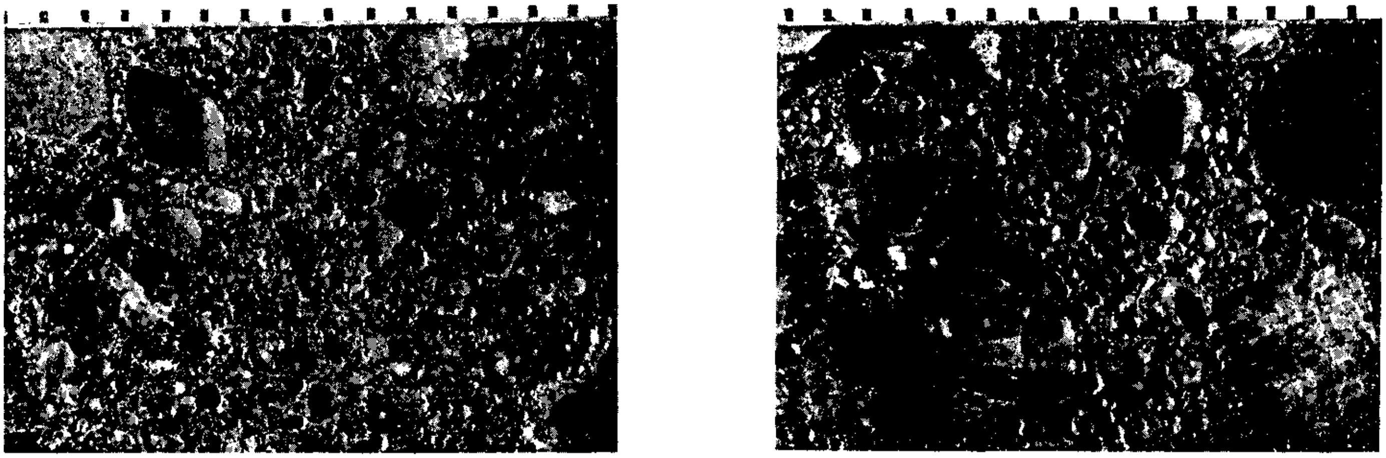
Load	Sampling Point	Surface	Void Content, % (ASTM C457)			14 Day Compressive Strength, psi	Unit Weight pcf	Length, in.
			$\geq$1mm	$\leq$1mm	Total			
			Cylinders					
6	Truck	(Total Sample)	-	-	6.8	4780	-	12.0
		Upper	2.4	5.4	7.9	-	-	-
		Middle	1.4	4.5	5.9	-	-	-
		Lower	1.4	4.3	5.7	-	-	-
6	Pumped	(Total Sample)	-	-	13.0	1700	-	12.4
		Upper	7.7	7.0	14.7	-	-	-
		Middle	7.3	6.9	14.3	-	-	-
		Lower	6.6	4.7	11.3	-	-	-
11	Truck	(Total Sample)	-	-	8.2	3940*	-	12.0
		Upper	2.9	6.5	9.4	-	-	-
		Middle	3.0	4.5	7.6	-	-	-
		Lower	1.9	4.3	7.2	-	-	-
11	Pumped	(Total Sample)	-	-	10.7	2280*	-	12.2
		Upper	6.6	6.1	13.7	-	-	-
		Middle	5.4	6.0	11.4	-	-	-
		Lower	4.0	4.3	8.7	-	-	-
14	Truck	(Total Sample)	-	-	8.1	4280	-	-
		Upper	2.4	6.3	8.7	-	-	-
		Middle	3.1	5.6	8.7	-	-	-
		Lower	2.6	4.3	6.9	-	-	-
14	Pumped	(Total Sample)	-	-	11.2	2110	-	-
		Upper	5.4	6.5	11.9	-	-	-
		Middle	5.5	5.8	11.3	-	-	-
		Lower	4.6	5.6	10.2	-	-	-
			Cores					
Placed Area #1			3.0	3.4	6.4	-	-	-
Placed Area #2			-	-	-	-	147.3	3820
Placed Area #3			-	-	-	-	146.6	4440
Placed Area #4			-	-	-	-	151.6	4500
Pumped Area #5			7.8	6.9	14.7	-	-	-
Pumped Area #6			-	-	-	-	140.4	2050
Pumped Area #7			-	-	-	-	139.8	2060
Pumped Area #8			-	-	-	-	141.6	2910

*Determined from companion specimens from the same batch as the specimens on which the air void determinations were made.



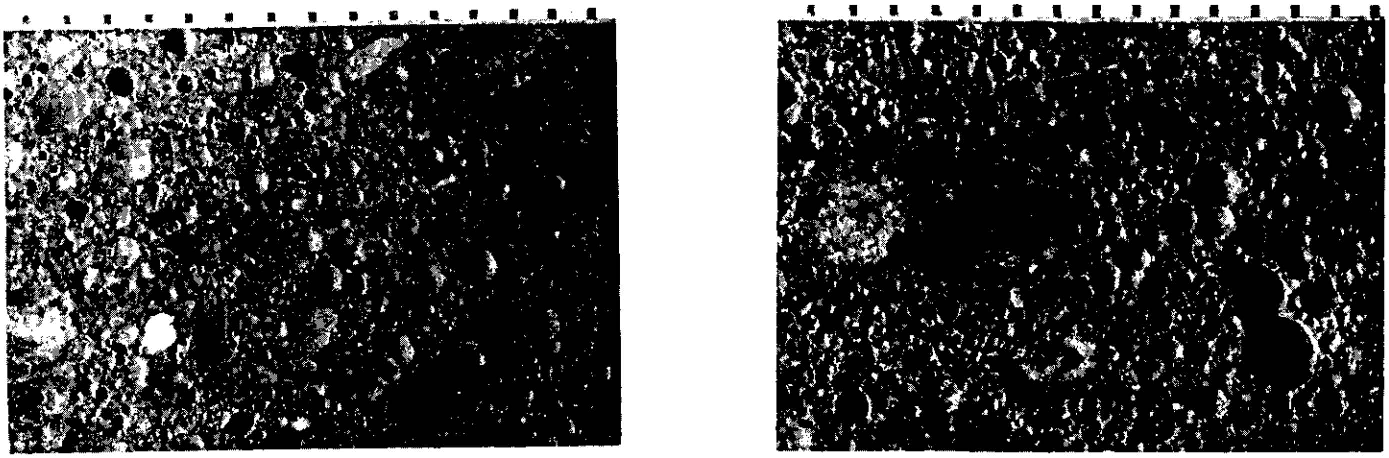
A. Core from area of original deck placed by bucket.

B. Core with same concrete as in A. but placed by pumping through aluminum delivery line. Note coarser and more abundant air voids.



C. Test cylinder from area of original deck placed by bucket. Same concrete as A & B but sample from truck before pumping.

D. Test cylinder with same concrete as in but placed by pumping through aluminum delivery line. Note coarser and more abundant air voids.



E. Demonstration cylinder; sample collected at discharge end of steel line.

F. Demonstration cylinder, same concrete as E but sampled from discharge end of aluminum line. Note coarser and more abundant air voids.

Figure 4. Typical void systems: scale in mm.

The salient features of the data given in Table III are: (1) the close agreement between results from cylinders cast during construction and cores subsequently removed from the deck slab, (2) the increased void content of the pumped concrete as compared with the corresponding conventionally placed concrete (this increase is proportionately greater in the larger size voids), and (3) the excellent correlation between the differences in void content and the significant properties of the hardened concrete.

For cylinders from batches 6 and 11, the increases in length of 4 and 2%, respectively (which is equal to the volumetric increase) agree reasonably with the increases in void content of 2.5 and 6.2% measured on the hardened concrete. The relationship between compressive strength and the measured void contents from both cylinders and cores is shown in Figure 5.

