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PAPERS AND DISCUSSIONS

OF GENERAL INTEREST

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CONCRETE TECHNOLOGY

BY MILES N. CLAIR, MEMBER*

(Presented at a joint meeting of the Boston Society of Civil Engineers and of the American Society of Civil Engineers, Northeastern Section, held on April 17, 1940.)

THE first reference to concrete in the Transactions of the American Society of Civil Engineers is in the tenth paper of the first volume which has the title, "Béton-Coignet, Its Fabrication and Uses". This paper was presented by Leonard F. Beckwith, member of the Society, on March 3, 1869. Mr. Beckwith defined the materials with which his paper was concerned as follows:

"Béton-Coignet—is an artificial stone formed of sand, lime and water, and is used in blocks, or in continuous masses."

"Common beton or concrete, is a conglomeration of sand, pebbles, broken stones, common lime, and water."

"Common beton for marine uses is a conglomerate of similar stones, hydraulic lime and water."

The Proceedings of the Boston Society of Civil Engineers do not show a paper exclusively devoted to concrete until a much later date, but there was a reference to portland cement in the paper by Mr. Dexter Brackett entitled, "Description of the Brighton Temporary High Service Works" presented November 19, 1879.

These facts are of interest in that they indicate that among the matters given consideration in the early meetings of the two oldest engineering societies of this country was the art of making mortar and concrete. This was natural because (1) practically all construction

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involved the use of such materials, (2) there was the constant urge to obtain a more durable mortar for masonry and a construction material which could be cast in place or precast to the form required at less cost than masonry made with brick or natural stone.

Mr. Beckwith's definitions of concrete also deserve attention as indicating to some extent the state of concrete technology at that time. Before him there had been centuries of use of mortars and of some kinds of mixtures that could be called and, in fact, were called, concrete. As an example, heading the first list of gifts of specimens of engineering interest, as given by the Proceedings of the Institute of Civil Engineers of the Institute of Civil Engineers of England, 1837, was this description:

"SPECIMENS"

"Concrete. A portion from the South Wall of the Tower of London"
"—Mr. Tucker"

Previous to Mr. Beckwith's paper not only had there been a long period of use of mortars and concrete dating from the Romans, but there had also been the studies by John Smeaton, Parker, Vicat, Frost, Aspdin, and many others. Most of this early work, however, was on the development of hydraulic cements with little attempt to evaluate the other factors entering into mortars and concrete.

During the latter part of the nineteenth century study of cement, mortars and concrete, on a more scientific basis, was fostered by the work of Rene Feret, Michaelis, and LeChatelier, followed in the early part of the twentieth century by S. B. Newberry, A. N. Talbot, W. F. Fuller, S. E. Thompson, and Duff Abrams. A tremendous amount of study and experimentation has been carried on in the past twenty-five years throughout the world and more especially in the United States to determine the true composition of cements, the influence of the several constituents on the properties of cements, the effect of the characteristics of aggregates on the resulting concrete, methods of proportioning, and the relation of water quantity, temperatures and external factors to the quality of concrete. Despite the attention that has been given concrete, only a few fundamental relations have been established and some of the most necessary tools such as a real measure of workability are not yet fashioned.

These studies have been fostered largely by the technical societies and the material-producer associations, with relatively less interest being shown by the contractors or builders who practice the art of making concrete. The attempts by Stanton Walker to apply the water-cement ratio theory of Abrams in the field about 1923, were the first serious efforts since the earlier work of Fuller and Thompson to bring science to the art of concrete construction. There is much science today, but relatively little application of it, to the art of concrete except on very large jobs. The final determination of the quality of the concrete is left largely in the hands of the "Romans" whose native art is debased by the urge of speed in a highly competitive market. The result is that although we get concrete on most work which is reasonably satisfactory, it is far from the quality that could be obtained.

A better known contemporary of Mr. Beckwith, namely, Prof. William J. M. Rankine, gives in his Manual of Civil Engineering, published about 1862, a definition of concrete as, "Common concrete is a mixture of mortar with gravel in proportions such that the gravel and sand together are about six times the volume of the lime." . . . "Strong Hydraulic Concrete, . . . is made by mixing angular fragments of stone of from 1½ to 2 inches in diameter, with hydraulic mortar in such proportions, that the mortar is a little more than enough to fill the spaces between the stones;—a proportion which is easily found by trial in each case." Except for the use of the word "lime" this sounds strangely like many specifications still in use.

Within the last decade, F. M. McMillan[1] defined concrete as ". . . a mass of aggregates held together by hardened paste of portland cement and water" which is about the same thing as Mr. Beckwith's definition of common beton for marine uses except for the substitution of portland cement for hydraulic lime. The element of this mixture which has changed most is the cement or binder. The change came because of the need for greater strength at earlier ages and greater durability.

Since hydraulic lime has always been used to a considerable extent in Europe and is again appearing in our market for certain uses, it may be of interest to consider its composition. The hydraulic lime of the earlier period was naturally of variable composition as it was made by burning limestone containing a small but variable amount of clay, slaking by sprinkling with water and then sieving the resulting

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[1]Basic Principles of Concrete Making by F. R. McMillan, McGraw-Hill Co., 1929.

TABLE No. 1
REPORT OF TEST OF CEMENT

Brand
Bin—34, 35, 36
Barrels—8400
Samples Taken—October 19, 20, 21, 1939
Samples Received—October 24, 1939

Date Briquets Made—October 24, 1939
Temperature - Laboratory—76° F
Storage—70° - 85° F
Humidity - Laboratory—52%
Storage—99%

PHYSICAL TEST

Test No.	% Water	Setting Time - Gillmore Initial > 60 Minutes	Setting Time - Gillmore Final < 8 hours	Soundness 5 Hr. Steam	Soundness P C A Autoclave [< 0.15 %]	Fineness Passing 200 90 - 98 %	Fineness Specific Surface [1700 - 2300]	1 Day Neat > 300#/□"	7 Days Neat > 600#/□"	7 Days 1 : 3 > 275#/□"	28 Days 1 : 3 > 375#/□"	Sodium Sulphate
J270	22.5	2:40	5:35	OK	0.0865	96.0	1730	390	630	330	505	OK
								380	680	320	485	
								360	750	320	475	
275	22.2	2:35	5:15	"		96.2		450	710	350	465	
								380	690	330	445	
								400	650	380	465	
280	22.8	2:35	5:25	"	0.083	95.8	1925	370	610	330	485	OK
								410	660	330	505	
								360	660	370	385	
285	22.7	2:50	5:35	"		95.8		365	710	390	500	
								390	730	330	510	
								375	770	350	520	
290	22.5	2:35	5:30	"	0.0785	96.2	1910	440	720	340	450	OK
								390	740	350	490	
								420	760	370	500	

CHEMICAL ANALYSIS

Test No.	SiO_2 > 21.50 %	Fe_2O_3 < 4.67 %	Al_2O_3 < 5.60 %	CaO [< 65.00]	MgO < 4.00 %	SO_3 < 1.75 %	Loss on Ignition < 0.90 %	Insoluble Residue < 0.30 %	Molecular Ratio < 2.60 %	Lime Silica Ratio < 2.90 %	Alumina Iron Ratio 1.20 - 1.60	Alkalinity < 3.8 %	Free Alkali < 3.5 %
270	22.96	3.42	5.06	62.55	3.51	1.34	.68	.12	2.47	2.73	1.48	2.87	2.20
275	22.72	3.23	5.13	62.50	3.42	1.55	.70	.08	2.43	2.75	1.58	2.92	1.42
280	22.88	3.41	5.07	61.80	3.52	1.59	.75	.08	2.44	2.70	1.48	2.14	.98
285	23.00	3.46	5.06	62.10	3.47	1.58	.66	.14	2.43	2.69	1.46	2.36	1.25
290	22.56	3.50	5.42	62.50	3.49	1.49	.74	.10	2.47	2.77	1.55	2.20	1.11

SUGAR TEST

1st or Phenolphthalein End Point < 8.0 2nd or Final Clear Point < 10.0

Test No.	270	271	272	273	274	275	276	277	278	279	280	281	282
1st End Point	3.08	2.86	3.08	2.66	3.44	3.06	2.96	2.63	2.87	2.98	2.66	2.52	3.16
2nd End Point	3.08	2.86	3.08	2.66	3.66	3.06	3.11	2.62	2.87	3.26	2.66	2.52	3.40
Test No.	283	284	285	286	287	288	289	290					
1st End Point	2.91	2.93	2.60	2.86	3.03	2.90	2.44	3.38					
2nd End Point	3.08	2.93	2.60	3.08	3.20	3.08	2.44	3.59					

product. The limestone used for this purpose contained from 55% to 65% calcium oxide, alumina and iron oxide up to 6% and silica over 13%. Modern hydraulic lime is, by the definition contained in the specifications of the ASTM,[2] "the hydrated dry cementitious product obtained by calcining a limestone containing silica and alumina to a temperature short of incipient fusion so as to form sufficient free lime (CaO) to permit hydration and at the same time leaving unhydrated sufficient calcium silicates to give the dry powder, meeting the requirements herein presented, its hydraulic properties". The chemical composition is prescribed as calcium and magnesium oxides 60% to 70%, Silica 16% to 26%, iron plus aluminum oxides 12% maximum, and carbon dioxide 5% maximum. Hydraulic limes have about 10% of the strength of portland cements at normal construction use ages and are applied in this country only to mortars for masonry and as an admixture for concrete to increase the stick-togetherness of the same. The necessity for the use of the term "stick-togetherness" shows the failure of technical studies to develop to date a measure of workability.

Although it is not the purpose of this paper to extensively explore the subject of cements, the present exploitation of many types makes it desirable to at least indicate the probable usefulness of each type and discuss more fully the important ones. In addition to normal portland cement today, there are used high-early-strength portlands, natural cements, treated, blended or admixture cements and modified portlands.

Normal portland cement, produced under ASTM standard specifications, has been used for some twenty years without much change in specification requirements except an increase in the strength. Much of the attention of the specification committees during this period has been given to the development of test methods both physical and chemical so as to better measure the factors that influence the concrete making value of the cement. This work is far from complete, which is the principal reason for slowness in markedly changing the specifications.

The deterioration of concrete structures as indicated by cracking, spalling and disintegration caused the serious concern (starting about

[2]Tentative Standard Specifications for Hydraulic Hydrated Lime for Structural Purposes, ASTM C141-38T.

ten years ago), of many engineers as to the durability of concrete. The consideration at about the same time of construction of very large dams by the Federal Government where the questions of heat generation, volume change and durability were of vital importance lead to critical examination of the composition of cement and its effect on the qualities of the same. As a result of these studies, and sometimes without full justification but in desperation, the Reclamation Bureau, the New York Board of Water Supply, and others discarded the standard cement specifications and set up their own.

Engineers in general also have gradually come to the conclusion that a single standard portland cement cannot meet all the requirements that arise in use and since Committee C-1 of the ASTM did not move fast enough there have appeared a large number of specifications based on more or less data and finally there came the Federal Specifications covering normal portland, high early strength portland, moderate low heat, and sulphate resistant cement as well as one for Puzzolanic cement. The principal changes in these specifications were in the chemical limitations with the strength properties adjusted to suit. Mr. Thaddeus Merriman not only modified the chemical requirements but also stressed the importance of the effect of manufacturing procedure upon the quality of the cement. Committee C-1 of the ASTM has finally acted and is submitting to that Society a specification which includes five types of cement essentially as follows:

Type 1—Normal Portland Cement which is the same as the present standard specification for portland cement ASTM C9-38 except for the possible addition of a limit of 0.5% expansion in the 5-hour autoclave test.[3] This cement should be satisfactory for unexposed concrete in New England and where volume change is not important.

Type 2—A moderate heat of hydration cement, similar to the Federal Specification SS-C-206, in which the alumina and iron are restricted to a maximum of 6% and the silica to a minimum of 21%. The computed tricalcium aluminate is also limited to 8% and the tricalcium silicate to 50%. A specific surface requirement is given and the strength requirements are slightly lowered. An autoclave expansion limit of 0.5% is included. This

[3]Test for Autoclave Expansion, Proc. ASTM Vol. 38, Part 1, P. 297.

type of cement should be satisfactory for exposed concrete in New England and where low volume change is important.

Type 3—A high-early-strength cement which is the same as the present standard specification for high-early-strength portland cement ASTM C74-39 except for the inclusion of an autoclave expansion limit of 0.5% and a C_3A (tricalcium aluminate) limit of 15%. This cement is of value in the unusual case where 28-day strength is needed in 2 or 3 days.

Type 4—a low heat of hydration cement in which the iron is limited to 6.5%, the tricalcium silicate to a maximum of 35%, the dicalcium silicate to minimum of 40% and the tricalcium aluminate to a maximum of 7%. The specific surface is limited to 1,700 to 1,800 sq. cm./gm. and the autoclave expansion to 0.5%. The tensile strength limits are reduced to 175#/sq. in. at 7 days and 300#/sq. in. at 28 days. The heat of hydration at 28 days is limited to a maximum of 75 calories per gram. This cement is a modified portland and should be satisfactory where very large masses of concrete are to be used and low heat generation is important.

Type 5—A high sulphate resistant cement in which the iron and alumina are limited to 4%, the silica to a minimum of 24% and the tricalcium aluminate to 5%. The same limitations are placed on physical properties as for Type 4 cement except that there is no limitation on the heat of hydration. This cement is a modified portland and should be desirable for exposures where sulphate ground waters or sea water are encountered.

In considering these specifications, it is important to keep in mind first: the limitations of the use of chemical analysis in determining composition, and second: whether or not the desired qualities will be obtained by such specifications.

The researches of Dr. Bates and Dr. Bogue at the Bureau of Standards on the composition of cement lead to the use of compound compositions instead of oxides when considering analyses. Unfortunately, as has been pointed out by others, in discussing the composition of cements the fact is often overlooked that the usual method of chemical analysis does not actually give the amounts or composition of the compounds which exist in cement except possibly for the magnesia. The use of the oxides as determined by the normal analysis or of the compositions derived from the same by mathematical steps only provides a convenient basis for discussion until more is definitely known about cement composition.

Logically a specification should contain only the quantitative values of the qualities desired. What is wanted in a cement for the usual construction such as buildings, roads and small dams is durability, good strength qualities, workability and low volume change. It would appear that the type 2 cement will more nearly produce these qualities. The limits of 1,700 to 1,800 sq. cm. per gm. for the specific surface could better be 1800 sq. cm./gm. minimum to provide a desirable additional early strength and workability. The requirements for tensile strength also should be the same as those for Type I. The autoclave expansion requirements should be reduced to at least 0.25%. Many thousands of barrels of cement have been made under limitations of 0.15% expansion without difficulty and with excellent results in the field.

The autoclave test in one form or another is an old test and the reluctance of the cement industry to allow the introduction of autoclave test limits into specifications is surprising in view of the fact that a number of investigators have pointed out that a limitation on the magnesia content in itself is no certain safeguard against the expansion and disintegration that may occur in the period between the third and tenth year and that the autoclave test is of value for this purpose. It is the author's opinion that in addition to the value of the autoclave test as a measure of delayed expansion that it also gives an indication of the relative total volume change. The autoclave test produces an acceleration in the chemical changes that occur in the hydration of cement. It does this under conditions of ample available water and at a temperature of 420°F. which may or may not cause the formation of compounds which do not form at normal temperatures even over a period of years. These conditions are admittedly different from those to which cement in the concrete is exposed in practice but the author believes from studies on high pressure steam curing that it represents an appreciable part of the potential hydration of the cement and of its volume change. The data of Table 1 shows the relation from a recent test between the volume change of a standard autoclave bar of neat cement 1″ square and 10″ long autoclaved, of one not autoclaved, and of a 1:6 concrete of $W/C = 6.65$ gal./sack made with the given cement. The data is also shown for the same cement blended with a small percentage of another type of cement. It is to be noted that although the difference in volume change is very small between the two sets, the autoclave indications were in the same direction.