Bridge deck concrete used by the Virginia Department of Highways is proportioned by the contractor in accordance with ACI 613. The proportions selected and used for the deck slab and the properties required by VDH specifications are given in Table IV.

The contractor did not request any adjustments in the proportions to improve "pumpability", and while no significant difficulties were observed the sand content is lower than would be obtained with a suggested modification of ACI 613 to permit an increase in sand content for concrete intended for pumping.

Because no unusual behavior was anticipated, no tests of materials beyond those normally associated with routine project control were run. The fine aggregate was a natural sand, perdominantly quartz, and the coarse aggregate a crushed granite-gneiss. The mixture proportions were based upon the following aggregate properties: fine aggregate — specific gravity 2.61, and F.M. 2.70; coarse aggregate — specific gravity 2.80, and unit weight 107.3 pcf.

The cement was ASTM Type II. The alkalies, (expressed as equivalent Na_2O), normally range between 0.6 and 0.7%; a very large portion is readily water soluble.

The mixture was duplicated for the special demonstration approximately one month later and special materials tests were made at that time. Prior experience with the materials indicates that the materials data obtained during the demonstration and presented later are equally applicable to concrete from the deck placement.

Although it appeared certain on the basis of the observations thus far presented that the expansion and strength reduction resulted from reaction between the cement paste and the aluminum pipe, questions were raised as to

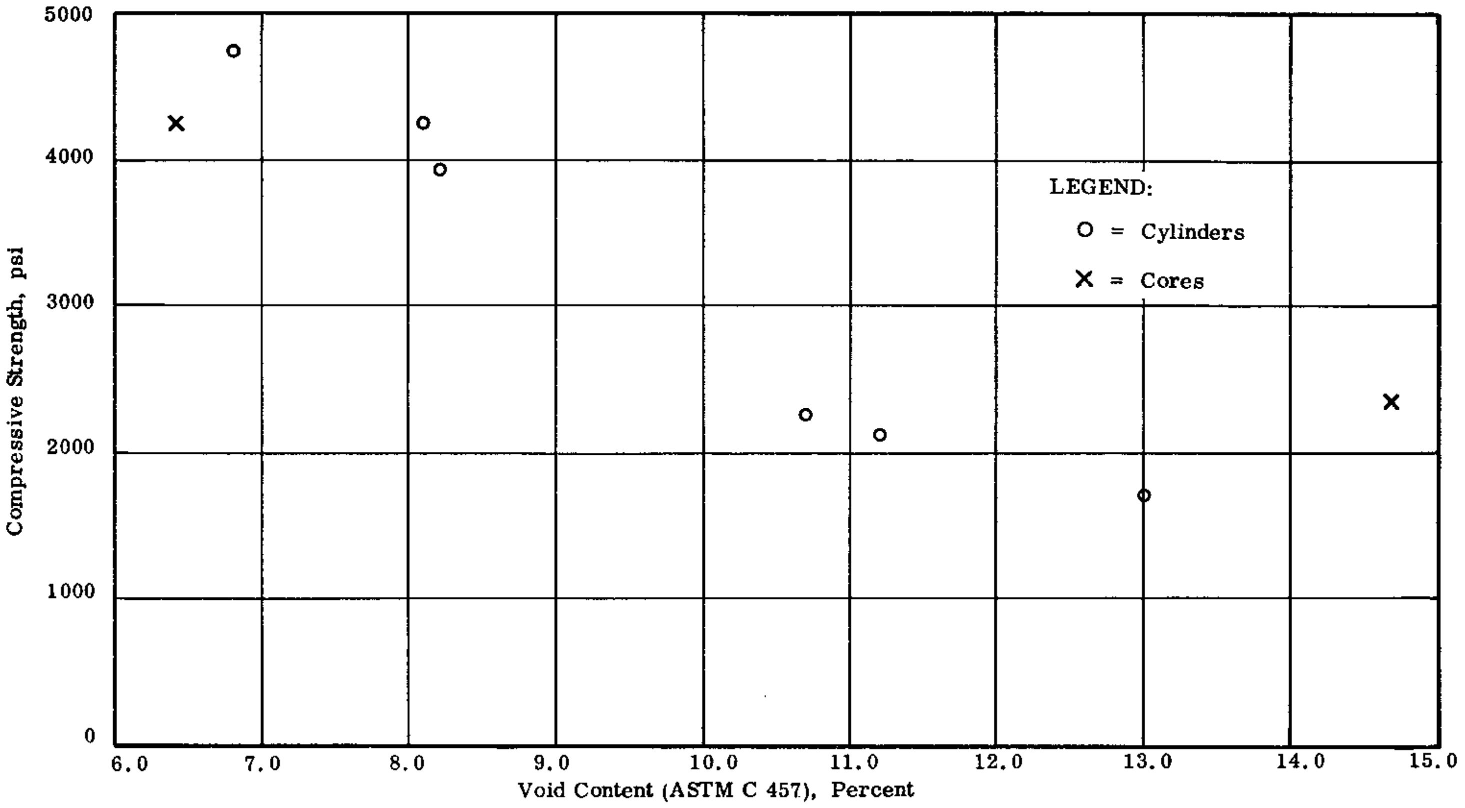


Figure 5. Relationship between strength and void content for cores and cylinders.

TABLE IV

PROPORTIONING OF DECK CONCRETE AND VIRGINIA DEPARTMENT OF HIGHWAYS SPECIFICATIONS

Proportions:	
Cement Content —	635 lb./cy. (6-3/4 sks/cy.)
Water-Cement Ratio	0.44 (4.95 gal/sack)
Proportions (cement: FA, CA, by weight)	1:1.66 : 3.06
Sand Content/Total Aggregate	0.352
Water Reducing — Retarder	3 fl. oz/sack
Properties Specified by VDH	
Slump	3 ± 1 inches
Air Content	$6\frac{1}{2} \pm 1\frac{1}{2}\%$
Intended Compressive Strength, 14 Days	3400 psi*

*Based upon 85% of anticipated 28 day strength of 4000 psi.

the contribution of materials factors such as aggregate shape and/or hardness, cement alkalies, and the presence of the retarding admixture. To evaluate these factors as well as to confirm the contribution of the aluminum pipe, a demonstration was arranged using the same plant and equipment.

Summary of Deck Concrete Behavior and Characteristics

Cylinders from concrete pumped through the aluminum pipe showed variable expansions up to approximately 5%. The expansion was also observed in the deck concrete. The effects of the expansion were reflected in the hardened concrete by increased void contents of 4 to 8% and strength reductions of 40 - 65% as compared with the conventionally placed concrete. Similar strength reductions as well as a reduction in density of 5% were observed in cores subsequently taken from the bridge deck. Because of the low strengths the deck was removed and replaced.

SPECIAL DEMONSTRATION

Variables and Procedures

Through the cooperation of the ready mixed supplier, the pumping subcontractor, and various units of the Department of Highways, a demonstration was arranged in which three batches of concrete, each containing four cubic yards, were pumped simultaneously through 20 ten-foot sections of parallel 4 inch diameter steel and aluminum pipes. Each pipe was connected directly to one of the dual discharge ports that normally are connected by a Y-connection to the single delivery line. The last ten-foot section of pipe was turned up to discharge into a truck. The line discharge point was separated from the intake point by approximately 210 feet horizontally and 11 feet vertically. A general view of the setup is shown in Figure 6.

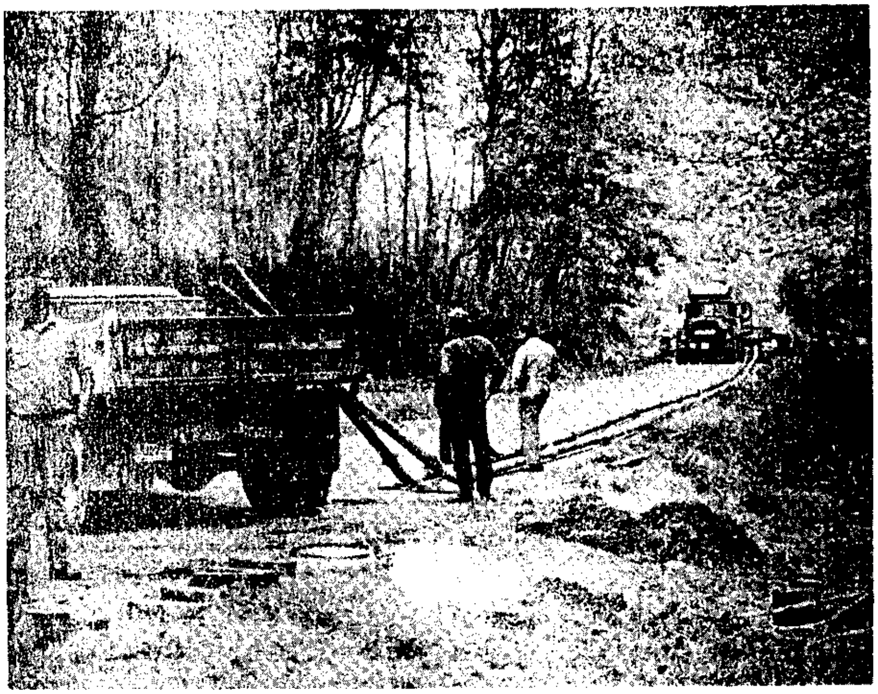


Figure 6. View of special pumping demonstration with aluminum and steel pipes in parallel.

The variables were limited for practical and economic reasons to those that could be accommodated in three batches. These included two cements with different alkali contents, one of which was that used in the deck placement. In one batch the retarding admixture was omitted. Variations of the aggregate were not included since it was reasoned that any commercial aggregate available in Virginia would be harder than aluminum, and the particular crushed stone used had as satisfactory a particle shape as would likely be encountered in crushed material throughout the state.

The three batches were intended to meet the requirements for Virginia bridge deck concrete and the significant variables are summarized as follows:

Batch	Cement (Type II)	Water Reducing Retarder
1	A	Yes
2	A	No
3	B	Yes

Cement A was Type II from the same source as that used during the deck placement. Cement B was also a Type II cement of the same brand but from a different plant. It had approximately the same aklali content as Cement A, but differed in that very little of the total alkalies was readily water soluble. The admixture, all other materials, and equipment were those used in the deck placement. Detailed analyses of the materials are presented later. Thus, the availability of cement alkalies and the presence of a retarding admixture were the primary variables included.

The batches were pumped consecutively and the tests were made from samples taken before and after pumping in sufficient number to provide a coverage of the important properties. These tests included:

Fresh Mixed

Slump (ASTM C143)
Air Content (ASTM C231)
Yield (ASTM C138)
Time of Set (ASTM C403)
Mix and Air Temperature –

Hardened

Compressive Strength (ASTM C39)
Void Structure, Microscopic (ASTM C457)
Freezing and Thawing Specimens (ASTM C290)
Deicer Scaling Specimens –

Before charging each load, samples of the cement and aggregate were taken at the plant for chemical analysis and gradation respectively.

Results

Freshly Mixed Concrete

Because of the difficulty of processing different batches through a plant without the opportunity for adjustment, the three batches were not as well controlled with regard to slump and air as would have been desirable. They did however, represent a wide range of consistency, air content, and materials. The important mixture proportions are listed in Table V.

TABLE V

INTENDED AND MEASURED MIXTURE PROPORTIONS

Property	Batch 1	Batch 2	Batch 3
Cement Content (Design)	635# (6-3/4 sk/cy)	635#	635#
Cement Content (Calculated)	645 (6.86 sk/cy)	619 (6.59)	645 (6.86)
Water-Cement Ratio (Design)	0.44	0.46	0.44
Water-Cement Ratio (Calculated)	0.42	0.45	0.45
Proportions (Actual)	1:1.66:3.06	1:1.51:3.14	1:1.66:3.06
Yield, Before Pumping (Actual)	98.5%	97.5	98.5
Fine Aggregate/Tot. (Actual)	.351	.324	.351
AEA (Actual)	3/4 fl. oz./sk.	3/4 fl. oz./sk.	3/4 fl. oz./sk
Water Reducing Retarder (Actual)	3 fl. oz./sk.	0	3 fl. oz./sk.
Cement	A	A	B

Load 1 was the standard bridge deck concrete that incorporated materials and proportions used in the daily operation of the plant. Prior to pumping, it met all requirements and was quite similar to the batches used during the deck placement.

The slump of Load 2, 6½ inches, was excessive and very likely a result of the excessive air content of 9.5%. Economy dictated use of this concrete rather than refusal and subsequent adjustment. Subsequent inquiries suggested that the coarse aggregate, rather than being separated 50 - 50 between #5's and #7's, actually incorporated 60% #5's (1" to 3/8") and 40% #7's (1/2" to No. 4). This increased the total aggregate F. M. from 6.67 to 6.90. This increase combined with the different sand content and the slightly leaner mixture likely was responsible for the increased air and/or slump.

The third mixture was made with a different cement from that used in Batches 1 and 2. Logistical problems did not permit trial mixing so that this cement was simply incorporated into the mixture established for Load 1. The mixture was stiffer (slump 2-7/8") and, while significantly different from Load 1, met Virginia Department of Highways requirements for bridge deck concrete.

The significant properties of the freshly mixed concrete are given in Table VI. The differences before and after pumping are not dramatic; however, there is a suggestion of higher fluidity of the concrete discharged from the aluminum line than for that from steel, as evidenced by the increased slump. Only for Load 2 was there a significant loss of air during pumping, but this loss was much less in the aluminum pipe than in steel.

TABLE VI

PROPERTIES OF FRESHLY MIXED CONCRETE

Load	Cement	W-R-R Admixture fl. oz/sk.	Slump, inches			Air Content, %			Temperature, °F		
									Mixture		
			Before Pumping	Pumped Aluminum	Pumped Steel	Before Pumping	Pumped Aluminum	Pumped Steel	Before Pumping	After Pumping	Air
1	A	3	4¼	6¼	5½	7.0	7.4*	7.8	65	66	58
2	A	0	6½	5	4½	9.5	9.0	7.8	64	66	60
3	B	3	2-7/8	2½	1¼	5.2	4.5	4.6	63	64	61

*Rerun at intervals without disturbing the concrete in the meter bowl with the following results:

Initial	7.4
After 15 minutes	8.0
After 30 minutes	8.2
After 55 minutes	8.6

As noted in Table VI, air content measurements were repeated periodically for the concrete from Load 1 on a sample left undisturbed in the bowl of the air meter. As shown there was a gradual increase of air during the hour of testing from 7.4 to 8.6%.

Observation of Reaction During Pumping

During the pumping of all three batches, the evidence of reaction of the concrete with the aluminum line was apparent. The concrete discharged from both pipes showed the normal "slickened" appearance, but that from the aluminum line additionally showed substantial "foaming". This is illustrated in Figure 7. That this foaming was caused by hydrogen generation was further evidenced by the characteristic "pop" that occurred when a lighted match was touched to the bubbles. Evidence of the pressure generated by the reaction within the line was seen during periods when the pump was cut off. The concrete remained even with the discharge opening of the steel pipe while it periodically spurted out of the aluminum pipe from pressures created within (Figure 8).