TABLE 1

Cement	Autoclave Expansion	Autoclaved Neat Bar	One-Year Shrinkage Neat Bar	One-Year Shrinkage Concrete
A	0.0368″	0.0029″	0.0297″	0.0068″
A Blended	0.0372	0.0034″	0.0308	0.0073″

The limitations on iron oxide, alumina, silica, alumina-iron ratio, tricalcium silicate and tricalcium aluminates are desirable from the standpoint of durability, volume change and heat evolution. Hubert Woods[4] states: "It is well known that resistance to sulphate waters is enhanced by low alumina and iron oxide, or by low potential tricalcium aluminate and tetracalcium aluminoferrite. It appears also that there may be improved resistance, even with the same ferric oxide and alumina, when the ratio of lime to silica, or the ratio of tricalcium silicate to dicalcium silicate, is relatively low." Gonnerman concluded, from an elaborate investigation including freezing and thawing tests, that for good resistance to freezing and thawing the total calcium silicates should be high and the total calcium aluminates low and that tricalcium aluminate was the least desirable of the aluminates. A number of investigators have found that for low heat the tricalcium aluminate and the tricalcium silicate must be limited. Professor Carlson concluded that of the three important potential compounds of cement, "a given amount of tricalcium silicate contributes least to shrinkage, a like amount of tricalcium aluminate contributes most, and dicalcium silicate is intermediate between the other two compounds."

Recognizing the fact that there are many differences of opinion in regard to the conclusions just summarized relative to the specifications for cement of Type II, still it must be accepted that the indications at least are that this cement in general is superior to Type I from the standpoint of durability and volume change. The cement of this type has possibly three disadvantages. The color of the cement is normally dark and when used architecturally may not be desirable

[4]Symposium on Specifications for and Additions to Portland Cement, ASTM Washington, D. C. 3/18/40.

under certain conditions. The early strengths are sometimes lower (5% to 10%) than the Type I cement. The gain in strength with age, however, is generally better. Some cements of this type show a preliminary or false set which may lead to difficulty during warm weather under ready-mixed concrete procedure.

The specification for cement proposed by Mr. Thaddeus Merriman deserves some consideration because it includes limitations on alkalinity and free alkali, solubility in a sugar solution and inspection with certain forms of limitations of manufacture. The presence of too much Na_2O and K_2O lead to excessive efflorescence, less durability, staining of certain stones, such as limestone, and cement burns to workers in fresh concrete. The results obtained with Mr. Merriman's test for alkalinity are variable and affected by other factors than the alkali present. At the present time its use in a specification must be considered experimental. The sugar test is based on the ability of a cane sugar solution to dissolve lime. The purpose of the test is to detect whether or not a clinker is underburned or affected by addition of water or by air storage. The test is influenced by the fineness of the cement, the amount and type of SO_3 and probably other factors. Although there has been considerable controversy over this test, it is recognized to have some value in detecting the type of treatment of the clinker.

The use of plant or manufacturing control is the part of Mr. Merriman's specification which probably received the most opposition from the cement industry and the least approval from those outside and yet it has been of real value to that industry and to the consumers of cement. The purpose was to insure the use of manufacturing procedure which would result in greater uniformity of product and at the same time obtain a record of manufacturing conditions as to temperature, rate of burning, etc. which would be of value in the future if the concrete made with the cement either failed or performed particularly well. It was recognized that conditions varied at the different plants and that the limitations on procedure could not be made too close until more experience was gained. The inspection consisted of seeing that the producer (1) used proper temperature measuring and recording equipment, (2) installed counters for determining the rotation of kilns, (3) set up means of measuring clinker production, (4) arranged by-passes for clinker produced when temperature or other conditions were not satisfactory, (5) quenched clinker with water only over red heat, (6) protected handling and storage of clinker from the weather, and (7) did not add water or other agents in grinding. The Inspector also took proper samples for test representative of the cement as made. Practically all plants making this cement for the first time had no temperature recording equipment or kiln rotation recording apparatus. The flue dust had to be by-passed in order to keep down the alkalinity and by-passing equipment for unacceptable clinker had to be installed. The principal difficulty was in getting the mills to maintain sufficiently high and uniform temperatures.

It is of real interest to note that after the difficulties of manufacture were overcome some of the cement mill operators felt that the cement they were producing under this specification was the best they had ever made. The use of such a specification is desirable where the magnitude of the work warrants the use of every possible precaution. If used for a sufficient number of projects it will eventually improve the uniformity of cement to the benefit of all consumers.

Treated, blended or admixture cements include those (1) in which appreciable quantities of lime, natural cement, slag, diatamaceous earth and many other materials of this type are added to portland cement or natural cement, (2) in which small percentages of stearic acid, tallow, stearates, sulphonated petroleum waste, carbon black and other organic compounds are used. There appears to be some merit to these additions for some special purposes; particularly is this true relative to the improvement in grinding rate by the use of additions of Group 2. The plasterizing effect is usually definite but the claimed waterproofing effectiveness and pozzolonic action is not always reproducible according to the author's investigations. Cements of this group should be very carefully studied before being accepted as there are many still in the experimental stage.

Natural cement deserves separate mention because of its use in blended cements and masonry mortars with claims of superior physical properties relative to durability. Actually Natural or Roman Cement was originally a portland cement with lower lime and higher magnesia content than the usual portland cement. The present ASTM specifications for natural cement, however, state as follows:

"Natural cement is the product obtained by finely pulverized

> calcined argillaceous limestone, to which not to exceed 5 per cent of nondeleterious materials may be added subsequent to calcination. The temperature of calcination shall be no higher than is necessary to drive off carbonic acid gas."

A cement of this type has low strength and good plasticity and under certain circumstances may be of value as a blend.

The study of the effect of aggregate characteristics on concrete lapsed after the early work of Feret, Fuller and Thompson, and Edwards. Recently the attention to this part of concrete has increased as evidenced by the establishment of the S. E. Thompson Prize Award by Committee C-9 of the ASTM and the Stanton Walker Fellowship at the University of Maryland.

The inert materials or aggregates will affect the characteristics of concrete by shape of particle, surface texture, size of particle, strength, and cleanliness of the particle. The shape affects the interlocking of particles and thus the strength, workability, economy and density. Elongated pieces in appreciable proportions definitely reduce compressive strength. Surface texture affects bond and the formation of voids adjacent to the coarse aggregate and thus affects strength. There is very little fundamental data on the effect of surface texture and shape of particle on strength and workability, particularly is this true of artificial aggregates such as slag, cinders and burned clay. Exclusive of the artificial aggregates, the effect of shape on strength would not exceed 15% and of texture 10%. Equally good concrete can be made with gravel or crushed stone but the mixtures must be different for the same workability.

The effect of size and distribution of size or gradation have received a great deal of study. Size alone affects the strength and durability depending only on whether large particles are of material of better strength or surface texture than small particles, assuming, of course, that the size of section in which the concrete is used is ample. Relative to the entire mixture larger particles have less surface area and require less paste to cover them. The distribution of size of particles affects the voids to be filled and surface area to be covered in a given volume of concrete. This affects only the economy of mixtures for a given strength since a given strength can be obtained with a poorly-graded as well as with a "perfect" gradation but at a different

TABLE NO. 2

VARIATION OF COMPRESSIVE STRENGTH OF CONCRETE ON FOURTEEN PROJECTS REPRESENTING APPROXIMATELY 100,000 YARDS OF CONCRETE

		1:6 Dry and Loose Volumes									
		Compressive Strength at 7 days			Max. Deviation From Average		Compressive Strength at 28 days			Max. Deviation From Average	
Project	No. of Tests	Max.	Min.	Ave.	+	—	Max.	Min.	Ave.	+	—
A	101	2580	923	1771	45.6%	47.9%	3660	1785	2634	39.0%	32.3%
B	95	2400	1055	1636	46.6	35.5	3200	1310	2309	38.6	43.3
C	103	2720	650	1597	70.5	60.0	3820	1520	2341	63.0	35.1
D	71	2650	350	1596	66.2	78.0	3390	777	2326	45.8	65.6
E	86	2680	920	1750	53.0	47.4	3380	1590	2400	40.8	33.8
F	98	2820	1060	1953	44.3	45.6	3640	1560	2540	43.3	38.6
G	141	3140	850	2047	53.4	58.4	4400	1610	2788	57.9	42.2
H	86	2770	990	1803	53.6	45.0	3810	1520	2678	42.4	43.3
I	14	2310	623	1326	74.0	53.0	3330	1420	2169	53.6	34.5
J	39	3130	1380	2330	34.3	40.5	4830	2120	3700	30.5	42.7
K	124	2825	810	1895	49.1	57.3	3360	2550	2835	18.5	10.1
L	16	3410	2190	2794	22.0	21.6	4980	3100	3889	28.1	20.5
M	26	3000	1420	2200	36.3	35.4	4450	2455	3219	38.3	23.8
N	124	2960	1270	1986	49.0	36.0	3540	2330	2788	27.0	16.4
			Maximum		74.0	78.0		Maximum		63.0	65.6
			Average		49.8	47.3		Average		40.5	34.4

cost. Since the question of economy relates to proportioning, the gradation of aggregates will be considered more fully under that heading.

The composition of the aggregate particle has no appreciable effect on the concrete strength provided the particle is of adequate strength. Durability is affected if the particles are not chemically stable in concrete and sound relative to physical action of salts or ice. Some differences in strength which in the past were thought to be due to composition have been found to be due to surface texture characteristics of the material. Certain cherts are definitely unstable in concrete while shales, schists and certain sand-stones also have poor resistance to weathering. Most of such unsound materials may be detected by visual examination, by the sodium sulphate test, the magnesium sulphate test, or freezing and thawing tests. The limitations on loss in the standard tests for the number of cycles specified are not sufficiently severe to eliminate poor materials. On important work the aggregates should be investigated by freezing and thawing tests.

The composition of aggregates greatly affects the resistance of concrete to fire. The Joint Committee on Standard Specifications for

Concrete and Reinforced Concrete (1937) gives the following classification:

"Group 1: Blast-furnace slag, limestone, calcareous gravel, trap rock, burnt clay or shale, cinders containing not more than 25 per cent of combustible material and not more than 5 per cent of volatile material, and other materials meeting the requirements of these specifications and containing not more than 30 per cent of quartz, chert, flint, and similar materials.

"Group 2: Granite, quartz, quartzite, siliceous gravel, sandstone, gneiss, flint, chert, cinders containing more than 25 per cent, but not more than 40 per cent of combustible materials and not more than 5 per cent of volatile material, and other materials meeting the requirements of these specifications, and containing more than 30 per cent of quartz, chert, flint, and similar materials."

Materials of both groups are available in New England and where superior fire resistance is desired Group I aggregates should be used.

The strength of the aggregate particles within a wide range does not influence the strength of concrete up to about 2500#/sq. in. The relative freedom of the particles from coatings of organic or inorganic materials which will affect the bond or hydration of the cement is reflected in the strength and durability of the concrete. Very small

TABLE No. 3

VARIATION OF SLUMP ON FOURTEEN PROJECTS REPRESENTING APPROXIMATELY 100,000 YARDS OF CONCRETE

Project	No. of Tests	Max.	Slump Min.	Ave.	Max. Deviation From Average +	—
A	66	5.0"	1.0"	2.7"	85.1%	63.0%
B	51	6.0	1.0	2.6	13.1	61.5
C	75	8.0	1.0	3.0	166.7	66.7
D	36	6.0	1.0	3.5	71.3	71.3
E	44	3.0	0.5	1.9	58.0	73.6
F	49	4.5	1.5	3.0	50.0	50.0
G	72	5.0	2.0	3.8	31.6	47.3
H	42	4.0	1.0	2.7	48.1	63.0
I	5	7.3	3.0	4.5	62.2	33.3
J	37	6.1	2.5	3.9	56.4	35.9
K	71	7.5	1.0	4.6	63.0	78.3
L	21	6.5	3.8	5.0	30.0	24.0
M	27	7.5	3.3	5.0	50.0	34.0
N	56	8.0	2.0	4.2	90.5	52.4
			Maximum		166.7	78.3
			Average		62.5	53.9

percentages of organic matter tremendously reduce the strength. Organic materials of some types not in excess of the usual 250 parts per million in terms of the standard tannic acid test will cut the strength of concrete 50%. Clay films on coarse aggregate can cause reduction in strength of 20%.

The third ingredient of concrete is the water which has been given much attention relative to quantity but not as to quality.

The question of water impurities was comprehensively studied by Mr. Duff Abrams[5] who found decreases in strength for most impure waters of not over 10% and for a few over 20%. The effect of impure water on the setting and early strength is decidedly greater than the percentages given for 28-day strength. In general, it may be stated that water quality which is satisfactory for drinking purposes will normally show no effect on strength of concrete. Swamp and marsh waters, sea water and mineral waters should not be used.

Admixtures for improving concrete seem literally to be without number. Unquestionably certain admixtures have merit under special conditions but the author has found very few such cases where the use of additional cement would not as economically accomplish the same purpose. Where the special properties to be imparted by the use of admixtures are necessary, it would be preferable for the sake of uniformity to use a cement in which the admixture has been added at the mill. Admixtures like admixtured cements should be employed only after thorough study not only of the claims to improve certain characteristics but of the other qualities including those of job handling which may be adversely influenced.

The most information available in regard to the qualities of concrete is that relating to strength. Attention has been given to strength because it is the immediately important factor in most cases and it is the simplest factor to determine. Qualities of durability, imperviousness, fire resistance, and volume change are under many conditions equally or more important but their determination is not as simple a problem and notable progress in determining fundamental relations has only recently been attained. However, as many of the other qualities bear some relation to strength, this characteristic serves in such cases as a convenient measure of the other qualities.

The determination of proportions to produce concrete of a desired

[5]Tests of Impure Waters for Mixing Concrete by Duff Abrams, A.C.I. Vol. 20, 1924.

compressive strength has received more attention than the proportioning for all the other properties combined. The basic principle which has been evolved and which may be stated in many ways is that for a workable mixture the compressive strength is proportional to some function of the water-cement ratio. The relation is naturally greatly dependent on the characteristics of cement and less so on the characteristics of the aggregates. It cannot apply to non-homogeneous or readily segregated mixtures or those mixtures which lack sufficient workability to allow the concrete to form a dense mass under the conditions of placement.

The relation between placeability and water-cement ratio depends on the materials and must be determined experimentally for the given materials. The workability or placeability will be approximately constant with given materials for mixtures with equal water contents per cubic yard. Sufficient cement paste must be available to coat all particles and fill the voids. Increasing the maximum size of the aggregates will decrease the water-cement ratio required for a given workability. Increasing the proportion of the coarser portion of the aggregate will decrease the water-cement ratio required for a given workability.

Inerts or aggregates may be considered as a unit or in division of sizes. Coarse and fine are only relative terms and separations into

TABLE No. 4

VARIATION OF FINENESS MODULUS OF SAND ON FOURTEEN PROJECTS REPRESENTING APPROXIMATELY 100,000 YARDS OF CONCRETE

Project	No. of Tests	Fineness Modulus Max.	Min.	Ave.	Max. Deviation From Average +	—
A	23	3.11	1.99	2.55	22.0%	22.0%
B	30	3.73	2.87	3.23	15.5	11.1
C	39	4.02	2.30	3.17	26.8	27.4
D	57	3.89	2.06	2.91	33.6	29.2
E	59	3.67	2.16	2.88	27.4	25.0
F	72	3.67	1.69	2.83	29.7	40.3
G	54	3.51	2.37	2.88	21.9	17.7
H	60	3.53	2.28	2.89	22.1	21.1
I	22	3.44	2.16	2.97	15.8	27.3
J	47	3.62	2.93	3.15	14.9	7.0
K	130	3.25	2.05	2.76	17.8	25.7
L	57	3.10	1.99	2.72	14.0	26.8
M	32	3.08	2.39	2.73	12.8	12.5
N	148	3.40	2.31	2.78	22.3	16.9
			Maximum		33.6	40.3
			Average		21.2	22.1

coarse and fine are only of value to prevent segregation and to allow combinations to suit various conditions of use. Feret, Talbot, Edwards, Furnas, and most recently Weymouth have studied mortars and the effect of gradations of fine aggregates on the voids and strength. The Fuller-Thompson studies of many years ago developed a theory of maximum density gradation curves which were the first to include coarse aggregate as a unit with a fine aggregate. Also these investigations first included the cement in the consideration of gradation as affecting proportions.

Although by the step gradation theory an excess of intermediate sizes cause interference of particles and thus increase voids and so reduce strength, the fact is that such gradations give very undesirable characteristics to the mixture as to volume change, segregation, and workability. It is still an accepted truth admitted by inference by many authorities, if not actually stated, that from the standpoint of workability if not the theoretical maximum economy of mixture, the best gradation is that of a curve approximating a straight line on a plot of cumulative percentage passing the standard sieves versus the logarithm of the sieve openings. The ASTM specification limits for gradation include such a gradation within its limits but in general the limits are too wide for the best results in a particular case. From the standpoint of cost and concrete quality, it is better to use the aggregate that can be produced economically in a given area with close restriction on its uniformity than to require a special gradation and not restrict the variation in use.