Gross expansions such as were observed during the deck placement were not observed. Evidence of lesser expansion was observed for all concrete pumped through the aluminum line. This expansion was just sufficient to overcome the normal shrinkage. The surfaces of cylinders made from the aluminum pumped concrete rose slightly above the rim of the mold while those from steel pumped concrete receded about the same amount. The total difference was less than 0.1 inch.

Figure 7. Discharge of concrete. Note foaming of concrete from aluminum pipe on right and normal appearance of concrete from steel pipe.

Figure 8. Discharge of concrete from aluminum pipe (on left) from pressure buildup while pump was cut off.

Tests of Hardened Concrete

The compressive strength results are given in Table VII. The seven day results are for single specimens while the 14 day values are averages of two cylinders. Also given in Table VII are the changes in strength based on both the concrete before pumping and the differences between the concrete delivered through steel and aluminum.

TABLE VII

COMPRESSIVE STRENGTH RESULTS* — SPECIAL DEMONSTRATION

Batch #	Age, Days	Before Pumping Strength, psi	Pumped-Steel		Pumped-Aluminum		Difference between Steel & Aluminum
			Strength psi	Difference %	Strength psi	Difference %	
1	7	3270	3625	+10.8	2990	- 8.6	-19.4
	14	4385	4430	+ 1.0	3615	-17.6	-18.6
2	7	2425	2830	+16.7	1680	-30.6	-47.3
	14	2990	3405	+17.2	2440	-18.4	-35.6
3	7	5180	5360	+ 3.5	3165	-38.8	-41.3
	14	5925	6055	+ 2.2	3915	-34.0	-36.2

*Each value is average of two cylinders.

Slight to moderate increases in strength resulted from pumping through the steel pipe. Such increases are usual (Mattison — 1968). Although these tests are too limited for generalization, the increases are greatest for the higher slump or lower strength mixtures (Loads 1 and 2).

Strengths were decreased significantly by pumping through the aluminum pipe as compared with the strengths before pumping. If the strength differences between the steel and aluminum pipes are taken as measuring the influence of the aluminum, then the reduction is approximately 20 to 50%. By this criterion, Mixture 1, which was representative of that placed in the deck, was less affected than Mixtures 2 and 3.

Although no relationship is apparent between the magnitude of the strength decrease and any mixture characteristic, the effect of the aluminum pipe in decreasing strength is evident in all cases.

In addition to tests of strength, concrete was subjected to rapid freezing and thawing in a 2% NaCl solution. With the exception of substitution of the salt solution for water, the freezing and thawing tests were conducted in accordance with ASTM C290 "Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water". Eight cycles were obtained every 24 hours.

The characteristic deterioration was surface scaling and loss of material rather than cracking. Thus, no significant losses of dynamic modulus were noted. Weight losses are presented in Figure 9. Each point represents the average of three beams, which agreed within accepted limits.

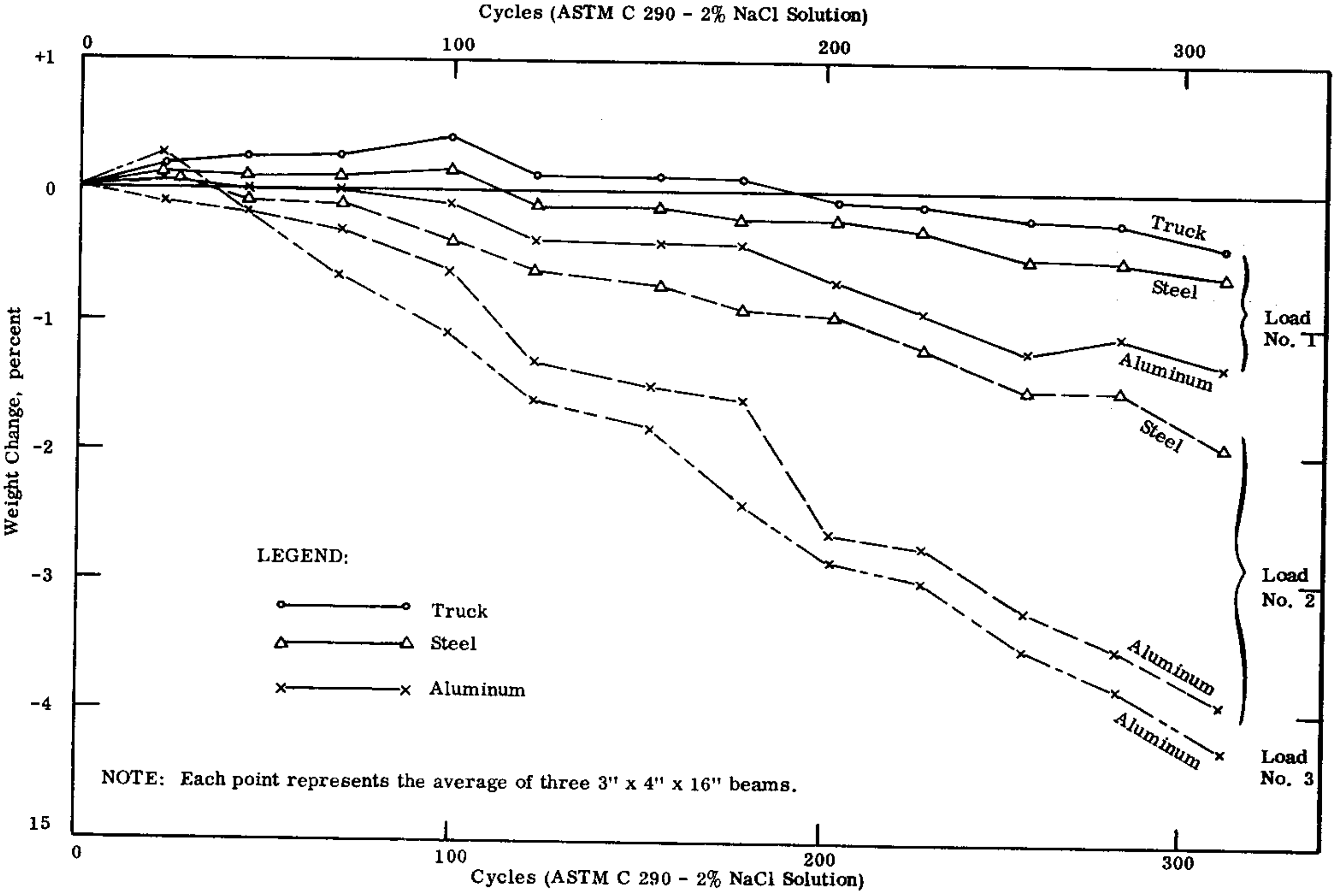
Equipment limitations did not permit complete coverage of all combinations of mixtures and pipes. It can be seeen, however, that the concrete pumped through aluminum pipe showed the greatest weight losses in Mixtures 1 and 2. The greatest loss was for concrete pumped from Load 3 through aluminum lines. The behavior in these freezing and thawing tests is in general agreement with the strength results in that Mixtures 2 and 3 were more affected than was Load 1.

Slabs were also made for exposure to natural freezing and thawing in the presence of deicing chemicals. These tests will be conducted in the Council's outdoor exposure area. Results will not be available until the passage of one winter's exposure.

Petrographic examinations were made on the compressive strength specimens. Sawn, polished sections from upper, middle and lower portions were examined as described previously in presenting the results in Table III. These results are given in Table VIII.

The differences in void contents were much smaller than those observed in the specimens from the deck. This is consistent with the absence of excessive expansion but inconsistent with the observed effects on strength. Even though the differences are small, void content increases are more common for the aluminum pumped concrete than vice versa. Assuming a difference of 0.5 percentage point to be significant, then based upon the results of the total samples, all three show an increase. Of the nine subsamples four show an increase, four no change, and only one a decrease. Thus, there is a significant but modest increase in void content that is comparable with the modest expansion observed; but it is not sufficient to account completely for the reduced strength. This subject is discussed more fully later.

Determinations of stiffening rate or time-of-set by penetration measurements (ASTM C403) were made on samples representing seven of the nine combinations of mixture-truck-pipe. The times of initial set as measured by the time to reach 500 psi resistance are given in Table IX.



NOTE: Each point represents the average of three 3" x 4" x 16" beams.

Figure 9. Weight changes during freezing and thawing tests for concretes pumped through steel and aluminum pipes.

TABLE VIII

VOID CONTENTS OF CONCRETE FROM SPECIAL DEMONSTRATION

Load	Freshly Mixed Air Content, % (ASTM 231)			Level	Hardened Concrete			
						Void Content, % (ASTM 457)		
	Before Pumping	Steel	Aluminum		Void Size Distribution	Before Pumping	After Pumping Steel	After Pumping Aluminum
1	7.0	7.8	7.4	Total Sample	Total	8.7	9.0	9.5
					> 0.01 mm	2.7	3.1	3.6
					< 0.01 mm	6.1	5.9	5.9
				Upper	Total	9.2	10.1	10.2
					> 0.01 mm	3.0	3.1	3.9
					< 0.01 mm	6.2	7.0	6.3
				Middle	Total	9.9	9.6	9.4
					> 0.01 mm	2.7	4.0	3.0
					< 0.01 mm	7.3	5.6	6.4
				Lower	Total	7.1	7.2	8.9
					> 0.01 mm	2.3	2.2	4.0
					< 0.01 mm	4.8	5.0	4.9
2	9.5	7.8	9.0	Total Sample	Total	9.8	11.1	11.9
					> 0.01 mm	2.2	4.4	5.4
					< 0.01 mm	7.4	6.8	6.6
				Upper	Total	9.9	12.4	14.7
					> 0.01 mm	2.0	4.6	6.7
					< 0.01	8.0	7.9	8.0
				Middle	Total	11.7	12.5	12.5
					> 0.01 mm	3.2	4.7	5.1
					< 0.01	8.5	7.8	7.4
				Lower	Total	7.8	8.6	8.6
					> 0.01 mm	1.8	3.9	4.3
					< 0.01 mm	6.0	4.7	4.3
3	5.2	4.6	4.5	Total Sample	Total	5.3	4.5	5.2
					> 0.01 mm	1.9	2.3	2.2
					< 0.01 mm	3.4	2.2	3.0
				Upper	Total	4.6	4.9	5.9
					> 0.01 mm	1.2	2.7	2.9
					< 0.01 mm	3.4	2.2	2.9
				Middle	Total	5.8	3.9	5.4
					> 0.01 mm	2.2	1.5	2.0
					< 0.01 mm	3.5	2.4	3.4
				Lower	Total	5.5	4.9	4.2
					> 0.01 mm	2.3	2.9	1.7
					< 0.01 mm	3.2	2.0	2.6

TABLE IX

SETTING TIME RESULTS

Load	Sampling	Cement	WR-R Admixture	Initial Set (500 psi penetration, ASTM C403 hrs:min.
1	Truck	A	3 fl/oz	6:47
	Steel Line	A	3 fl/oz	6:38
	Aluminum Line	A	3 fl/oz	7:00
2	Steel Line	A	0	4:48
	Aluminum Line	A	0	4:44
3	Steel Line	B	3 fl/oz	8:05
	Aluminum Line	B	3 fl/oz	4:23
	Unretarded*	B	0	4:16

*Extrapolated from other field tests with this cement.

For Mixture 2, which contained no retarding admixture, the setting time was the same regardless of the type of line. This was likewise true for Mixture 1, which contained the water-reducing, set-retarding admixture. The slight increase in setting time between the steel and aluminum is likely not significant.

The setting times determined for Mixture 3 are quite different. The set was greatly accelerated by pumping through aluminum. Unfortunately, no tests were run on the concrete from Load 3 prior to pumping, and no batches were made with Cement B in the absence of the retarding admixture. A review of data from four field compatibility tests conducted during the period using cements A and B indicates that on an average Cement B reaches initial set about 30 minutes earlier than Cement A. The four tests were selected from the large number available because they were conducted at the same temperature. It would thus appear that the initial set time of the concrete delivered through the aluminum line was essentially that of the same concrete without the admixture.

Materials

The aggregates used in this demonstration were the same as those used in the deck concrete. The coarse aggregate was a crushed granite-gneiss and the fine aggregate was a natural quartz sand. Two samples were taken — one prior to batching Load 1 and the second between Loads 2 and 3. Significant characteristics of these aggregates are given in Table X.

TABLE X

AGGREGATE PROPERTIES

	Fine Aggregate		Coarse Aggregate		Combined (Calculated)		
	Sample 1	Sample 2	Sample 1	Sample 2	1	2	3
Specific Gravity	2.64	2.63	2.80	2.80			
Absorption	0.5	0.5	0.7	0.4			
Fineness Modulus	2.82	2.72	--	--	6.67	6.90	6.67
Passing #50	21.0	17.2	--	--	6	7	7
Passing #100	3.1	2.9	--	--	0.5	1	1.5
Maximum Size	3/8"	3/8"	1"	1"	--	--	--

Gradation curves for the coarse and fine aggregates are shown in Figure 10. The combined gradation curves for the three mixtures are shown in Figure 11.

The gradation of the fine aggregate was continuous and near the center of the band required by ASTM C33. The Virginia Department of Highways requirements are slightly more restrictive than those of ASTM. The amounts passing the 50 and 100 mesh screens respectively were close to the 15 - 20% and 2 - 3% suggested by Wilson (1967). The coarse aggregate was also well within the limits required by ASTM C33, which coincide with those of the Virginia Department of Highways. Mixtures 1 and 3 were slighly finer than Mixture 2 in which the #5's and 7's were split 60 - 40 rather than 50 - 50. Because the mixtures pumped without difficulty except for the reaction already discussed, there is no evidence that the aggregate gradations or other properties had any significant influence on the delivery. There also is no relationship between the expansion and/or reaction and these aggregate properties.

The calculated cement compounds, alkalies, and sulfate contents are given in Table XI. The complete oxide analyses are given in Appendix A.

Both cements met the requirements for Type II and their compound compositions were quite similar. Cement B was slightly finer than Cement A. Two significant differences are evident. While both cements have moderate and approximately equal alkali contents, more than 80% of the total alkalies in Cement A are rapidly water soluble whereas only 10% of the alkalies from Cement B are rapidly soluble. The alkalies in Cement B were predominantly sodium while those in Cement A were predominantly potassium. It will also be noted that the SO_3 content in Cement A was above its optimum, while that in Cement B was considerably below its calculated optimum. The significance of these compositional differences is discussed later.