It would be convenient to sit down with a pencil and paper and a few constants of the materials and some universally applicable formulas or charts and come out with the mixture desired for a given set of conditions relating to strength and workability. Fuller and Thompson, Abrams, Talbot and Richart, and many others have proposed methods, all of which are still in limited use. We, unfortunately, lack laws that will definitely relate the properties of the cement to its water-strength ratio or the properties of this paste to the workability-aggregate properties ratio. The simplest and most used procedure therefore is the empirical method of trial mixtures which gives the data for equations and charts usable for computations of mixtures within a limited scope. Aggregates are examined for gradation. Separated aggregates are combined by trial or Fuller-Thompson curve to give a maximum density combination which will give least voids to be filled and thus usually best economy. This combination will normally be somewhat high in the larger sizes, so several combinations close to the maximum density are tried with a range of water-cement ratios and cement contents to give the strength and workabilities desired for the given project. Specimens made with these mixtures for strength tests give the water-cement ratio, strength, workability relations desired.

Durability is not the same quality as strength but studies by various groups have indicated that it is related to the water-cement ratio. The Joint Committee report gives an excellent guide to limitations for the water-cement ratio for various use conditions of concrete. There must be sufficient cement paste present to fill all voids, however, for these limits to apply. Irrespective of the strength exposed concrete should contain at least five bags of cement. However, since volume change increases with paste content and with increased slump for the same paste content, the cement and paste should be kept as low as possible. F. R. McMillan reports data that indicates the volume change of a 1:1:2 mixture to be about the same at 28 days as a 1:2:4 mixture but 50% greater at six months.

TABLE No. 5

VARIATION OF FINENESS MODULUS OF COARSE AGGREGATE ON FOURTEEN PROJECTS REPRESENTING APPROXIMATELY 100,000 YARDS OF CONCRETE

Project	No. of Tests	Max.	Fineness Modulus Min.	Ave.	Max. Deviation From Average +	—
			1½" Gravel			
A	23	8.02	6.92	7.67	4.56%	9.75%
B	30	7.81	6.62	7.35	6.25	9.95
C	40	7.97	6.34	7.28	9.5	12.9
D	57	8.04	6.18	7.65	5.14	6.18
E	53	8.07	7.21	7.70	4.8	6.36
F	18	7.99	6.88	7.70	3.77	10.6
G	18	7.99	7.43	7.76	2.96	4.25
H	40	8.04	7.39	7.50	7.2	1.46
I	9	7.94	7.22	7.56	5.03	4.5
J	42	7.65	7.05	7.20	6.25	2.09
K	12	7.95	6.87	7.50	6.0	8.4
L	38	7.98	7.24	7.47	6.81	3.21
M	13	7.38	7.00	7.18	2.88	2.5
N	102	8.19	6.62	7.12	15.0	7.02
			Maximum		9.50	12.90
			Average		6.16	6.37
			1½" Crushed Stone			
F	41	7.91	6.88	7.42	6.60%	7.28%
G	35	7.86	6.88	7.44	5.33	7.54

One of our greatest handicaps at present in regard to approaching our goal of determining fundamental laws governing concrete quality is in the previously-mentioned lack of a proper measure of workability. A great deal of work has been done but at present the slump test remains the most widely used, which is at its best probably a measure of the consistency which is only one factor of workability. The ASTM has just moved the flow test to a Standard which is possibly a better test of workability than the slump test but still is not a true measure. The best measure we have at the moment is visual examination and experience supplemented by these tests.

Although much still needs to be done to simplify the work of proportioning concrete and to develop fundamental laws, the problem of getting good concrete is not so much the difficulty of determining an economical workable mixture of a desired quality as it is of uniformly and economically getting that mixture in practice in the field. The aggregates vary in gradation and moisture content which causes changes in workability. The normal procedure has been to adjust for these differences in workability by varying the water content which obviously will change the water-cement ratio and yield and cause wide fluctuations in strength and other characteristics.

Changes in mixtures for different gradations involve changes in cement contents if the workability and water-cement ratio are to be maintained. A 10% variation in fineness modulus may cause a change of 15% to 25% in the strength and may have an even greater effect on the slump. It is important therefore to control the gradation.

The best place to correct variations in aggregate gradations is at the source of production. A limitation of the variation of the fineness modulus to plus or minus 0.1 as well as requiring the aggregate to meet the limitations on particular sieve sizes will accomplish the purpose. The tolerance should be applied to the typical sample submitted by the producer as that which he can supply. Variations in gradation due to stock piling and handling can be reduced greatly by proper procedure. Corrections for moisture can be made quickly by several procedures but automatic methods are desirable. Methods based on variation in the electrical resistance of the aggregates have been used with fair success.

Change of consistency or workability of concrete during a pour is an indication that some factor has changed and therefore much attention has been given to the development of methods of measuring such workability while the concrete is still in the mixer. Methods in use are based in principle upon the change in power required to operate the mixer, reaction of the concrete tending to tilt the tilting type of mixer, reaction of the concrete on an obstacle placed in the path of flow of the concrete in the mixer, and the swing back of mixer on release of drum from power drive. A given mixer can be calibrated for given materials and mixes so that some of these methods work well. They need constant attention, however, and the set-ups although desirable are too expensive except for large scale or permanent plants.

The introduction of ready-mixed concrete during the past two decades has changed considerably the picture in metropolitan areas. In principle, the ready-mixed concrete operation allows the proportioning of concrete at central plants which, because of the permanency and magnitude of operations, should be able to have the best of equipment for that purpose. Few of such plants, however, are anything but glorified job plants and very few have automatic equipment for timing, moisture and workability control. Automatic recording of weights of materials and automatic cut-offs are employed at only a few plants although of obvious importance for both the producer and the consumer. Weight measurement gives definitely better control of quantities, making for uniformity but many plants still use volume measurement of one or more ingredients. A large number of the plants operate on the truck mixer scheme whereby the mixing is done on a truck mixer during transportation or at the job. Such procedure is making concrete blindfolded and leaves the control largely to the truck driver or the job foreman or laborer. The only approach to control is by utilizing the truck mixer as a mixer, loading it at the proportioning plant, mixing there, and examining the concrete before it leaves.

The mixing of concrete has as its purpose the combining of the aggregates with the cement and water into a uniform mass. There is involved the mixing of the cement and water and the coating of the aggregates. Mixing too short a time results in failure to combine the materials. A longer time accomplishes this and in addition gets the cement and water combined. Increased mixing time to some point increases workability and strength, after which for a period of mixing up to thirty minutes or one hour no change occurs except some de-

TABLE NO. 6

RELATIVE UNIFORMITY OF STANDARD BRIQUET STRENGTHS FOR CEMENT MANUFACTURED TO MEET STANDARD SPECIFICATIONS WITH NO CEMENT PLANT INSPECTION VS. MERRIMAN SPECIFICATIONS WITH PLANT INSPECTION

Cement, with No Plant Inspection

Designation	Per Cent Spread Maximum to Minimum Relative to Numerical Average 7-day	28-day
A	24.9	18.1
	13.6	16.4
A-1	17.4	13.8
B	7.4	7.6
B-1	15.0	24.9
	16.0	13.1
B-2	13.2	16.8
	19.2	11.1
C	13.0	8.6
	15.4	16.2
Average	15.0%	14.7%

Cement, with Plant Inspection

Designation	Per Cent Spread Maximum to Minimum Relative to Numerical Average 7-day	28-day	Designation	7-day	28-day
A	6.0	10.4	E	13.3	4.8
	9.3	7.7		6.8	8.5
B-1	10.1	4.7	F	18.1	9.3
	10.4	3.6	G	13.9	7.3
	9.6	5.3		5.3	8.3
	13.9	3.3		19.1	13.7
	16.3	8.6		14.6	12.5
	8.7	11.2	H	15.4	12.7
	15.6	9.3		11.4	18.3
	11.6	3.4		13.8	12.2
	13.6	4.6		12.7	6.2
	21.5	13.8		16.2	13.9
	9.2	1.8		13.0	9.7
B-2	12.0	14.6		9.5	12.7
	7.1	5.6		8.3	5.0
	9.8	13.6		12.2	4.2
	15.2	8.5			
D	10.7	17.7	Average	12.1%	9.0%
	10.5	6.2			

crease in slump. After this decrease in slump and strength may be rapid. Very few changes or improvements have been made in mixers until recently although it was recognized that with the increased sizes in use and the drier mixtures generally employed, results were not satisfactory. The tilting type double and single cone mixers with improvement in blading arrangement can mix and handle most expeditiously the large aggregates and dry consistencies for large projects. Truck mixers with elongated bodies give poor mixing end to end. Overloading of mixers of the truck or other type seriously affects the quality of the concrete. Mixers with worn blades and buckets filled with hardened concrete cannot produce properly-mixed concrete and are the cause of much variation in quality.

Much concrete today on large projects and in metropolitan areas because of the use of ready-mixed concrete is not placed until an appreciable period after mixing. The effect of this is not important under normal conditions if the period does not exceed one hour, but there may be very serious consequences in hot weather for rich mixtures, certain placement conditions, and fast-setting cements. The ASTM has an excellent specification for Readymixed concrete which should be used whenever such concrete is allowed.

Properly mixed and proportioned concrete can be greatly damaged by placement. Certainly what is finally wanted is concrete in place no matter what it is at any step previous to this. Chuting of concrete, except for short distances, has become eliminated from most jobs. The objection to chuting arises (1) from its misuse which results in segregation and loss of water from the mass, (2) from the difficulty of control of flow, and (3) from the dropping of concrete from the end causing segregation and improper distribution in forms. The proper procedure is to chute at slopes that will allow flow without segregation and feeding to a receiving and remixing hopper from which the concrete is taken to the place of deposit by other means. Drop bottom buckets will properly handle dry concrete and buggies will best handle plastic concrete. Each allows distribution of concrete more definitely than with chutes. The distribution of concrete on the site by means of the concrete pump is a recent placement development where plastic concrete can be used. It will operate well only when the consistency or workability is kept uniform. Abuses will result from its use, however, if it is allowed to discharge concrete directly into forms.

Getting the material into the forms and getting the concrete distributed in the forms and compacted are two different matters. One of the most glaring failures of modern concrete production is in the placement. On the average project there is not sufficient placement labor and the labor used is not properly directed. Honeycombed concrete cannot be patched with any certainty that it will be durable when exposed to weather. Yet much of the concrete that causes honeycomb can be recognized before it is placed and could be thrown away. The cost of a buggy of poor concrete is small compared to the damage done the structure.

The increased stresses allowed, the design on the basis of continuity, the use of increased strength concrete, all mean thinner sections and more difficult placement. The tendency toward the use of mixtures containing less than 5 bags of cement per cubic yard for such reinforced sections has resulted in considerable poor work. The better procedure is to design for higher stresses and use mixtures containing not less than 5½ bags of cement per cubic yard. The use of plastic mixtures rather than wet to avoid segregation also necessitates a greater amount of work expended for placement of concrete. The use of mechanical vibrators to aid in placement has greatly increased.

TABLE NO. 7

RELATIVE INCREASE OF STANDARD BRIQUET STRENGTHS FROM 7 TO 28 DAYS FOR STANDARD PORTLAND VS. MERRIMAN SPECIFICATIONS

Cement

No Plant Inspection

Average Percentage Increase in Strength from 7 to 28 Days

Designation	% Increase	Designation	% Increase
A	18.7	B-2	20.8
	15.1		28.9
A-1	31.3	C	14.9
B	11.5		14.1
B-1	17.6		
	22.2	Average	19.5%
With Plant Inspection			
Designation	% Increase	Designation	% Increase
A	24.4	D	44.7
	24.5		29.0
B-1	32.9	E	39.6
	39.8		26.6
	25.9	F	30.8
	28.6	G	51.4
	49.8		39.1
	38.5		32.9
	51.6		40.3
	47.5	H	23.5
	40.2		18.5
	35.5		26.1
	39.7		28.8
B-2	36.6		19.5
	47.3		30.6
	41.8		28.4
	42.0		17.1
			25.0
		Average	34.2%

This equipment must be used with care as over-vibration will obviously cause segregation and pump air into the concrete. Its use has real value with concretes of 2″ slump or less. Vibration does not affect concrete strength directly. It allows the use of drier consistencies and thus lower water-cement ratios with resultant increase in strength.

The Proposed Recommended Practice for Measuring, Mixing, and Placing Concrete by Committee 614 of the American Concrete Institute gives some important suggestions on these matters.

Concrete properly proportioned, mixed, and placed may be potentially concrete of ideal characteristics but it will not obtain the potentially possible and desired quality unless it is properly cured. The effect of temperature and moisture on the strength gain, volume change, permeability and durability has been demonstrated by many investigations, but despite the fact that these two factors may have more effect on quality than any other here considered, little attention is given to curing on the average job. The results of freezing are readily observable so attention is normally given to keeping temperatures above freezing during the first few days. Moist curing, however, is limited to half-hearted efforts during the first day or two after placement despite the fact that failure to moist cure for a proper period of 5 to 7 days may result in a 25% reduction in strength and much cracking.

The specifications and building laws under which concrete is made are in many cases a real handicap to good concrete. A 1:2:4 mixture requires usually over 5½ bags of cement per cubic yard but may be inferior to a leaner mixture or one with the same cement content but with a different proportion of coarse to fine aggregate. In the face of this fact much concrete is still specified by arbitrary proportions. The contract specifications for concrete should define the quality of the materials and of the concrete and only so much of the construction procedure as seems necessary to insure the obtaining of this quality. One type of specification will not be suitable for all types of jobs even of small size. The Joint Committee report suggests two methods, one of which allows greater freedom on the part of the contractor in proportioning than the other. The use of a good specification incorporating the practical parts of the developments of the studies of concrete along with strict enforcement so that the Contractor knows that inferior concrete will not be accepted, will help as much as any other factor to bring improvement in the quality of concrete.

"CONTRIBUTION TO A STUDY OF THE ALLEN SALT-VELOCITY METHOD OF WATER MEASUREMENT"

By Martin A. Mason*

(Presented at a meeting of the Boston Society of Civil Engineers held on May 15, 1940)

Purpose of Study

THE measurement of water by the salt-velocity method was conceived by Professor Charles M. Allen, and was described in an article[1] presented by Professor Allen and his assistant, Mr. E. A. Taylor, at the annual meeting of the American Society of Mechanical Engineers in December 1923. The authors stated that the method was conceived primarily to measure simply and accurately the discharge of short concrete conduits of variable section and, more generally, to serve as an accurate measurement method under various conditions.

The article presented the results of studies made both in the laboratory and in the field over a period of three years and the results obtained clearly justified the claim of the authors to have found a measurement method that was simple, accurate, rapid in operation, and which required neither calibration nor the use of an experimental coefficient. It thus appeared that the Allen method offered possibilities for use as a primary standard of measurement.

Subsequent to the publication of Allen and Taylor's article, certain investigations, having as their object a study of the applicability of the method to particular cases, were undertaken in Germany,[2] Switzerland,[3] and other countries. The investigators in each case utilized the technique described in the original article and did not concern themselves with the principles on which the method was based. Further, except for some studies made at Walchensee,[4] the investigations were all in reference to the measurement of flow in closed conduits.

The results of these studies again showed clearly that the method

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[1]C. M. Allen—The Salt-Velocity Method of Water Measurement—Trans. A.S.M.E., Vol. 14, 1923.
[2]O. Kirschmer—Zeit. V.D.I., Vol. 74, No. 17.
[3]Müller—Schweizerische Bauzeitung, Jan. 23, 1926.
[4]H. Rouse—The Kaiser Wilhelm Research Institute—Trans. A.S.M.E., Vol. 54, No. 9.

was simple and quick, but also demonstrated that the accuracy of the measurements could vary through wide limits according to conditions.

These results we believe to be attributable principally to the absence of a true physical conception of the operation of the method and of any definition as to its probable field or fields of application. Those who attempted to use the method proceeded mainly by analogy, without exploring its physical basis or its applicability to the particular use envisaged. It follows that the majority of the comparative tests reported are probably of questionable value for use in defining the field of the method and that they have probably retarded rather than assisted in the development of the method.