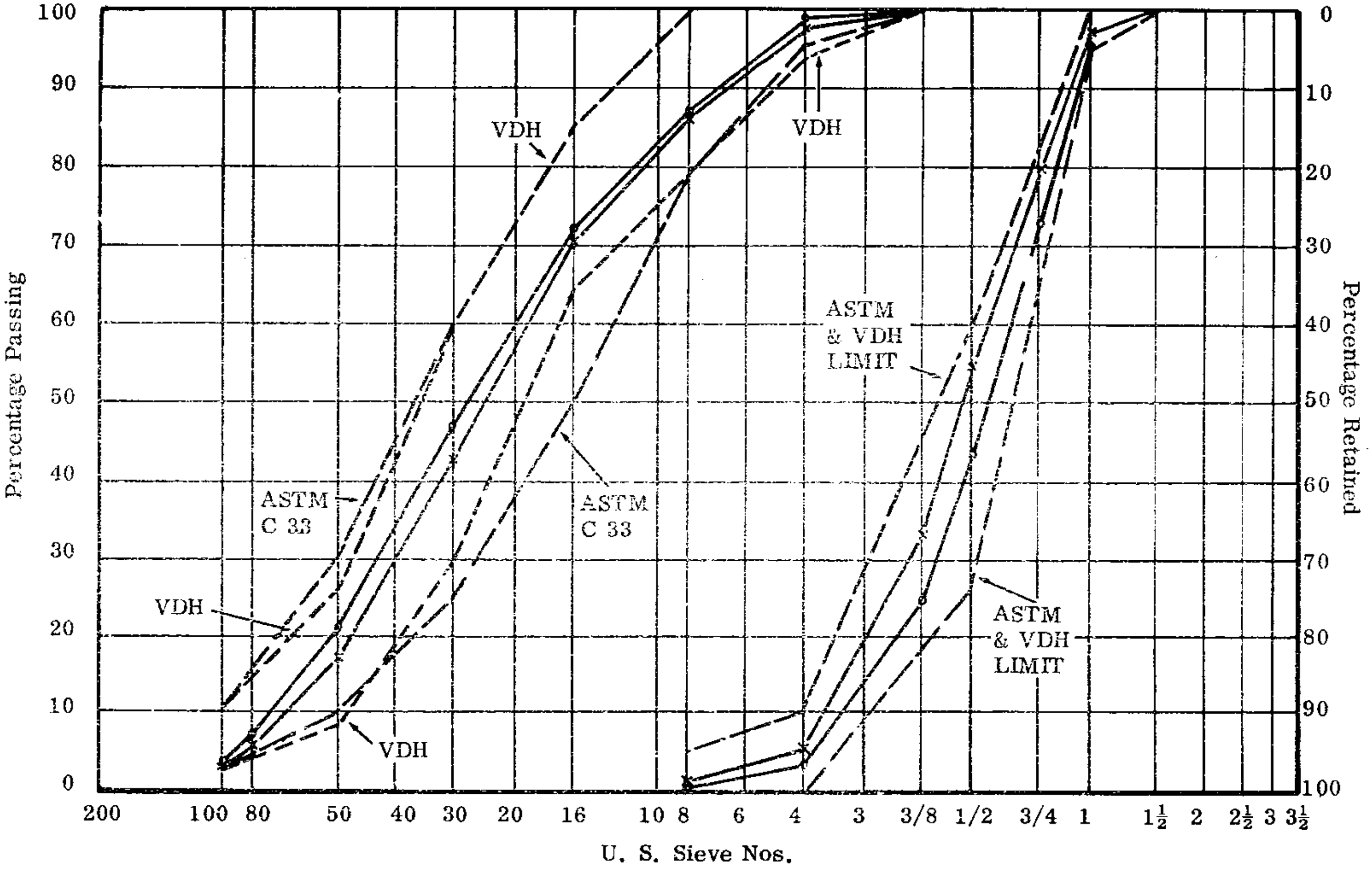


Figure 10. Gradation of coarse and fine aggregate.

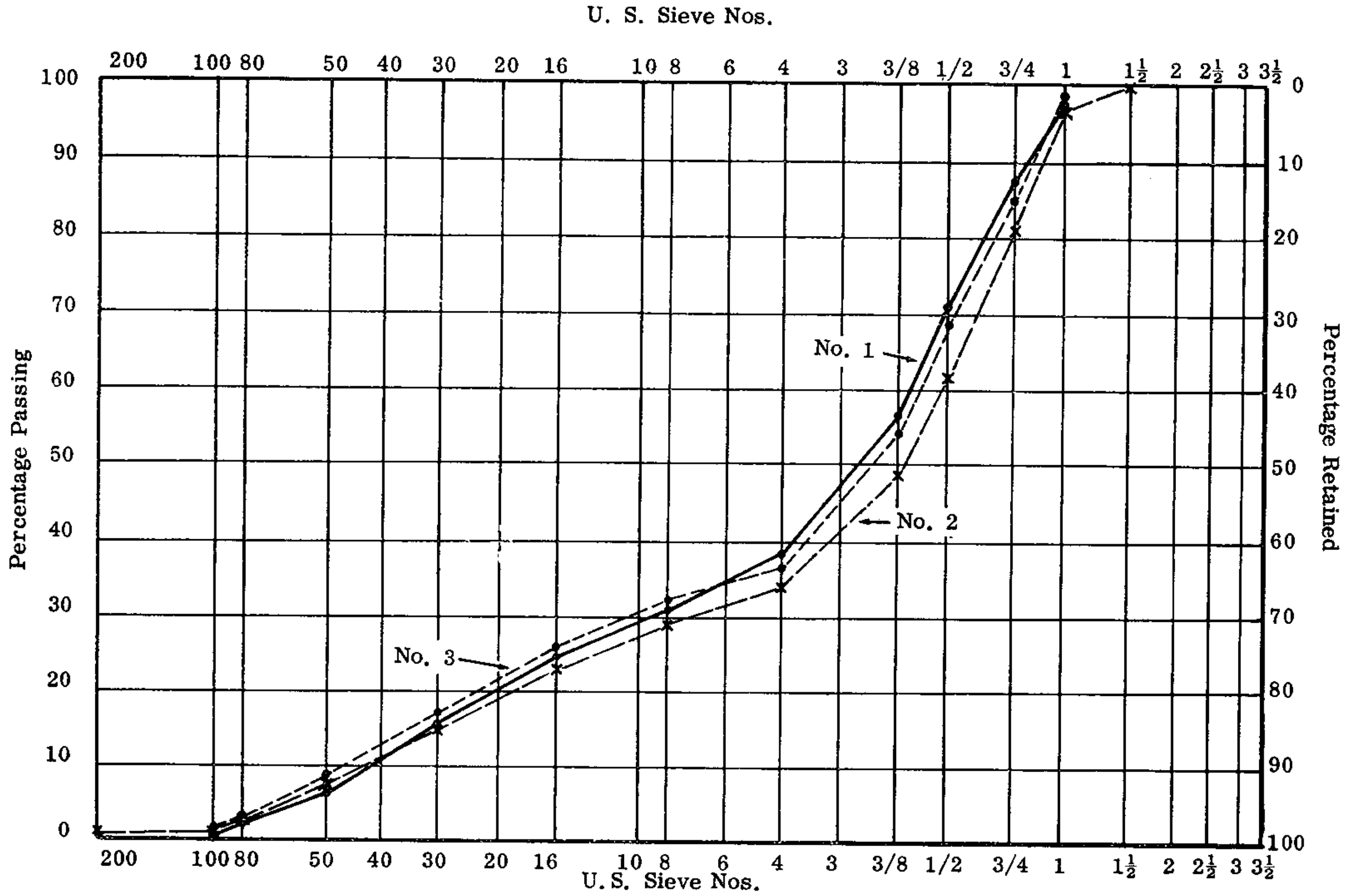


Figure 11. Gradation curves for combined coarse and fine aggregate.

TABLE XI

POTENTIAL COMPOSITION
(All values expressed in percent except as noted)

	Cement A	Cement B
C_3A	3.5	3.0
C_2S	16.6	18.7
C_3S	60.2	57.4
C_4AF	12.8	12.9
Alkalies:		
Total as Na_2O	0.64	0.69
Na_2O	0.21	0.73
K_2O	0.66	0.06
Water Soluble Alkalies:		
Total as Na_2O	0.52	0.07
Na_2O	0.13	0.06
K_2O	0.60	0.02
SO_3	2.16	1.86
Optimum SO_3	above optimum	2.82
Fineness, cm^2/gm		
Wagner	1879	1910
Blaine	3042	3323

Summary of Behavior and Characteristics of Concrete Pumped in the Special Demonstration

Regardless of the cement used or the presence of a water-reducing, set-retarding admixture concrete pumped through aluminum pipe showed reductions of strength when compared with concrete from the same batch simultaneously pumped through steel pipe. The reductions ranged from 20-50%. Weight losses during accelerated freezing and thawing were also increased for the aluminum pumped concrete. During pumping, reaction was obvious for all three batches tested. Expansions, while observable were smaller than those which occurred during the deck placement. There was also less difference in the void contents from the hardened concretes, although those for the aluminum pumped concretes were generally higher than those for the concrete pumped through steel.

The effect on strength cannot be completely explained by the differences in void contents. This fact suggests that there are chemical as well as physical effects of the reaction. Chemical effects are also suggested by a negation of the influence of the retarding admixture when the concrete made with cement with less than optimum SO_3 was delivered through the aluminum lines.

Reactivity in the form of foaming and pressure buildup within the aluminum pipe was evident in all three mixtures.

THE MECHANISM AND SOME IMPLICATIONS OF THE OBSERVATIONS

The reaction between aluminum and cement alkalies is well known and its expansive effects are, in fact, utilized commercially to offset sedimentation in fresh concrete and grouts. The use of gas-forming admixtures such as aluminum powder is discussed in the report of ACI Committee 212 (1968). Much of the data that serves as the basis for using aluminum powder is drawn from the comprehensive paper by Menzel (1943). More recently Linger (1968) developed similar data. These studies document the influence on strength and expansion of various factors such as increasing amounts of aluminum powder, restraint, and temperature.

Menzel found that strength was reduced roughly 10% for each gram of aluminum powder added per 100 lbs. of cement. Dosages of .005 to 0.02% by weight of cement are suggested by ACI Committee 212, and Linger showed that regardless of dosage rate, confining pressure, etc., the strength reduction was related to the volume change of the freshly mixed concrete. His data suggest a slightly greater reduction with higher strengths.

The reaction is generally attributed to the reaction of the cement alkalies with the aluminum powder. Normally the term "alkalies" refers to the compounds of sodium and potassium that are usually present in quantities of less than 1%. Several authors report also the reaction of aluminum powder with calcium hydroxide. Lea (1957) and Neville (1963) make general statements as to the reaction betweer aluminum and lime. Lea also refers to the process developed in Sweden to produce aerated or lightweight concrete by formation of hydrogen produced gas voids. This process is discussed in more detail by Bessey (1964), who gives a formula suggesting the formation of tricalcium aluminate hydrate as follows:

$$\overset{\text{Aluminum Powder}}{2\ Al} + \underset{\text{Hydrated Lime}}{3\ Ca(OH)_2} + 6\ H_2O \longrightarrow \underset{\text{Tricalcium Aluminate hydrate}}{3\ CaO.Al_2O_3 \cdot 6\ H_2O} + \overset{\text{(hydrogen)}}{3\ H_2} \uparrow$$

Because finely divided calcium hydroxide is a product of the hydration process and because lime is much more abundant than the more active alkalies, it is probable that the lime-aluminum interaction is a significant contributor to the observed reaction. This is supported by the data from the special demonstration where the reaction was apparently independent of the proportion of soluble alkalies, which varied ten-fold between the two cements used.

Thus, the reaction between aluminum and alkalies (including $Ca(OH)_2$) from cement paste is well understood and is to be expected. The unusual aspect in this case is that sufficient aluminum would be available from the pipe during pumping. Although no aluminum particles were observed in the petrographic examination of the hardened concrete, calculations based upon several reasonable assumptions and measurements are consistent with the observations.

The pipeline alloy was positively identified as 6061-T6. The dimensions of the pipe at the time of the special demonstration were determined to be as follows:

Inside Diameter	—	4.123 inches
Wall Thickness	—	0.192 inch

Comparison of the dimensions with values tabulated for standard pipe sizes suggests that the pipe was nominal 4 inch Schedule 40" pipe, which has the following dimensions:

Inside Diameter	—	4.026 inches
Wall Thickness	—	0.237 inch

Thus, approximately 0.04 inch of material had been removed. As developed in Appendix B, the relationship between the thickness of material removed by one cubic yard of concrete and the important characteristics of the concrete and pipeline is given by:

$$t = \frac{Wa}{5.3 \times 10^{4} \, \pi \, Dl}$$

where:

t = thickness of material uniformly removed from inside of pipeline, by one cubic yard of concrete, inches.

W = weight of cement per cubic yard of concrete, pounds

a = weight of aluminum per 100 lbs. of cement, grams

D = inside diameter of pipe, inches

l = length of pipeline, feet

The pumping contractor indicated that approximately 8,000 cy of concrete had been delivered by the pump prior to the special demonstration. As the above relationship indicates, the thickness of material removed is affected by interacting variables and is very sensitive to the specific values assumed for each. A cement content of 5.5 $^{sks}/cy$ (517 lbs.) would be reasonable for the class of concrete conventionally used. A length of 300 feet for the 4 inch diameter pipeline also appears reasonable.

Menzel found that one gram of aluminum per hundred pounds of cement resulted in a strength decrease of 10%. Assuming a strength reduction of 40%, which is consistent with data given in Table VII, 4 grams per hundred pounds of cement would be required.

Using the above figures, the thickness of aluminum removed by 8,000 cy of concrete would be 0.083 inch. While this value is larger than the 0.04 inch measured, it is of the proper order of magnitude and reinforces the probability of the aluminum-concrete reaction.

Whether the aluminum was removed physically or chemically or by a combined process cannot be stated definitely. The absence of aluminum particles in the hardened concrete could mean either that the aluminum was removed chemically or that it was abraded in particles of such fine size that they were completely digested.

The velocity with which the concrete moves through the pipe varies from zero to some instantaneous value, which may be approximated in terms of the delivery rate and pipe diameter as shown in Table XII.

No data were found relating the abrasive capability of concrete to velocity, but undoubtly the velocities of 4 to 6 fps would be abrasive. It is possible that for combinations of pipe size and discharge volume which result in low velocities, the detrimental effects of aluminum removal would be significantly reduced.

TABLE XII

VARIATION OF VELOCITY WITH DELIVERY RATE AND PIPE DIAMETER

	Velocity	Feet Per Second
Pipe Diameter, Inch	70^{cy}/hr.	35 ^{cy}/hr.
4	6.0	3.0
5	3.8	1.9
6	2.7	1.4

Abrasion by coarse aggregate would be expected to result in removal of comparatively large particles of aluminum. The abrasive quality of fine aggregate is obvious and the sound of the concrete passing through the pipeline suggests a "sandpaper" effect. It is likely that this abrasion removes the thin aluminum oxide coating and exposes the aluminum to the cement alkalies, including the lime. Actually such an abrasion mechanism is not necessary since the stability of oxide decreases greatly at pH's above 10 (Goddard, et al — 1969). It would seem logical, however, that anything which would increase the resistance to movement would aggravate the reaction.

The observed ineffectiveness of the retarding admixture when Mixture 3 was pumped through the aluminum pipe also suggests some additional chemical phenomena. Although the data are limited, an explanation consistent with the observed behavior and cement compositions can be made by comparison with published studies of setting as influenced by C_3A, SO_3, alkalies, and the presence of an organic retarding admixture.