The numerous advantages inherent in the Allen method, which make it more desirable for use in certain difficult cases than other methods, justify a further study of the method, whose principal object should be to define its field of application and the possibility of its use in all types of conduits or channels. This paper reports some of the results of such a study undertaken by the author while attending the University of Grenoble, France, as a Freeman Scholar of the Boston Society of Civil Engineers. In the course of the study many problems were encountered, certain of which have been solved, while others, to the contrary, which are simply announced here, should form the object of future research.

The approach to the problem was first to develop a physical conception of the method and the theoretical and experimental means employed to clarify this conception; and, second, to prove this conception by experiment.

Theoretical Considerations

In developing a physical conception of the method it may be noted that certain authors, such as de Haller,[5] have attempted to formulate a theory of the Allen method; but, having based their analyses on physically erroneous or insufficient hypotheses, their studies have not clarified or solved the problem. The most common errors concerning the principle of the method arise either from considering the salt "cloud" as a material screen (analogous to that of

[5]P. de Haller—Considérations théoriques sur la mesure de debit d'eau par la méthode Allen—Helvetica Physica Acta, Vol. III, 1930.

Anderson) without taking account of the continual agitation of the particles and the resultant mixing; or from considering only the influence of local mean velocities and not turbulence velocities in the formation and deformation of the cloud.

Our thesis is that the form and evolution of the salt cloud as it is propagated along the conduit after injection depend directly upon the mean local velocities, such as are measured by current meter or Pitot tube, only when the turbulence is very slight, i.e. at low Reynolds numbers and small head losses; and that as the turbulence increases its effect on the evolution of the cloud becomes more important than the distribution of the mean local velocities. It appears to us that the use of the salt velocity method may be limited to these latter conditions.

This study therefore should be concerned chiefly with the influences of turbulence and studies should be made of at least two flow conditions; one, in which the turbulence is insufficient (Allen method not accurate) and two, in which the turbulence is high (proper field of application of the method).

Before proceeding to a study of the behavior of a "cloud" in water let us consider the flow process in a conduit. First recall the characteristics of two modes or regimes of flow in a conduit or channel.

The laminar or viscous regime, in which one may liken the flow to the sliding of concentric liquid cylinders on each other, much as the elements of a telescope tube;

The turbulent regime, in which the liquid particles are subject to absolute instantaneous velocities widely variable in magnitude and direction.

In the laminar regime the velocities of the particles or liquid filaments are a function of their distance from the walls and the viscosity of the fluid, the velocity distribution and head loss being dependent only on viscosity.

The turbulent regime is characterized by an abrupt augmentation of head losses, which can no longer be attributed solely to viscosity effects, but also to internal losses, many times greater than those due directly to viscosity. These losses appear to result from the formation and motion of a multiple series of eddies, originating at the solid boundaries and dispersed throughout the flowing mass. Every liquid particle in turbulent regime is a part of one of the multiplicity of small eddies and participates in the rotational movement of the eddy at the same time as the eddy is displaced in a body along the axis. The instantaneous vector velocity, more or less inclined to the conduit axis, thus results from a combination of a general movement along the axis and a pulsatory transverse component.

The exact form of the velocity distribution curve depends on the degree of turbulence in the conduit, characterized in part by the size of the existing elementary eddies, i.e. the scale of the turbulence, and in part, by their agitation, i.e. the intensity of the turbulence. Note that the mean velocities considered here represent the average of the instantaneous velocities, in a point of a section of the conduit, of all the particles which successively pass the point, and not the mean of the instantaneous velocities of a single particle over its trajectory. These *latter* velocities are those which are concerned with the true mean velocity in a conduit as measured by the Allen method.

From the description of a turbulent flow regimen it appears that the displacement of a single particle along the conduit is the resultant of a succession of translatory movements and small elementary rotations, causing a continual mixing and interchange of particles. This conception emphasizes the impossibility of the evolution of any "cloud", salt or other, introduced in a conduit depending directly on the mean velocities or their distribution, and shows rather its dependence on the agitation and degree of mixing existing in the conduit.

Thus we foresee that, in a rough conduit, characterized by an elongated velocity distribution curve, a "cloud" introduced into the channel will be preserved as a homogeneous mass regardless of the great differences in mean velocity between various parts of the conduit section, while according to the hypothesis of direct dependence on mean velocities the "cloud" would elongate or draw out at the center very rapidly. One likewise notes the interest attaching to a study of the details of the evolution of a "cloud" based on following the exact motion of the liquid particles by means of streak lines. A new process for the observance of these lines will be described later.

The preceding description of the character of turbulent movement in a conduit shows how liquid particles, of a density very close to that of water, when injected into flowing water, are entrained and tossed about by the multitude of small eddies which characterize the flow. It has already been noted that the entrainment and mixing of the injected particles takes place, not under the influence of the mean local velocities, but under the action of instantaneous velocities. The mean of these latter velocities is obviously the true mean velocity of flow.

It may be stated here that the effect of molecular diffusion on the mixing process may be neglected in the study of "cloud" propagation, primary importance attaching to the stream turbulence.

As the cloud progresses along the conduit it increases in length as a result of the mixing process. The mean cloud velocity will therefore be defined as the mean of the velocities in the sense of flow of all of the injected particles. If the mixing between the injected and the water particles is sufficient the mean cloud velocity as defined is equivalent to the mean velocity of flow.

Consider a salt cloud, of any size or shape, traveling along a channel or conduit. Its shape and size both change continually by reason of the particle movement under the action of the stream turbulence. Let L be the axial distance traveled along the conduit by a salt particle p_1. The average axial distance traveled by n identical particles is then $L_n = \frac{1}{n}\int_0^n L$; which is recognized as the equation of the center of gravity of a group of n identical particles. Thus, regardless of the shape assumed by the cloud, one can obtain its mean velocity by measuring the velocity of its center of gravity.

The cloud injected into the water, and dispersed among and mixed with the water particles after traveling a certain distance, may be represented by a curve of cloud concentrations with respect to cloud length. (Fig. 1.) If we accept the hypothesis that in highly turbulent flow the motion of the water particles is completely at random, then at a certain distance from the point of injection all these distribution curves will take on the appearance of Gauss or normal distribution curves. We will designate the distance from the injection point to the point at which the bell curve distribution is first obtained as the "effective good mixing length" a term whose importance will become evident later.

The conception presented of the nature of turbulent movement accords with observation to prove that, always under the assumption of sufficient mixing, the initial cloud form always disappears, and

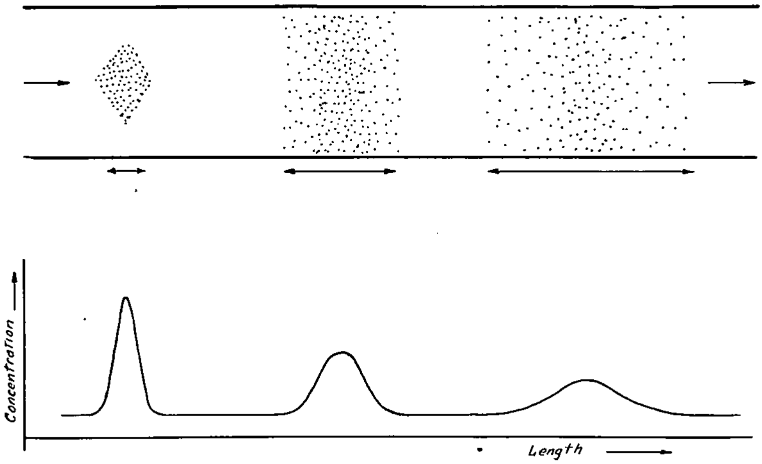

FIG. 1.—DIFFUSION OF AN INJECTED CLOUD

after a certain distance has been traversed, the successive forms taken on by the cloud are independent of the initial form. If, therefore, one wishes to establish mathematically the law of evolution of the cloud on the basis of turbulent flow theory, it is permissible to assume a simple initial cloud form, e.g. that of a thin screen.

An identical conclusion is found in probability calculus when one studies the successive permutations of a large number of objects mixed indiscriminately from some initial disposition. Whatever be the initial order or distribution of, for example, a number of playing cards, one always finds the *same* probability for a given distribution after a certain number of mixings. This principle has been described by Poincaré as the "principe ergodique".

It appears to be accepted that in a uniform canal with high turbulence the mixing of the injected particles with the water is completely at hazard since the motion of the water particles is random. We may therefore assume that an initial plane form is transformed according to Gauss' law, and if one likewise admits that every elementary plane section of a Gauss curve is transformed according to the same law, then one finds that the entire bell curve is transformed into some other, flatter, bell curve, whose reduction in height is proportional to $\sqrt{L}$, where L designates the distance along the conduit axis from the point of the initial Gauss curve to the points of each of its succeeding states. It is probable moreover that this law of reduction is sensibly valid for all bell curves other than that of Gauss, on the hypothesis that they are transformed into curves of the same family by successive sections.

In the course of the preceding examination of the physics of the Allen method account has not been taken specifically of the nature of the cloud particles. In fact, the discussion is perfectly valid for any sort of particles, including the case of an isolated group of particles of the flowing water itself.

To be enabled to actually follow the evolution of definite particles it suffices to modify or change in some way some property of the transporting liquid or to add to it some property not previously existent. If one can perceive and measure with precision the variation of this property with respect to time one has, obviously, a means of measuring the mean cloud velocity, and, therefore, the discharge of the conduit or channel.

It will be recalled that in the Allen method the passage of a salt cloud past electrodes is detected and registered by means of a galvanometer placed in an electrode circuit. The time required for the cloud to traverse a section of the conduit limited by two pairs of electrodes is determined by the successive registration of the variation of conductivity of the electrode circuits as the cloud passes. The exact time of traverse is defined on the current curves registered as functions of time, as the elapsed time between certain mean points of the curves. The determination of these points will be discussed later.

The measurement of the variations of electrical conductance of the water caused by the passage of a salt cloud is nothing more than a means of following the movement of the salt cloud, whose mean velocity over the conduit section defined by the measuring electrodes is to be determined. For this purpose it is necessary to know the relation which must exist between the concentration and the conductance of the salt-water mixture in order that the location of the mean point of the cloud may be determined from the registered current curves. Similarity between the concentration curve of the cloud (whose deformation we will suppose to be interrupted during its passage past the electrodes) and the registered current curve is possible only if the conductance of the cloud varies linearly with the concentration of salt particles in the cloud. This is actually the case, for, although saturated salt solution is usually injected, its dissociation due to mixing is so rapid that, at normal temperatures, one quickly arrives at the zone where concentration and conductance are proportional.

Under these conditions, if a potential difference E is applied to two electrodes separated a distance l, the total instantaneous current resulting is $I = \frac{EA}{\rho l}$, where ρ is the specific resistivity of the solution and A is the area of the electrode plates. Replacing the resistance by the conductance $\frac{1}{\rho} = kn$ (n being the number of salt particles per unit volume of salt-water mixture and k some constant) it is noted that the total instantaneous current is proportional to the affected area of the electrodes and the cloud concentration.

In the discussion of the physics of the method there is considered the exact moment when the mean point of the cloud passes the electrode pair, but in practice, the measurement of the electrical conductance of the cloud—which is, of course, not effected for the entire cloud instantaneously—is characterized by a displacement on the current curve of the point corresponding to the mean point of the cloud. This displacement is a result of the cloud evolution which takes place during its passage past the electrode, for, since the cloud is longer than the space separating the electrodes of a pair, the electrodes measure the cloud concentration by successive cross-sectional increments rather than instantaneously. This point is important when determining the mean points of the current curves between which the fundamental time of passage measurement is made.

If it is supposed that the cloud ceases to change form at the moment of measurement and if the spacing of the electrodes is small, the cloud may be considered as being stationary and the electrodes as traversing the cloud; the resulting current curve will represent the cloud distribution since the current is proportional to the salt concentration, and the mean points of the cloud will be represented by the centers of gravity of the current curves.

The time required for the cloud to traverse the measuring section will then be measured by the distance between the centers of gravity of the two registered current curves. This is the method suggested by Professor Allen; but, for such reasoning to be valid it is necessary that the passage time of the salt cloud past an electrode pair be sufficiently short that the cloud deformation during the registration is negligible.

In reality such is not the case, particularly for the passage past the second, or final, electrode pair. The registered curves will, therefore, be deformed in the sense that they do not represent an instantaneous image of the cloud but rather a composite image of portions of the varying figures assumed by the cloud during its passage. The effect is to cause a drawing out or attenuation of the latter section of the curve; the abscissa of the center of gravity of the registered curve no longer representing under these conditions the center of gravity of the cloud. It should be noted that we have considered curves relating cloud concentration and cloud length to represent the cloud, while the registered current curves relate cloud concentration to time. The deformation under discussion could then also be described by stating that the registration time is not proportional to the cloud length.

However, in the particular case which has previously been discussed in connection with the description of the cloud evolution, i.e. where the initial form of the cloud could be represented as a Gauss curve which was continually transposed by elementary sections, it can be shown that the abscissa of the displaced center of gravity is moved a constant distance ahead of the true center of gravity; so that we may, regardless, employ the registered curve centers of gravity for the time measurement. This property has been verified only for an initial distribution and subsequent evolution in the form of a Gauss curve.

Experimental Verifications

Having formulated a concept of the physics of the salt velocity method experimental verification was sought. It will be recalled that the object of this study is to define the limits of application and the conditions of use of the Allen method by means of a study of its physical basis. In the course of the investigation we have not sought to determine the precision of the Allen method when properly employed, but rather to define the importance of the character of the flow regime on the form and evolution of the injected cloud. Certain tests to be described were made for the purpose of verifying the conclusions reached analytically.

Tests were performed in two adjoining concrete channels; one of rectangular profile (43 cm deep, 52.5 cm wide), the other parabolic (40 cm deep, 89 cm wide), each 18 meters long.

The injection apparatus was similar to that usually employed; the design permitting modification or substitution of the various injection valves.

Grill electrodes covering the entire cross-section of the channels were constructed of brass screen. Several portable miniature plate electrodes connected to an oscillograph were used to study cloud structure.

Current curves were registered on a direct current recording ammeter with a range of 1 ampere and sensitivity of the order of 10 milliamperes. The ammeter, current source and electrodes were connected in series and a switch in the circuit was arranged so that only one pair of electrodes could be in circuit at a time.

The first tests were designed to show, by means of colored injections, the general forms of an injected cloud in flowing water. Colored water could have been used for these tests in place of the colored brine actually employed but it was felt to be preferable to study the behavior of the solution usually used. The evolution of the cloud was studied as a function of the distance traveled and of the degree of turbulence.

To facilitate comparison photographs were taken of the most characteristic cloud forms resulting from changes in flow character or injection procedure. Obviously this method does not permit of a study of cloud concentration, being limited only to the definition of cloud shapes and sizes. Studies of concentration in the various sections of a cloud will be described later.

The coloration tests confirmed the thesis that the cloud form changed constantly. It was not possible to determine whether or not the colored salt particles moved in the same manner as the surrounding water particles, however, verification of the similarity of movement was later established.

The form assumed by the cloud front under the action of the entrainment forces approached that of the distribution curve of the mean local velocities, while the rear portion of the cloud was usually characterized by long tails in the neighborhood of the channel boundaries. At low velocities of flow and low Reynolds numbers these trains or tails may approach or exceed in length the main body of the cloud; while at high flow velocities they are greatly reduced and may not even exist.

Attempts were made to relate qualitatively the dispersion of the cloud to its distance from the point of injection by noting visually the color density of the cloud at various distances from the point of injection, in both channels.

In the rectangular canal the color appeared quite uniform at a distance of 10 m from the injection point for a flow velocity of 0.25 m/sec. At higher velocities the cloud was more concentrated but very irregular in distribution.

In the parabolic canal the color distribution was uniform at a distance of 10 m from the injection point for a flow velocity of about 0.40 m/sec., while for a flow velocity of 0.60 m/sec. it was still irregular at 16 m, the maximum observable in the canal. It will be noted that the same behavior was observed for both channels, a decrease in length and increased irregularity as the flow velocity increased.