Sulfate is added during the manufacture of portland cement to control the initial reactions and prevent flash set. Following from the classic work of Lerch (1946) it is well documented that there exists an "optimum" amount of SO_3 that results in maximum strength, minimum shrinkage and heat liberation, and also avoids abnormal expansion. It is also generally accepted that the SO_3 reacts with the C_3A to form either of two practically insoluble complex sulfo aluminate compounds. The formation of these compounds on the C_3A particles is believed to slow the reaction of the C_3A to a practical rate. The "optimum" amount for desirable physical properties also gives a properly retarded cement. The sulfate required for proper retardation increases with increasing C_3A, fineness, and alkali content.

An additional complexity is introduced in mixtures containing organic admixtures which also have a strong affinity for C_3A and influence the behavior of the sulfates. Various instances have been reported of early stiffening of concrete containing normally setting cement when used with set-retarding admixtures (Tuthill, et al, — 1961; Palmer — 1961; Newlon and Ozol — 1968). In these cases the rapid stiffening was overcome by addition of sulfate, which suggests that the admixture increased the "optimum" SO_3 requirement. Seligmann and Greening (1964) discussed this behavior in detail and concluded that certain classes of admixtures can accelerate the early hydration, deplete the gypsum, or delay its precipitation. In such cases they point out that cements with relatively low SO_3/Al_2O_3 ratios could cause flash or accelerated set. Palmer (1961) noted the rapid consumption of C_3A, sulfate, and retarding admixture in similar circumstances. This observation was confirmed by Seligmann and Greening (1964). Greening and Seligmann also showed acceleration when the calcium hydroxide release was restricted. The depletion of calcium hydroxide consumed by reaction with aluminum might cause a similar accelerating effect.

Most alkalies (sodium and potassium) of cement are present as alkali sulfates, which are readily soluble. Where there is more sodium than can combine with the available SO_3 during curing, the remainder is combined with the aluminate, according to Newkirk (1952), as the compound NC_8A_3. Data developed by McCoy and Eshenour (1958) show large differences between soluble and total alkalies among different cements. Such low soluble alkalies are interpreted to mean that they are present not in sulfate form but rather in other phases; for example, the sodium in NC_8A_3. This compound behaves much like C_3A and would increase the demand for SO_3.

One can thus postulate that when Mixture 3 arrived at the site, there was comparatively little SO_3 remaining to be reacted. In fact, the necessity for adding additional water and observed slight stiffening are consistent with this assumption. As the mixture passed through the lines, the aluminum reacted from the pipe would behave in the same manner as C_3A. Aluminate compounds would also remove the remaining SO_3 and/or the organic admixture, and leave the remaining cement to behave as a badly undersulfated cement or unretarded cement. The amount of SO_3 and retarder was sufficient for retardation when the concrete passed through the steel pipe without addition of aluminum. The cement in Mixtures 1 and 2, which contained excess sulfate, was able to accommodate the additional aluminum.

The question as to whether or not the quantity of reacted aluminum is sufficient to cause depletion of the sulfate can be answered by consideration of the approximations shown below.

Assumed Reactions:

$$2\ AL + 3\ Ca(OH)_2 \longrightarrow 3\ CaO\ .\ Al_2O_3 + 3\ H_2 \uparrow$$

then

$$3\ CaO\ .\ Al_2O_3 + 3\ CaSO_4 + 32\ H_2O \longrightarrow 3\ CaO\ .\ Al_2O_3\ .\ 3\ CaSO_4\ .\ 32\ H_2O$$

Two moles of Al require 3 moles of $CaSO_4$. Assuming 5 gms of Al per 100 lbs. of cement, 5/27 = .19 mole requires .57 mole $CaSO_4$ .57 mole $CaSO_4$ yields .57 mole SO_3 thus 5 gms of Al requires 46 gms of SO_3. This would represent a depletion of about .10%. While small, this depletion might be significant under the existing conditions.

In addition to explaining the setting behavior of Mixture 3, the above observations and explanations are significant in that they suggest that some of the strength decreases, particularly in Mixture 3, might result from the creation of conditions causing Cement B to be badly undersulfated. Such reactions might also have some influence on the behavior of Cement A.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the observations during the deck placement the following conclusions can be drawn:

(1) Concrete delivered by pumping through aluminum pipe is adversely affected by a reaction between the cement paste and the aluminum.

(2) This reaction, which generates hydrogen gas, causes:

expansion of plastic concrete
reduction in strength
reduction in resistance to freezing and thawing
erratic performance of water-reducing retarders.

(3) While variations in materials might mitigate (or aggravate) the reaction to some degree, the reaction observed with the two widely different cements, regardless of the presence of a retarder, the fairly common aggregates of several gradations, and a wide range of slump and air contents, suggests that elimination of the problem by modifications to the mixture would be of secondary importance.

(4) The data obtained as well as a literature review suggest that the lime ($Ca(OH_2)$ as well as the more active alkalies (Na and K) participates in the reaction.

(5) Since the alloy 6061-T6 is among the more resistant available, it is likely that most if not all practically available aluminum pipe would offer the risk of such reaction. The use of cladding would present special costs and monitoring difficulties.

(6) The effects on significant physical properties of concrete placed during the deck placement are completely explained by the increase in void content. From the special demonstration there are suggestions of additional chemical influences, particularly with regard to the setting characteristics, although the data are too limited for generalized conclusions.

In view of these conclusions it is recommended that concrete not be pumped through aluminum pipe. Although some modification of the alloy or internal cladding might mitigate the problem the enforcement of specifications based upon specific alloys would be difficult to administer, particularly in view of the small market for this application and the wide variety of aluminum pipe sold for various purposes.

APPENDIX A

CHEMICAL ANALYSIS OF CEMENTS USED IN SPECIAL DEMONSTRATION

(All values in percent except as noted)

	Cement A	Cement B
SiO_2	21.62	22.24
Al_2O_3	4.01	3.85
Fe_2O_3	4.19	4.23
CaO	64.75	64.75
MgO	2.00	1.44
SO_3	2.16	1.86
Loss on Ignition	0.83	0.91
Na_2O	0.21	0.69
K_2O	0.66	0.06
Na_2O (H_2O Sol.)	0.13	0.06
K_2O (H_2O Sol.)	0.60	0.02
Fineness — Blaine, $cm^2/gm.$	3042	3323
Fineness — Wagner, $cm^2/gm.$	1879	1910

APPENDIX B

CALCULATION OF AMOUNT OF ALUMINUM TO BE REMOVED FOR REACTION

Let:

D = diameter of pipe, in.

W = weight of cement per cubic yard, lbs.

a = weight of aluminum per 100 lbs. of cement, gms.

One cubic yard of concrete must contain:

$$\frac{Wa}{100} \text{ gms of aluminum}$$

Density of aluminum, $\gamma = 2.69 \ \text{gm.}/\text{cm}^3 = 2.69\,(2.54)^3 = 44.08 \ \text{gm.}/\text{in.}^3$

Volume of aluminum to be removed per cubic yard is

$$\frac{\frac{Wa}{100}}{44.08} = \frac{Wa}{4408} \ \text{in.}^3$$

The concrete-pipe surface, S, is

$$S = \pi D\,(l \times 12) \ \text{in.}^2$$

Thus one cubic yard must remove:

$$t = \frac{\frac{Wa}{4408}}{\pi D\,(12\,l)} = \frac{Wa}{4408 \times 12\,\pi D\,l}$$

$$t = \frac{Wa}{5.3 \times 10^4 \ \pi D\,l} \quad \text{(inches)}$$

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