The influence of the shearing forces at the channel boundaries on the cloud form and distribution was studied by changing the roughness of the boundaries. The walls of the parabolic canal were lined with a 0.5 cm mesh screen over a distance of about 10 m. Visual observation of the cloud form and distribution under these conditions showed that for a flow velocity of 0.40 m/sec. the minimum distance required to establish a uniform distribution was about 7 to 8 m, increasing to about 15 m for a flow velocity of 0.70 m/sec. The distribution appears thus to be aided by an increase in wall roughness —for smooth walls and a flow velocity of 0.40 m/sec. the good mixing length was 10 m, whereas for rough walls and the same velocity of flow this distance was reduced to 7-8 m. On the other hand, for the case of rough walls the cloud length was greatly increased, especially at the lower velocities. For instance, at a velocity of 0.10 m/sec. the cloud was observed at two stations separated 10 m. In that distance its length increased from about 0.5 m to about 4 m. Note, however, that these conditions represent an extreme case, probably outside of the range of use of the cloud method. At high flow velocities (above about 0.50 m/sec.) the change in cloud length in the short channel length available was too small to be noted.

The preceding results show the existence of a minimum distance from the injection point which the injected cloud must traverse before its distribution becomes sensibly uniform over the channel cross section and its concentration curve, considered as representing the cloud, approaches a bell curve. This distance, which we have called the effective good mixing length, appears to be a function of, at least, the flow velocity, the nature of the solid boundaries, and the form of the channel. It is probable that a mixing length criterion may be found of the form: $M = f(U)\,AT$ where M is the mixing length, $f(U)$ is a turbulence parameter, A the channel area, and T, a time.

The fact that the mixing length increases with the flow velocity as noted above is not in contradiction with the increase in turbulence with velocity. For above a certain minimum velocity, the effective *time* for good mixing corresponding to the ratio of the effective good mixing length to the mean velocity should decrease.

While traversing the effective good mixing length the cloud may not be employed to determine precisely the mean flow velocity because of its rapid changes in shape and concentration. Under these conditions there is no constant relation between the velocity of the center of gravity of the cloud and the velocity of flow, and it follows that a choice of standard points on the registered current curves for the measurement of passage time is therefore impossible.

The color tests described previously were not suited to a study of the details of the cloud structure and the variations of concentration in the cloud. In order to study the local changes in concentration with distance traversed from the injection point recourse was had to miniature electrodes connected to an oscillograph. It was hoped by this means to gain some idea as to the nature of the local evolution of different portions of the cloud, those close to the boundaries, in the center, or close to the free surface. Further, this method permitted a qualitative comparison of various injection procedures. The object of these tests was to formulate a clearer conception of the effective good mixing length and to obtain more complete information on the true behavior of a salt cloud in differing flow regimes.

In a turbulent mass of water composed of numerous superposed groups of eddy movements, of different sizes and intensities, the eddies

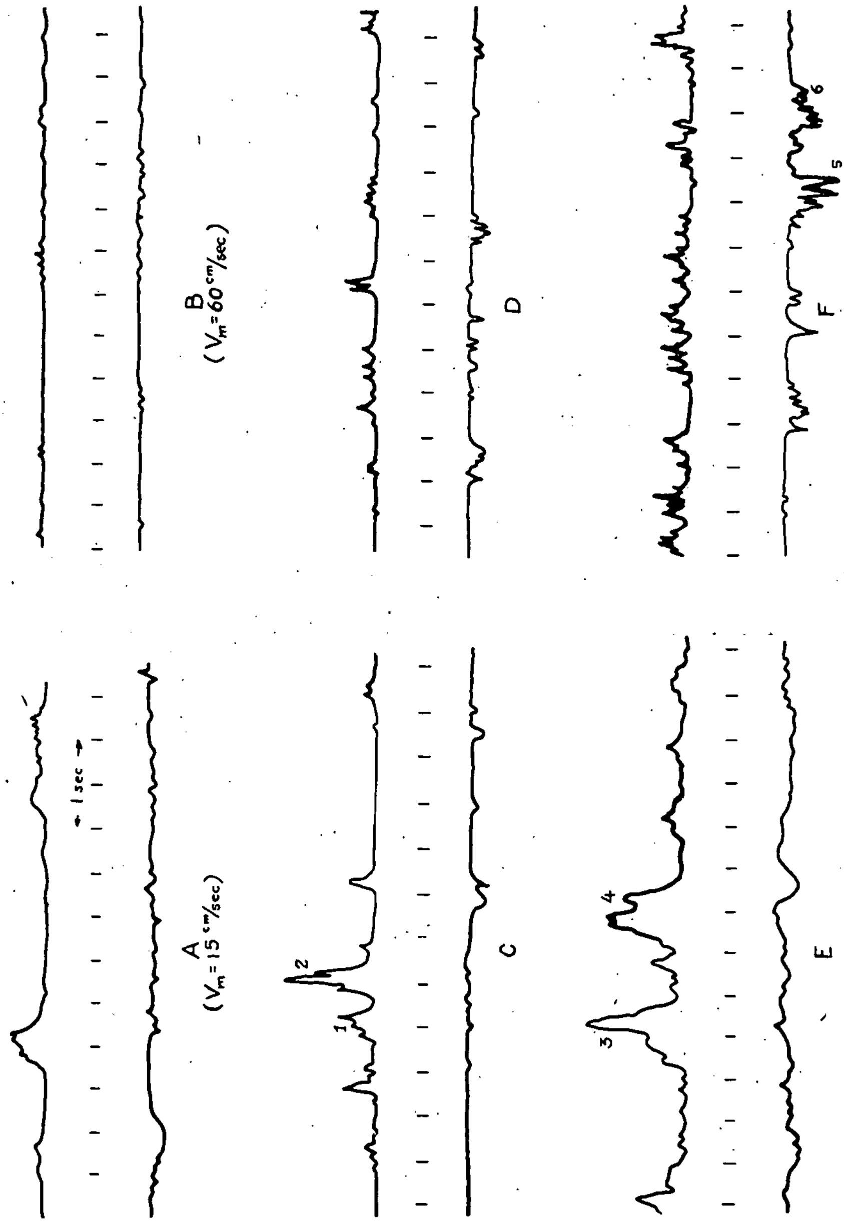

FIG. 2.—OSCILLOGRAMS SHOWING MIXING IN VARIOUS PARTS OF CHANNEL

of relatively large scale are capable of carrying a mass of water from the wall to the center of a channel more rapidly than a small eddy. But if these large eddies are not then dissociated into small scale eddies, one would have only a series of large groups, which would not result in good mixing. The importance to the Allen method of distribution of eddies of varying scales and intensities is apparent, as is its effect on the magnitude of the effective good mixing length. The tests reported are limited to a qualitative study of the problem rather than an attempt to define precisely the nature of the turbulence existing. It is proposed only to note the mixing of the water and the injected salt solution at various distances from the point of injection.

Results of the tests are shown in Fig. 2. For all curves shown in Fig. 2 the electrodes were located 0.50 m downstream of the injection nozzle.

Fig. 2 (A, B)—Oscillograms obtained with a continuous injection placed 2 cm from a side wall and 2 cm above the channel bottom. Curve A for flow velocity of 0.15 m/sec.; Curve B for a velocity of 0.60 m/sec.

Fig. 2 (C, D) Typical oscillograms obtained with the injection 2 cm from a side wall and 1 cm below the free surface, Curve C, flow velocity 0.15 m/sec.; Curve D, flow velocity 0.60 m/sec.

Fig. 2 (E, F) Typical oscillograms obtained with the injection in the channel center line 1 cm below the free surface, Curve E, flow velocity 0.15 m/sec.; Curve F, flow velocity 0.60 m/sec.

The effect of the tangential shearing forces at the wall is clear from a comparison of curves A, B, and C, D. In the case of curves A, B the first electrode was located 3 mm from the wall and 2 cm above the bottom, the second 3.8 cm from the wall and likewise 2 cm above the bottom. For a velocity of about 0.60 m/sec. (Curve B) it is seen that the mixing of the water and salt solution is quite intimate near the wall and the bottom at a distance of only 0.50 m from the injection point, while at the same distance but for a velocity of about 0.15 m/sec. (Curve A) the mixing is poor.

For Curves C, D the injection was made 1 cm below the free surface. It is apparent that the free surface has only a slight effect on the mixing process. The influence of the surface increases with an increase in the flow velocity but never becomes as important as that of the solid boundaries. Curves A and C are significant in this connection; Curve A contains numerous deviations with more or less rounded points, showing that the mixing in this portion of the canal is probably due to a large number of eddies of variable size and shape whose movement rapidly disperses the salt solution. Curve C contains fewer deviations, but these are characterized by acute points, indicating the passage of isolated eddies of large dimensions, high concentration, and slight mixing influence.

Comparison of Curves C, D and E, F shows the difference existing, from a mixing viewpoint, between the central portions of a channel and those in the neighborhood of the solid boundaries. The influence of the flow velocity on the degree of mixing is evident.

It is interesting to note that even in the central regions of the channel, where one would expect to find a preponderance of large scale eddies, a large number of small scale eddies are also present. It is surprising to observe small scale turbulence of this magnitude in the center of a channel, since it is generally admitted that the decay of small scale turbulence in the regions removed from a solid boundary is very rapid. The probability is that the small eddies are maintained or perhaps even formed by the rotational movement of larger scale eddies of which the smaller eddies are satellites (e.g. see points 1 and 2 of Curve C, 3 and 4 of Curve E, and 5 and 6 of Curve F).

These curves also appear to give evidence that the scale of turbulence produced in a channel is dependent on the flow velocity, turbulence of small scale corresponding to the higher flow velocities.

In the light of these results one may conceive of the mixing process between water and salt solution as taking place in the following manner: the injected solution is dispersed over the entire channel section by the action of the velocity components of the larger eddies without any appreciable mixing between the two liquids, at the same time that the injected particles are mixed intimately with the water near the solid boundaries by the small scale eddies formed there. This double mechanism continues simultaneously resulting finally in the injected particles being distributed in a more or less regular manner throughout a certain volume of water. Simply, one might say that small quantities of salt solution are carried in every direction by the transverse components of velocity and then dissociated and absorbed by the small eddies until the ensemble is assimilated by a definite volume of water.

The importance of the rotational movements arising from the tangential shearing stress at the solid boundaries in the mixing process is apparent. The oscillograms of Fig. 2 demonstrate the rapidity of mixing near the solid boundaries and the slower process in regions removed from the walls.

Fig. 3 shows that the favorable effect of the solid boundaries in promoting mixing decreases rapidly with distance from the boundaries. These curves were obtained by placing small electrodes at mid-depth of the stream and at one-half and one-quarter of the channel width

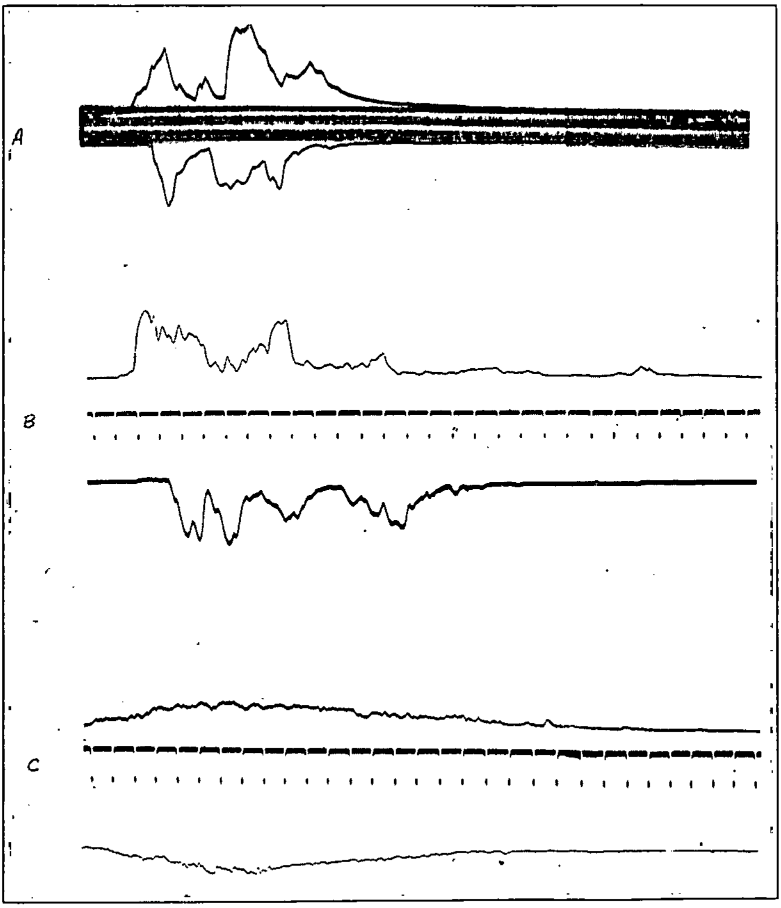

FIG. 3.—OSCILLOGRAMS OF CLOUD STRUCTURE

from a channel wall, in cross-sections at varying distances from the injection point. On the assumption that the mixing effect described above extends progressively from the wall toward the center of the channel the curve registered for the electrodes at one-fourth width should show a difference in form from that for the center electrodes.

Curves A, B, and C represent the cloud form and distribution at distances 1, 3.5, and 11.5 m from the point of injection. Several other curves obtained at intermediate distances show the same behavior as these curves and therefore have not been included.

It is seen that there is no essential difference in the nature of the cloud at the two regions studied, which seems to indicate that the mixing conditions are similar in the major portion of the channel section. At the flow velocity utilized, 0.60 m/sec., the cloud concentration was not yet uniform at a distance of 11.5 m from the injection point, verifying the qualitative results obtained by coloration tests.

Fig. 4 shows oscillograms obtained for point electrodes situated in two profiles respectively 3.5 and 11.5 m from the injection point and at one-half and one-fourth the channel width. Devices creating turbulence were located every 2 m between the two cross sections.

Comparison of Curve C, Fig. 3 and Curve B, Fig. 4 indicates

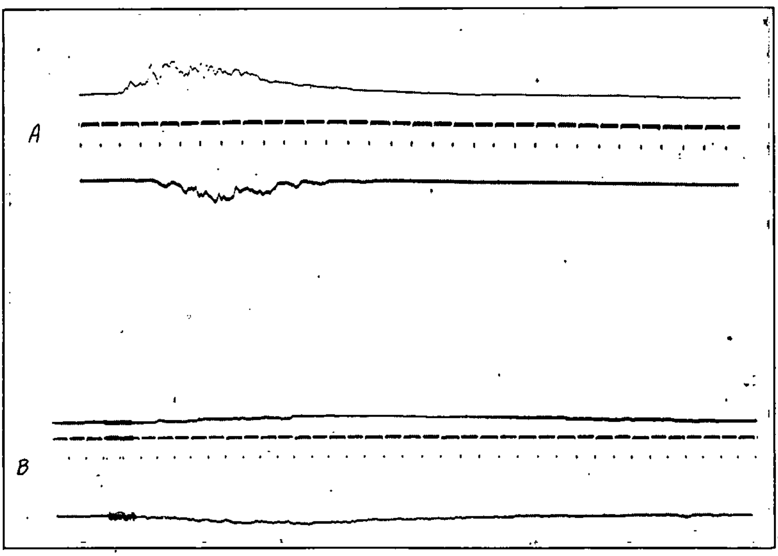

Fig. 4.—Oscillograms Showing Effect of Mixing

that the artificial turbulence thus introduced has sensibly improved the cloud distribution, which is, however, not yet homogeneous.

In all the preceding oscillograms the elongation of the salt cloud with distance traversed is evident. Unfortunately this elongation could not be studied with benefit because of technical difficulties in the registration by oscillograph. Therefore, we have not been able to verify systematically the law of evolution of Gauss curves previously announced. Some of the registered current curves do nevertheless show agreement with this law.

Following the oscillograph studies of cloud structure, attempts were made to render visible the motion of the water and salt particles and the mixing mechanism of turbulence by means of some of the methods commonly used for analogous research in air and water. As usual, however, the observation of the injected color solutions was rendered difficult by reason of the light diffused by the impalpable organisms or dirt in suspension in the water. It seemed logical therefore to seek a means of eliminating all parasitic light and at the same time augmenting the visibility of the flow lines whose behavior it was desired to study.

The new process developed for this purpose is based on the use of so-called black light (ultra-violet radiation) and fluorescent substances. As under these conditions one operates in almost total obscurity, only the fluorescent substance which is made visible by the ultra-violet light is observable. Certain of these substances emit a very intense light when exposed to ultra-violet radiation, making their observation and photography relatively easy.

Various substances were studied to ascertain those best adapted for use in the method. Chief among the substances examined were the various rhodamine and diazol organic dyes. The best of the materials studied was disulphogamma, perhaps better known as G-acid, or 2 naphthol, 6-8 disulphonic acid. Solutions of this acid were found to be particularly suited for photographic purposes, emitting very actinic blue light even for dilutions of 1 part in 50,000 by weight.

A slight surface tension exists between solutions of G-acid and water. If the turbulence is sufficiently intense the colored filaments are quickly dissociated by the turbulent movements into a series of small elements which retain their identity for some time due to the physical properties of the solutions.

It is seen that it is relatively easy by this new process to observe the mechanisms of turbulence; while the use of a solution which diffuses rapidly, such as potassium permanganate, results only in a colored cloud, making the observation of individual flow lines impossible.

Another advantage of this new process employing substances resistant to diffusion, is the possibility of making adjoining injections of different colors under ultra-violet light, thus permitting a study of the mixing of the two solutions. By a proper choice of substances the two injections can be made to retain their distinctive colors even when mixed.

The mechanism of turbulence was observed by the ultra-violet light method at various points in the canals and for numerous velocities of flow. Observation was made of the laminar flow in the boundary layer, the transition region from laminar to turbulent flow, and the change in nature of the turbulent flow at varying distances from a solid boundary. It was also possible to note the individual rotation of single eddies as well as the displacement, in the direction of flow, of groups of eddies.

Throughout the extent of the channel the eddies turned in all senses and their axes were oriented in every direction. However, in the neighborhood of the walls the axes of the eddies tended to become vertical and parallel to the wall, with the sense of rotation corresponding to that of a wheel rolling on the wall occurring most frequently. These tests confirm what has previously been said concerning the mechanism of turbulence and by consequence lend weight to our conception of the *modus operandi* of the Allen method.

The scale of the observed turbulence varied over a wide range. The angular velocities of the eddies were quite variable, the higher velocities apparently being associated with smaller eddies.

The mixing mechanism near the wall has a character quite different from that observed in the center of the channel where it is practically impossible to observe the displacement motion of the eddies.

A series of photographs were made with long exposures to determine the mixing angle at the point of injection. It is evident that the effective good mixing length previously discussed will be shorter as the mixing angle is larger. Also the magnitude of this angle should be related to the distribution of velocity. In effect, in a channel with a uniform velocity distribution it is not necessary to have a high degree of mixing, whereas for a non-uniform distribution a high degree of mixing is essential in order that the salt cloud evolution be not affected chiefly by the mean local velocities.

The study is particularly interesting from this point of view. It was found that the mixing angle varied considerably following the distance from the solid boundaries (See Table I). The mixing angle

TABLE 1

Location of injection nozzle in channel	Mixing angle, measured degrees
4 mm below the free surface:	
and { 2 cm from wall	9.2
at middle of channel	5.7
Mid-depth of channel:	
and { 2 cm from wall	9.1
at middle of channel	4.6
4 mm above channel bottom:	
and { 2 cm from wall	10.4
at middle of channel	8.0

Mean velocity of flow = 0.30 m/sec.
Reynolds number corresponding = 3.4×10^4

is seen to be larger as the gradient of the mean velocities increases. This is an advantage for the Allen method as the turbulence is most intense in the regions where it is most useful. Also these tests show the relative unimportance of the effect of the velocity distribution when the stream turbulence is high.

It should be noted that the mixing angle has previously been studied experimentally by Schubauer,[6] and theoretically by Taylor[7] and Von Karman.[8] Schubauer's tests concerned relatively homogeneous turbulence in a channel with a sensibly uniform velocity distribution, whereas in our tests the velocity gradient was not negligible. It appears probable that this line of study might permit a more profound experimental or theoretical study of the Allen method than we have been able to make.

[6]G. B. Schubauer—A Turbulence Indicator Using the Diffusion of Heat, N.A.C.A. Report No. 524.

[7]G. I. Taylor—Diffusion by Continuous Movements, Proc. London Math. Soc., Vol. 20, Aug. 1921.

[8]T. H. Von Kárman—The Statistical Theory of Turbulence, Jour. of Aero Sciences, Feb. 1937, Vol. 4, No. 4.

In theoretical studies of turbulence it is convenient to consider the turbulence as isotropic and homogeneous, but we believe that, to the contrary, studies of turbulence effects in the Allen method should take note that the chief cause of turbulence is at the solid boundaries, and that the various phenomena depending on the turbulence, e.g. a velocity gradient, mixing angle, etc. vary following the distance from a boundary.

TABLE 2

Approximate mean velocity m/sec.	Difference from measurement by weir	
	Fan type injection	Cone type injection
0.25	+4.55	+5.28
	+2.74	+5.86
	+2.58	+3.52
	Average +3.29	Average +4.89
0.35	+3.04	+3.66
	+3.76	+5.75
	+3.40	+6.10
	Average +3.40	Average +5.17
0.50	+3.04	+2.77
	+3.40	+1.91
	+0.54	+2.77
	Average +2.33	Average +2.48

Injection pressure = 20 m head of water.

It has been stated that if the degree of turbulence is high, and if the distance of the initial pair of electrodes from the injection point is sufficient, the mode of injection is not important (ergodic principle). In practice this consideration becomes of little value if for a given case, the effective good mixing length required to realize this independence is extremely large. For this reason there is interest in studying means of diminishing the required length. Further practical considerations dictating such a study are the fact that measuring electrodes cannot always be placed where desired, and the measuring sections available are usually not of great length. The measuring section should be preferably rather short as one avoids thereby an excessive attentuation of the salt cloud and current curve which may result in large errors.

The conception of mixing length helps us to explain the contradictory opinions which have been expressed concerning the mode of injection. For example, experiments made at Walchensee[4] indicated that the mode of injection is unimportant. However, the promoter of the method, with whom we agree, states that the injection conditions should not be ignored. Following our thesis the mode of injection is of greater importance under conditions of low flow velocity and low head losses than under conditions of high flow velocity and, in general, the importance increases as the turbulence decreases. Thus, in the Walchensee tests at high Reynolds numbers it is to be expected that the injection procedure would appear to be unimportant.

TABLE 3

Approximate mean velocity m/sec.	Difference in % of Allen method measurements from weir measurements — Injection pressure = 5 m head of water	Injection pressure = 20 m head of water
0.15	+2.48	+2.89
	+2.48	+0.26
	+6.34	+6.32
	Average +3.77	Average +3.16
0.25	+3.10	+2.90
	+5.32	+3.66
	+2.66	+4.57
	Average +3.69	Average +3.71
0.35	+3.48	+3.04
	+3.85	+3.76
	+3.52	+3.40
	Average +3.63	Average +3.40

The ideal injection would be one which resulted most rapidly in the theoretical normal form of evolution of the salt cloud in the particular channel involved, for, as the initial electrodes should be placed downstream of the point where this distribution is first achieved, the result is shortening of the required channel length. Thus a careful study of the injection conditions may be of value even though the stream turbulence be high. In other words the minimum effective good mixing length is practically always a function of the mode of injection. Thus there is no contradiction in the theoretical and experimental study of, on one hand, the normal evolution of a salt cloud as though it were independent of the mode of injection, and, on the other hand, the influence of the mode of injection on the primitive phases of this evolution; the important point being to determine where the initial electrodes must be placed with reference to the point of injection.

Studies were made of injection conditions by the use of colored solution. It was found, as might be expected, that the initial form of the cloud was very dependent on the mode of injection, changes in the injection pressure or the injection nozzle being reflected in the

TABLE 4

Approximate mean velocity m/sec.	Difference in % of Allen method measurements from weir measurements Cone type injections 1 nozzle	2 nozzles
0.25	+5.28	+2.08
	+5.86	+2.67
	+3.52	+5.35
	Average +4.89	Average +3.37
0.35	+3.66	+3.62
	+5.75	+2.93
	+6.10	+8.52
	Average +5.17	Average +5.02
	Fan type injection 1 nozzle	2 nozzles
0.25	+4.55	+2.32
	+2.74	+2.94
	+2.58	+3.71
	Average +3.29	Average +2.99
0.35	+3.04	+3.35
	+3.76	+3.01
	+3.40	+3.12
	Average +3.40	Average +3.16
0.55	+2.46	+1.42
	+6.30	+3.84
	—1.10	+1.78
	Average +2.42	Average +2.35

Injection pressure = 20 m head of water.

cloud form. A fan and a cone type nozzle were both studied, tests showing the fan type to be superior to the cone.

The influence of the injection conditions on the measured flow values is shown in Tables 2, 3, and 4.

The results show that study of the injection procedure might make it possible to reduce appreciably the minimum effective good mixing length without affecting the precision of the measures, and conversely, it is apparent that a defective injection may increase considerably the minimum effective good mixing length.

Baffles were placed upstream of the injection section in the parabolic channel in an attempt to investigate the influence of a dissymmetric velocity distribution. The baffles covered half the channel area and could be placed in various positions in the channel. Results of the tests are given in Table 5.

TABLE 5

Approximate mean velocity m/sec.	Difference in % of Allen method measurements from orifice measurements		
	Baffle at side	Baffle in middle	Normal distribution
0.30	—10.00	—3.03	—1.37
	—3.03	—7.80	—1.37
	—4.14	+2.23	—8.00
	—5.56	—5.73	—1.86
	—4.62	—4.14	—3.47
	Average —5.47	Average —3.69	Average —3.21
0.65	—9.08	—12.60	—10.40
	—6.78	—5.89	—7.54
	—8.17	—9.23	—2.79
	—12.50	—10.40	—3.70
	—8.17	—7.85	—11.10
	Average —8.94	Average —9.19	Average —7.11

Fan type injections

Tests were made with the initial pair of electrodes located 3.5 m from the injection point in the parabolic canal and with the addition of seven turbulence creating devices in the measuring section. Later, five turbulence devices were disposed at equal distances in the 3.5 m separating the injection point and the initial electrodes, replacing the seven in the measuring section. The results are shown in Table 6.

TABLE 6

Approximate mean velocity m/sec.	Difference in % of Allen method measurements from orifice measurements		
	Normal regime	7 "turbulators" in measuring section	5 "turbulators" between point of injection and initial electrodes
0.30	—3.54	—4.00	—1.60
	—2.32	—3.34	+0.64
	—2.46	—3.34	—0.48
	—4.00	—1.40	—3.93
	—4.01	—0.10	+1.60
	Average —3.27	Average —2.44	Average —0.75
0.65	—2.67	—2.08	—1.02
	—3.73	—2.91	—1.02
	—4.79	—2.08	+2.32
	—1.85	—3.73	—1.38
	—3.96	—3.26	+2.32
	Average —3.40	Average —2.81	Average +0.24

Fan type injection

Note that under these latter conditions the error in the discharge measurement is very small, even though the initial electrode is quite close to the injection point and the flow velocities quite low.

Table 7 presents the results of a later series of tests in both channels, employing added turbulence between the injection point and the initial electrodes. In every case the error in the discharge is smaller for the condition of higher turbulence.

In most field applications, where flow velocities are usually high, it is probable that the natural turbulence of the stream is sufficient for the use of the Allen method. It is nevertheless of interest to know that the minimum effective good mixing length can be reduced and accurate results obtained, by proper choice of the injection conditions and by the addition of turbulence to the stream. If turbulence producing devices are used it is believed best to divide them evenly over a section to the end that the cloud evolution approach that of the theoretical normal evolution.

For the same discharge the natural turbulence in the parabolic canal could be changed by regulating the flow velocity with an adjustable tailgate. Comparative tests of discharge were made in this man-

TABLE 7

Approximate mean velocity m/sec.	Difference in % of Allen method measurements from orifice measurements Parabolic channel Natural turbulence	Added turbulence
0.70	—3.91	+1.11
	—5.54	+0.56
	—2.98	+0.56
	—5 89	+0.19
	—5.02	—1.21
	Average —4.67	Average +0.24
0.50	—0.58	+1.51
	+0.47	—1.05
	—4.77	0
	—1.63	0
	—4.77	+1.51
	Average —2.21	Average +0.39
	Rectangular channel	
C.40	—4.77	—0.54
	—4.24	+0.18
	—3.88	—0.36
	—3.88	—1.07
	Average —4.19	Average —0.45
0.20	—6.90	—2.96
	—5.48	—0.42
	—4.93	—3.80
	—1.50	—0.42
	Average —4.70	Average —1.90
	Fan type injections	

ner. The results are shown in terms of Reynolds number and per cent error in Fig. 5. Reynolds number was calculated from the mean flow velocity and hydraulic radius of the channel.

It is seen that the comparative error, which is quite large at low Reynolds numbers decreases systematically with an increase in Reynolds number. For a Reynolds number of 9×10^4 the mean error of several tests was very small under the test conditions obtaining. It should be remembered that the Reynolds numbers corresponding to most penstocks or industrial conduits are of the order of 10 to 100 times as large as the maximum R possible in our tests.

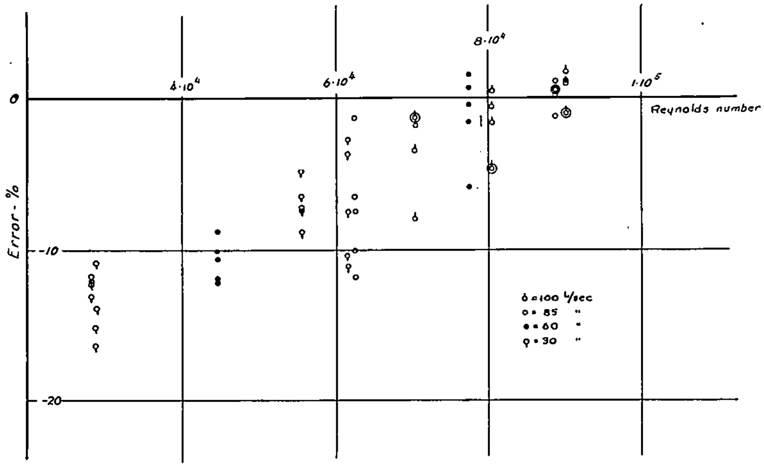

FIG. 5.—ERROR IN DISCHARGE MEASUREMENT BY SALT-VELOCITY METHOD

It is recognized that the Reynolds number does not of itself completely define the state of turbulence in a stream and we have employed it only as a base of comparison for the various tests made in the same channel by changing the flow velocity, but not varying the nature of the solid boundaries. The same test results have been studied in terms of the head loss, and the general aspect is analogous to that of Figure 5, leading to the belief that loss of head may be comparable to Reynolds number as a criterion of flow conditions for our purpose.

A peculiarity observed in several of the current curves obtained for high flow velocities in the parabolic channel should be discussed. It was noted that although the current curve for the initial electrodes had the aspect of a bell curve, the similar registration for the final electrodes was characterized by several peaks. We believe this effect to be due to eddies of a scale relatively large in proportion to the size of the salt cloud, which tend to divide the cloud into several distinct portions. Under these conditions the small scale turbulence tending to remix the portions is insufficient to equalize the action of the large eddies. In addition to the possible large eddies formed in the wake of an obstruction or by a flow discontinuity, the possible effect of a long pitched double helical movement which is so often present in open channels should be considered. It is known that this type of movement is a function of the flow velocity and the boundary roughness, but a quantitative study has never been made of the phenomenon, even though its existence has been known for many years. Obviously, the importance of the movement in the Allen method cannot be evaluated until more is known of its mechanics.

Conclusion

In the light of the preceding discussions it is now possible to examine the principal factors to be considered in the use of the Allen method for precise measurements.

1. Primarily it appears that the flow should be permanent and uniform, i.e. the measuring section between the electrode pairs and the point of the injection should be uniform in section and the state of turbulence should be essentially the same throughout the entire channel or pipe. However, if the turbulence is very high one may employ channels of slightly variable section without introducing appreciable errors. Also, the importance of these considerations will decrease as the ratio of the time required for the cloud to pass an electrode pair to the total mean time of passage through the measuring section decreases.

2. The disturbing influence of large scale eddies has been noted incidentally. In a general way it may be said that measuring sections subject to such conditions should be avoided.

3. The requisite length of measuring section appears to depend primarily upon the state of turbulence in the channel.

4. The electrodes should cover essentially the cross section of the channel. The mesh of the screen may perhaps be made larger as the turbulence is higher; the Reynolds number and loss of head permitting an evaluation of the state of turbulence for this purpose.

5. In this study which was essentially experimental we have limited ourselves, on the whole, to only the qualitative theoretical considerations necessary to guide and interpret the experimentation. In the domain of the theory of the method (which remains to be formulated) it is worthwhile to note the encouraging results obtained from the use of the calculus of probabilities when the stream turbulence is high, the condition we believe to be essential to the proper operation of the method.

It would be interesting to attempt to find a criterion for the application of the Allen method by the use of modern turbulence flow theory. In this connection reference is made to recent works on turbulence, for it is probable that the recent remarkable results in this field may serve as a guide to a solution of the Allen method problem.

6. The method may not be satisfactorily used without a sound knowledge of the essential principles of its application, any more than other measurement methods.

It is hoped that the work reported herein will contribute to the knowledge of the various phenomena affecting the use of the method and will lead to further research on the problem it has indicated but has not solved.

ACKNOWLEDGMENT

This work was made possible by the grant of a scholarship* accorded by the Boston Society of Civil Engineers from the John R. Freeman Fund. The expression of my grateful appreciation to the Society for the opportunity thus accorded me seems indeed inadequate.

*Recipient of the John R. Freeman Travelling Fellowship, July, 1937, to July, 1938.

DISCUSSION

By Leslie J. Hooper, Member*

Dr. Mason is to be congratulated on his fundamental approach to the Salt Velocity Method of Water Measurement. Many investigators of this method have wholly neglected the importance of the mixing process which is caused by the fluctuating components of flow. Mathematical analyses which neglect this important part of the flow process cannot possibly produce the correct result except by a combination of errors. Thus it is heartening to see the importance of this mixing process emphasized again by Dr. Mason in his work.

There are a number of items which are deserving of comment in this paper, some because a little extra emphasis will not be amiss and others because they are not wholly in agreement with experimental facts.

In the first place, one of the most striking details of this investigation was the employment of ultra-violet-light-sensitive dyes to indicate the direction and velocity of flow under turbulent conditions. From the data and examples given it is apparent that this process permits excellent pictures to be taken at relatively low light intensities. Thus a new technique for the study of flow in open channels and transparent pipes is made available for laboratory use.

Furthermore, the mathematical analysis of the flow on a probability basis is most interesting. Dr. Mason thus predicts that the recorded salt curves will elongate and flatten with the square root of the distance travelled by the salt slug. In his laboratory work there was not sufficient length of test section to verify this fact. In Prof. Allen's experience there have been several opportunities to study this phase of the method with test sections several miles long. It has been found that the exponent of the rate of elongation lies between 0.48 and 0.50 which is in very close agreement with Dr. Mason's prediction.

And again, his analysis indicates that the time between the centers of gravity of two salt velocity curves taken from successive elec-

*Assistant Professor of Hydraulic Engineering, Worcester Polytechnic Institute, Worcester, Mass.

trodes in a conduit gives the correct passage time for the salt slug. This fact also has been verified by a great many tests under a wide range of conditions.

Since the theory advanced by Dr. Mason and the experimental facts are thus in good agreement in two widely differing aspects, it would follow, in our opinion, that the theory is thus shown to be basically correct.

Turning to some of the details of the work, there are several statements which are not wholly in accord with the facts. In speaking of the electrode current, the equation is used which states that the resistance is proportional to the specific resistance and to the separation of the plates and inversely proportional to the area of the plates. This is true only when the electrode plates completely fill the cross section at the ends of a cylindrical volume. With two plates immersed in a fluid without nearby boundaries the resistance relation is much more complex, since the current flow can take place from the edges and backs of the plates and traverse a much larger volume than that contained between the plates. This fact does not alter in the slightest the discussion which was based on this formula, but it can assume great importance in the correct design of electrodes.

The details of the circuits with which Dr. Mason worked are not presented in the paper and a word of caution may not be amiss in this direction. In the first place, the resistance of the electrode leads must be kept small as compared to the resistance of the electrodes or else a serious distortion of the recorded electrode curve will occur with corresponding inaccuracy in the test result. It is also important that the voltage of the circuit be in excess of certain minimum values. With alternating current and commercial recording instruments, the voltage of the circuit should not be less than 20 volts to avoid serious distortion due to the effect of instrument impedance. With direct current the instrument resistance is usually very low but in this case the effect of polarization voltages must be kept to a minimum. It is usually unsafe to use less than 10 volts with direct current.

The paper states that long test sections are less accurate because of the attenuation of the second curve. This is contrary to our experience. Test sections as long as 3½ miles have been used with complete success. The proper recording of the second curve requires only the adjustment of the circuit voltage, instrument sensitivity, chart speed or the amount of salt injected to obtain definite curves which allow accurate computation of the test result. Furthermore, since the salt curves elongate with the square root of the distance traversed, it follows that the curve length becomes a smaller fraction of the passage time as the length of the test section is increased and hence, in general, the accuracy of the test result is improved.

It is not definitely stated in the paper whether the weirs and orifices used as a basis of comparison were calibrated or not. It is realized that for comparative purposes it makes little difference but there is always danger that the test values may be mistakenly given an absolute value by some reader who does not bother to obtain all the essential facts.

In the discussion of the "distance required for good mixing" an equation is given of the form:

$$M = f(U)\ A\ T$$

This equation does not seem to explain all the facts. In the first place, experimental work reported by Prof. Allen* indicated that the area covered by the diffusion of salt solution remained essentially constant for a considerable range of conduit velocities. Since it is known that the turbulence increases with the velocity, it follows that the diffusion or mixing is proportional to the product of the turbulence and the time. On this point we are in agreement. It is well known, however, that the turbulence in a given pipe is a function of the wall roughness and it would seem necessary to include a roughness factor in the equation. Moreover, eddies are dissipated by the viscosity of the fluid and it seems desirable to have this kinematic viscosity represented in the equation. Furthermore, the area of the cross section alone is not sufficient to express its hydraulic characteristics. This being the case, it seems that the area divided by the wetted perimeter would be more suitable, in other words, the hydraulic radius should be used. The difficulty of including these factors in a formula is due to the lack of any satisfactory method of expressing the degree of roughness. The only factor available at the moment is the "n" of Manning's and Kutter's formulas and these are empirically determined. For these reasons it is much simpler to criticise a formula for mixing distance than it is to construct a satisfactory relationship. It does seem, however, that the factors mentioned above have a bearing on the mixing distance and should be included in the analysis.

*"How Water Flows in a Pipe Line," Mechanical Engineering, February 1934.

Dr. Mason's experimental work has shown that there exists a minimum distance which provides good mixing for a given set of flow conditions. This distance is also a function of the design of the injection apparatus. By way of comparison, the angle of diffusion in the 40″ penstock at the Alden Hydraulic Laboratory was found to be 6.3° at the mid-radius which compares with the values of 5° to 5.5° in the channels used by Dr. Mason. The mixing distance in his investigation was found to be between 30 and 50 ft. when using a single pop valve. In the 40″ pipe the minimum distance for good mixing was found to be 8 ft. when using four ¾″ pop valves.

A considerable portion of his work was given over to a study of adding turbulence to the flow with "turbulators". His results are in agreement with the experience of Prof. Allen. "Turbulators" may be used with beneficial results in some cases as long as they are located either before the pop valves or between the pop valves and the first set of electrodes. When they are installed between the measuring electrodes, the errors may be increased rather than reduced. This results probably from the eddies which lie behind the obstructions. On the one hand they detract from the total test volume and on the other hand they cause a drag on the recorded salt curve which cannot be evaluated.

In the conclusion of the paper there occurs a statement that the Salt Velocity Method is accurate for uniformly turbulent flow in straight conduits. Our experience with the method shows that this method can be used with entire success in converging sections such as intakes to water wheels.

In conclusion, it is desired to emphasize a fact clearly stated by Dr. Mason that the tests presented in his paper were designed to define certain limits of the Salt Velocity Method. These limits are ordinarily far removed from the flow conditions met in practice. But we wholly agree that these limits must be appreciated and used with a thorough knowledge of the Salt Velocity Method if this method of water measurement is to be used successfully.

DISCUSSION

By Edwin A. Taylor, Member*

Dr. Mason's investigations at Grenoble, France, which he describes in this paper, were largely concerning the characteristics and behavior of a salt cloud following injection in a conduit and of the accuracy of the salt velocity results as compared with weir under various conditions.

These tests were made in two small open channels and the majority of the salt injections were made through one pop valve located at the center of the channel cross section. The results recorded by Dr. Mason agree with the results of similar studies made in 1922 at the Worcester Polytechnic Institute.†

At Worcester, with salt introduced at the center of a pipe, the salt velocity results were always more than the weir results. This is to be expected, since the center water with higher velocity is overdosed with salt. The results illustrate how and where salt velocity should *not* be used.

An exception to the above conclusion on center dosing is at the intake entrance to a long penstock where one central injection valve will give accurate results. The instantaneous velocities for the whole cross section of an intake entrance are practically uniform.

The ideal salt injection would be through an infinite number of pop valves distributed over the cross section of the conduit, but practically the number of valves is limited by economical conditions. At the opposite extreme is salt injection through one pop valve.

For commercial tests in round pipes, four to six valves are used. In square concrete penstocks, six to twenty-four valves are used. For one open channel measurement, thirty-eight valves were used.

The low flow velocities at Grenoble, coupled with the smooth conduit walls, caused low turbulence and poor salt mixing in the test channel. In some studies made during 1939 at Worcester Polytechnic Institute, Prof. Hooper found that, with velocities above two feet per second, the differences between salt velocity and weir results were

*Consulting Engineer, Worcester, Mass.
†Transactions, A.S.M.E. 1923.

negligible. As the velocities decreased, the differences increased. In his summary, Prof. Hooper states that "The critical mixing velocity is a very definite limiting velocity, below which proper mixing of the injected brine is not secured."‡

At Grenoble, Dr. Mason introduced artificial turbulence in the conduit, which insured proper salt mixing and reduced the differences between salt velocity and weir results by 90%. See Table 7.

Dr. Mason states that "In most field applications, where flow velocities are usually high, it is probable that the natural turbulence of the stream is sufficient for the use of the Allen method." Compared with conditions found in commercial tests on hydraulic turbines, the flow velocities and the turbulence at Grenoble were both very low. But they were not lower than can be met with in pump testing.

In 1939, the pumps on the Colorado River Aqueduct were tested and salt velocity was used for water measurement. A combination of extremely smooth pipe and low velocities created a very low turbulence, too low for proper salt mixing, and, under normal flow conditions the preliminary results did not check. Artificial turbulence was introduced and, after that, all results checked.

In general, the writer agrees with Dr. Mason's conclusions.

1. In commercial testing, uniform flow or velocity is not essential for accurate results but any change in cross section should be a decrease in area, never an increase. Substantial reduction in area is permissible with long test sections.

2. Prof. Allen has refused commercial tests where eddy conditions are present.

3. With low turbulence, a long test section reduces the error in the method but will not eliminate it. With high turbulence, the minimum length of test section should be controlled by the time of passage of the salt cloud. This should be long enough for accurate timing.

4. Screen electrodes, covering the entire cross section of the conduit are preferable for the laboratory but there are practical objections to screen electrodes in the field.

5. With artificial turbulence introduced in the salt velocity test section, the turbulence problem is solved for commercial testing.

6. Very true, no discussion.

‡Transactions, A.S.M.E. 1940.

FRANK B. WALKER

Members of the Boston Society of Civil Engineers were stunned to learn of the sudden death of President Frank B. Walker on June 3, 1940.

Mr. Walker began his Presidential year on March 20, 1940, and with characteristic enthusiasm had undertaken to formulate a program of activities which would be of interest to the members of the Society.

During his twenty-five years of membership in the Society, Mr. Walker had served on numerous special committees and had been keenly interested in the Society affairs, so that the Presidency was a logical honor for him. His more intimate friends knew that this honor gave him a great personal pleasure and he rejoiced in the privilege of directing the activities of the oldest engineering Society in the country. The loss of so genial a member, one who was endowed with a liberal point of view, will be felt keenly by the members of this Society.

OF GENERAL INTEREST

Marine Excursion—Boston Harbor and Port Facilities—Sponsored Jointly by Boston Society of Civil Engineers and Sanitary Section, B.S.C.E.,— and Attended by Members of All Sections

A most unusual outing—a Marine Excursion—was held for members of the Boston Society of Civil Engineers and their friends and the Ladies, on Saturday, June 8, 1940.

The objectives of the excursion were many points of interest in Boston Harbor. These included the piers and terminal facilities and water front developments and industries which constitute the maritime interests of the Port of Boston.

The party, numbering 67, started from Commonwealth Pier 5 at South Boston. This pier is under the control of the Division of Waterways, Gen. Richard K. Hale, Director, Massachusetts Department of Public Works. The arrangements for the use of this pier for the departure and return of the excursion were made through Mr. Clement Norton, Superintendent of the pier.

Commonwealth Pier 5 was constructed by and is now operated by the Commonwealth. The solid fill portion was built about 1900. The buildings on the pier and the track connections were built in 1914. The pier is 1200 feet long and 400 feet wide and has a covered floor area of 600,000 square feet. The available depth of water at this pier is 40 feet at mean low water. The wharf platform was originally supported on wooden piles, but damage by marine borers made replacement necessary in 1936, so that the present construction consists of steel piles driven

THE EXCURSION COMMITTEE

to rock. The piles are arranged in clumps of four, and each clump is surrounded by a steel shell filled with concrete. A silicon steel frame spans these supports and carries the concrete deck.

Leaving this pier at 10 o'clock, aboard the Diesel-motored boat, the *Francis,* the party proceeded easterly, passing the work now under way in the Main Ship Channel, where the Federal Government is deepening this channel to 40 feet at mean low water. The drilling boat *East River,* drilling for the removal of ledge, was of interest. This work is being done under the supervision of the Corps of Engineers, U. S. Army.

The route passed the outer end of the U. S. Navy Dry Dock No. 3, built by the Directors of the Port of Boston, and sold to the U. S. Government in 1919. This dock was included in a great program of port developments inaugurated by the Directors. It is located practically on the Main Ship Channel and is constructed of concrete and granite, and has an overall length of 1200 feet and provides a depth of water over the sill of 35 feet at mean low water.

A landing was made at the U. S. Army Base, where the party was conducted through many of the typical wharf and warehouse buildings by guides arranged through the courtesy of Mr. M. H. McGann, Superintendent, Boston Terminal, U. S. Maritime Commission. The methods of loading and unloading vessels at this terminal were explained, and excellent views were obtained of the harbor from the roof of these buildings.

Heading down the harbor, the party had a "close up" of the garbage disposal plant at Spectacle Island, operated by the City of Boston.

Leaving this point for fairer breezes, in the easterly part of the harbor, the group had a fine opportunity to pass near the *U. S. S. Wasp.* the new airplane carrier anchored at President Roads.

Continuing northeasterly, this part of the trip afforded a good opportunity to enjoy the box lunches.

A landing was made at Deer Island where all went ashore to view the Deer Island Pumping Station for the sewage of the north Metropolitan Sewer District.

THE EXCURSION—EN MASSE

While the party was assembled on this island, Vice-President Arthur L. Shaw appropriately paid tribute to the late President Frank B. Walker, who died June 3, 1940. He stated that this harbor excursion had been of particular interest to Mr. Walker and that he had given much personal thought to the planning of many of the details to insure its success.

Veering then towards the inner harbor, the route went past Governors Island, the Boston airport located on Commonwealth property, under lease to the City of Boston, and passed the piers along the East Boston waterfront, including the Simpson Yard, Bethlehem Steel Company, the Cunard Piers, Commonwealth Pier 1, the Atlantic works, and, passing through the drawbridge an excellent view was obtained of the so-called "oil farms" on that estuary. Returning, and passing through the big drawbridge across Mystic River, the large industrial developments on this river proved of interest. A landing was made at the Wiggin Terminal Lumber Wharf where this company had arranged to show the methods of handling large quantities of lumber.

The return trip followed along the Charlestown Navy Yard, the Hoosac Docks of the Boston and Maine Railroad and the Atlantic Avenue waterfront and the South Boston piers of the New York, New Haven and Hartford Railroad, and finally back to Commonwealth Pier 5.

The party then went to the Fish Pier (Commonwealth Pier 6), and noted the equipment and boats engaged in the wholesale fish business.

Another feature of particular interest was the *S. S. Hydrographer* tied up at the inner end of the fish pier. Under the direction of Lt. Roland R. Moore of the U. S. Coast and Geodetic Survey, the members had an opportunity to see the equipment for obtaining hydrographic data, and all the complicated equipment for rapid and accurate surveys of the ocean bottom.

The Excursion Committee consisted of Mr. H. Daniel Hurley, Chairman, John H. Harding, E. F. Kelley, J. D. Guertin and E. N. Hutchins. Assisting the Committee in various ways were Vice-Presidents A. L. Shaw, A. Haertlein, the Section Chairman, C. Frederick Joy (Sanitary Section), K. R. Garland (Designers Section), D. W. Taylor (Highway Section), D. F. Horton (Hydraulics Section), and E. B. Cobb, R. M. Soule, T. R. Camp and A. D. Weston. Mr. Horton furnished the map of the Harbor and the general description of the Port of Boston from data available at the office of Major Leonard B. Gallagher, District Engineer, Corps of Engineers; Mr. Weston furnished data covering the Metropolitan Sewerage System; and Mr. Hurley furnished data on Commonwealth Piers and other points visited on the trip. Mr. Frank S. Bailey made the photographic record of the excursion and committee groups.

BOSTON SOCIETY OF CIVIL ENGINEERS SCHOLARSHIP IN MEMORY OF DESMOND FITZGERALD AWARDED TO DANIEL W. MILES, STUDENT AT NORTHEASTERN UNIVERSITY

Daniel W. Miles, of Norwood, a senior student, Class of 1940, in the Civil Engineering Course at the School of Engineering, Northeastern University, was awarded the Boston Society of Civil Engineers Scholarship in Memory of Desmond FitzGerald, on May 8, 1940, at a convocation of students at Symphony Hall. The presentation of the Scholarship of $100 was made by Arthur L. Shaw, Vice-President of the Boston Society of Civil Engineers.

THE NORRIS PROJECT

Tennessee Valley Authority

The Tennessee Valley Authority announces the recent publication of its Technical Report No. 1, "The Norris Project." This report was prepared for the purpose of giving to the engineering profession the important and useful facts about the planning and construction of the Norris Dam and Reservoir. This volume, the first of a proposed series of TVA technical reports, contains 840 pages of text and 375 illustrations. To make this report of greatest use to those engaged on similar projects, relatively little space was devoted to such parts of the work that followed well-established engineering practice, but novel or unprecedented features have been described and explained in considerable detail.

Among the topics covered in this report are: history of the Tennessee River development; the Norris Project investigations; social and economic studies in the Norris Reservoir region; dam and powerhouse designs; access roads; employee housing; construction plant; river diversion; construction methods; analyses of construction costs; size of various construction crews; highway, railroad, and other adjustments made necessary by the creation of the reservoir; initial operations; unit costs; and total construction costs. The appendices include a comprehensive statistical summary of the physical features of the project; copies of the engineering and geologic consultants' reports; details of the design, models, cement and aggregate studies; specification forms; allocation of project costs; TVA employee relationship policy and wage rates; and the Tennessee Valley Authority Act. The report also contains comprehensive bibliographies on each phase of the work.

Cloth bound copies may be procured from the Superintendent of Documents, Washington, D. C., at $1.50 each.

PROCEEDINGS OF THE SOCIETY

MINUTES OF MEETING

Boston Society of Civil Engineers

APRIL 17, 1940.—A regular meeting of the Boston Society of Civil Engineers was held this evening at the Engineers Club. This was a Joint Meeting with the Northeastern Section, American Society of Civil Engineers, Prof Charles W. Banks, presiding for that Society. One hundred fourteen members and guests attended; seventy-eight persons attended the supper.

President Frank B. Walker, Boston Society of Civil Engineers, made two announcements for the BSCE:—

1. The organization of a new Section in the BSCE to be known as the Hydraulics Section. The first meeting for election of officers, and for any other business, to be held on May 1, 1940, at 715 Tremont Temple.
2. The next meeting of the Society will be held on May 15, at which Mr. Martin A. Mason, Chief of the Research Section, Beach Erosion Board, U. S. War Department, Washington, D. C., will be the speaker.

Mr. Banks introduced the Speaker of the evening, Miles N. Clair, Vice-President, The Thompson Lichtner Co. Inc., who gave a very interesting paper on "Concrete Technology". Discussion of the paper was given by Prof. Walter C. Voss, M.I.T., and O. G. Julian of Jackson and Moreland.

The talk was illustrated by lantern slides.

The meeting adjourned at 10 P. M.

EVERETT N. HUTCHINS, *Secretary.*

MAY 15, 1940.—A regular meeting of the Boston Society of Civil Engineers was held this evening at the Engineers Club and was called to order by the President, Frank B. Walker. Fifty-five members and guests were present; fifty-three attended the dinner preceding the meeting.

The President announced the death of Walter E. Spear, who had been elected as member on May 18, 1898, and who died March 29, 1940.

The Secretary reported the election of the following to membership on May 15, 1940:

Grade of Member—Edgar F. Copell, Earl R. French, Daniel G. Lacy, Charles H. Moloy, Carroll T. Newton, Edward H. Rebhan, *Lincoln W. Ryder.

Grade of Student—Carl F. Anderson, Richard J. Brennan, Joseph J. Caputi, Frank B. Cook, Daniel J. Conlin, Philip R. Director, Austin B. Henderson, John T. Grover, Arnold Kaufman, Arthur M. O'Connor, Lloyd S. Lawrence, Alfred J. Patterson, Russell J. Rogers, Charles B. Swift Jr., Emery P. Spidell, John P. White, Richard E. Wright.

The President called upon Vice-President A. L. Shaw to report on the matter of his representing the Society in presenting the Boston Society of Civil Engineers Scholarship ($100) in Memory of Desmond FitzGerald, to Daniel W. Miles, a senior (Class 1940), at Northeastern University, at a convocation of Students at Symphony Hall, on May 8, 1940.

The President announced the inauguration of the new Hydraulics Section on May 1, 1940.

The President outlined the plans for the Marine Excursion, to be held on Saturday, June 8, in Boston Harbor, and that the Society will be joined by the Sanitary Section BSCE, for members, friends and ladies with lunch served aboard the chartered boat.

The President then introduced the speaker of the evening, Mr. Martin A. Mason, Chief of the Research Division, Beach Erosion Board, United States War Department, Washington, D. C.

Mr. Mason was the recipient of the John R. Freeman Scholarship of the Boston Society of Civil Engineers, for the year beginning June, 1937. At that time he was connected with the Hydraulic Laboratory of the National Bureau of Standards, Washington, D. C., and until recently, with the same Bureau. At the present time he is Chief of the Research Division, Beach Erosion Board, War Department, Washington, D. C.

Mr. Mason's year of study abroad included visits to the leading hydraulic laboratories of Europe and particularly in France, Switzerland and Italy. He obtained his Doctorate Degree at Grenable University (France).

Mr. Mason's paper was entitled "A Study of the Allen Salt-Velocity Method".

Following the paper, discussions of the paper were given by Prof. Charles M. Allen, Dr. Leslie J. Hooper, Prof. Clyde W. Hubbard, and Mr. Rheingans.

A rising vote of thanks was given to Dr. Mason for his interesting paper.

Adjourned at 9.00 P. M.

EVERETT N. HUTCHINS, *Secretary.*

DESIGNERS' SECTION

APRIL 10, 1940.—The meeting of the Designers Section was called to order by the Chairman, Kimball R. Garland, at 6:40 p. m. The Clerk's report of the last meeting was read and accepted. Following a few remarks by the Chairman, the speaker of the evening, Professor Howard R. Staley, was introduced. Professor Staley's paper, "Structural Characteristics of Brick Masonry", the result of several years research at Massachusetts Institute of Technology, proved most valuable and interesting.

The results of extensive strength and volume change tests with a variety of Portland cement-lime mortars and types of brick were presented, together with some observations on bond. The general conclusions reached were that durability and structural integrity are not guaranteed by use of high strength mortars in brick construction.

Professor Staley suggested that wearability is more likely to be obtained by using mortars of adequate rather than highest strength, the lime content used to be such as to provide the foregoing plus-tight construction.

The material presented aroused active interest and led to many questions and comments from those present.

Following an expression of thanks to the speaker, the meeting was adjourned at 8:30 p. m. Attendance, 53.

EMIL A. GRAMSTORFF, *Clerk.*

MAY 8, 1940.—The May meeting of the Designers Section was called to order at the Society rooms by the Chairman, Kimball R. Garland, at 7:00 p. m. The Clerk's report of the April meeting was accepted as read.

In this, the last meeting of the season, the Section was particularly favored in its speaker, Col. Charles R. Gow, whose subject was "Some Practical Suggestions to the Modern Engineer, derived from the Experiences of an Old Timer." The talk was both interesting and entertaining, covering some highlights of the speaker's long period of engineering service.

Mr. Frank B. Walker, President of the Society, was present and was asked to say a few words. He commented upon the career of Col. Gow and added some interesting items of engineering experiences.

Following a general discussion period, the meeting adjourned at 9:00 p. m. Attendance, 60.

EMIL A. GRAMSTORFF, *Clerk.*

APPLICATIONS FOR MEMBERSHIP

[July 20, 1940]

The By-Laws provide that the Board of Government shall consider applications for membership with reference to the eligibility of each candidate for admission and shall determine the proper grade of membership to which he is entitled.

The Board must depend largely upon the members of the Society for the information which will enable it to arrive at a just conclusion. Every member is therefore urged to communicate promptly any facts in relation to the personal character or professional reputation and experience of the candidates which will assist the Board in its consideration. Communications relating to applicants are considered by the Board as strictly confidential.

The fact that applicants give the names of certain members as reference does not necessarily mean that such members endorse the candidate.

The Board of Government will not consider applications until the expiration of fifteen (15) days from the date given.

For Admission

GILES L. EVANS, JR., Cambridge, Mass. (b. November 30, 1914, Fayetteville, Tennessee). Sept. 1932-June, 1933, Vanderbilt University. July, 1933-June, 1937, U. S. Military Academy at West Point, New York. (B.S. degree from U.S.M.A. June, 1937) Commissioned as 2nd Lt. Corps of Engineers, U. S. Army, June, 1937. Assistant to District Engineer, U. S. Engineer Office at Memphis, Tennessee, Sept., 1937-Sept., 1939. Transferred to Massachusetts Institute of Technology, Sept., 1939, as U. S. Army Engineer student and candidate for M.S. degree, under department of Civil Engineering. Refers to *J. B. Babcock, A. J. Bone, C. B. Breed, K. C. Reynolds, D. W. Taylor.*

RUTGER E. PETERSON, Mansfield, Mass. (b. January 10, 1906, Holbrook, Mass.). Graduated from Summer High School in 1923. Received degree of Bachelor of Civil Engineering from Northeastern University in 1930. Experience: employed at the office of H. L. White, Braintree, Mass., as co-operative student until graduation; with E. Worthington of Dedham, Mass., as inspector and assistant engineer on sewer construction and survey work, until 1936; engineer and assistant superintendent on sewer construction for P. DeCristofaro Inc. in 1937; resident engineer on sewer construction for Frank A. Barbour, until March, 1940. At present employed as engineer and superintendent on sewer construction by R. Zoppo. Refers to *F. A. Barbour, E. A. Gramstorff, H. L. White, E. Worthington.*

For Transfer from Grade of Junior

HARRY S. PERDIKIS, Providence, Rhode Island (b. June 25, 1912, Lawrence, Mass.). Graduated from Northeastern University, June, 1936, with B.S. degree in Civil Engineering. Experience—September, 1936, to date with U. S. Engineer Office, Providence, Rhode Island. Work consists of Hydrographic Surveying, mapping, estimating, dredging operations. Started as under Engineering Aide. Advanced by promotion to present position as Junior Engineer. At present in charge of the drafting room in the Rivers & Harbors Division. Refers to *C. O. Baird, W. A. Grady, E. A. Gramstorff, A. J. Ober.*

LINCOLN RYDER, Wollaston, Mass. (b. January 21, 1912, Wollaston, Mass.) Graduated from Massachusetts Institute of Technology in 1933, with B.S. degree in Civil Engineering. Experience—July, 1933, to November, 1933, assistant in the real estate management office of the Property Management Corp., Boston; January, 1934, to March, 1934, draftsman, Massachusetts Traffic Accident Survey, Boston; March, 1934, to June, 1934, signalman with triangulation party under direction of Corps of Engineers, Army Base, Boston; July, 1934, to August, 1934, November, 1934, to February, 1935, September, 1935, to December, 1937, and August, 1938, to present time assistant engineer, Metcalf & Eddy, Boston; March, 1935, to May, 1935, rodman, Engineering Dept., City of Quincy; May, 1935, to September, 1935, 2nd Lt. O. R. C., C. of E., active duty, Asst. District Construction Officer, 3rd C.C.C. District, Fort Devens, Mass.; December, 1937, to January, 1938, Assistant engineer with Mr. S. L. Ellsworth, Boston; January, 1938, to August, 1938, Assistant Engineer, L. H. Shattuck, Inc., Manchester, N. H. At present an assistant Civil Engineer with Metcalf & Eddy, Boston. Refers to *Prof. J. B. Babcock, S. M. Ellsworth, F. A. Marston, A. L. Shaw.*

For Transfer from Grade of Student

HAROLD E. SANFORD, West Springfield, Mass. (b. June 6, 1916, Fall River, Mass.). Graduated from Northeastern University, June, 1938, with B.S. degree in Civil Engineering. Experience—Summer of 1936, with Department of the Interior, doing survey and drafting work at Westfield C.C.C. Camp; cooperative work periods, 1937 and 1938, with Boston Division of New York, New Haven and Hartford Railroad as Blueprinter, Rodman, and Instrumentman; October, 1938, to June, 1939, with Metropolitan District Water Supply Commission as Junior Engineering Aide, Rodman, Instrumentman and Office Estimator, at Enfield, Mass.; June, 1939, to date with U. S. Engineer Office, West Springfield, Mass., as Assistant Engineering Draftsman on Connecticut River Flood Control. Refers to *C. O. Baird, A. E. Everett, E. A. Gramstorff.*

ADDITIONS

Members

EDGAR F. COPELL, 25 Bourne Street, Jamaica Plain, Mass.

EARL R. FRENCH, 251 Marlboro Street, Boston, Mass.

DANIEL F. LACY, Town Hall, Brookline, Mass.

CHARLES H. MOLOY, 17 Elijah Street, Woburn, Mass.

LIEUT. CARROLL T. NEWTON, 9 Ellery Street, Cambridge, Mass.

EDWARD H. REBHAN, 17 Cummings Road, Brighton, Mass.

LINCOLN W. RYDER, 79 Winthrop Avenue, Wollaston, Mass.

Students

CARL F. ANDREWS, 224 Huntington Avenue, Boston, Mass.

RICHARD J. BRENNAN, 161 Huntington Avenue, Boston, Mass.

JOSEPH J. CAPUTI, 32 Westland Avenue, Boston, Mass.

DANIEL J. CONLIN, 19 Wycliff Avenue, West Roxbury, Mass.

FRANK B. COOK, 12 Pomeroy Street, Allston, Mass.

PHILIP R. DIRECTOR, 118 Trowbridge Street, Cambridge, Mass.

AUSTIN B. HENDERSON JR., 8 Lakeview Avenue, Beverly, Mass.

JOHN T. GROVER, Palmer Road, Halifax, Mass.

ARNOLD KAUFMAN, 32 Porter Street, Malden, Mass.

LLOYD S. LAWRENCE, 85 St. Botolph Street, Boston, Mass.

ARTHUR M. O'CONNOR JR., 15 Harrington Street, Revere, Mass.

ALFRED J. PATTERSON, 132 Day Street, Jamaica Plain, Mass.

RUSSELL J. ROGERS, 20 Harrison Street, Brookline, Mass.

EMERY P. SPIDELL, 120 Wilmington Avenue, Dorchester, Mass.

CHARLES B. SWIFT JR., 6 Belvoir Avenue, Taunton, Mass.

JOHN P. WHITE, 29 Brent Street, Dorchester, Mass.

DEATHS

WALTER E. SPEAR.....March 29, 1940

ROBERT B. FARWELL......May 7, 1940

FRANK B. WALKER......June 3, 1940

ADVERTISEMENTS

The advertising pages of the JOURNAL aim to acquaint readers with Professional and Contracting Services and Sources of Various Supplies and Materials. You would find it of advantage to be represented here.

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BOSTON SOCIETY OF CIVIL ENGINEERS

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