NATIONAL BUREAU OF STANDARDS REPORT

9415

Final Report

On

EVALUATION OF REFRACTORY QUALITIES OF

CONCRETES FOR JET AIRCRAFT WARM-UP, POWER CHECK

MAINTENANCE APRONS, AND RUNWAYS

By

J. V. Ryan

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Fire Research Section
Building Research Division

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U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

SUMMARY REPORT ON
EVALUATION OF REFRACTORY QUALITIES OF CONCRETE FOR
JET-AIRCRAFT WARM-UP, POWER CHECK, MAINTENANCE
APRONS, AND RUNWAYS

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ABSTRACT

A long-term study was carried out on the resistance of concrete and concreting materials, to thermal shock, particularly with consideration of the effect of jet engine exhaust on runways and other traffic areas. Concretes were subjected to elevated temperatures in an oven and, in a later phase, before a small-scale burner simulating a jet engine exhaust, both as to discharge velocity and gas temperature. In the final phase, specimens were fabricated in various sizes and shapes to investigate the mechanism of spalling.

This report summarizes the work carried out and, briefly, the results obtained. A detailed index to the progress reports is included.

1. INTRODUCTION

The development and extensive use of jet-powered aircraft introduced new problems in airfield trafficway design. The modern jet engine discharges gases at temperatures in excess of 1000° F and at velocities of the order of the speed of sound and greater. From some aircraft, this discharge (somewhat attenuated by distance from the engine) impinges on the surfaces of the runways, taxiways, and maintenance aprons, subjecting them to severe thermal shock and abrasive forces. The result has been extensive damage characterized by breakup and dislocation of the concrete to depths and over areas such that the particular trafficways are rendered hazardous or even unusable. There is the added hazard that particles from the broken-up concrete may be swept into the engine with the intake air and cause accelerated engine deterioration or malfunction.

A study was made of concreting materials and of concretes in an attempt to gain understanding of the mechanism of spalling, of the factors that affect the tendency of a concrete to spall and of means to minimize this tendency. The study was sponsored by the Department of the Navy through its Bureau of Yards and Docks. They provided financial support and cooperated in providing materials, specimens, and correlation of laboratory test procedures with typical field exposures.

The initial phase of the study consisted of selection of materials and concrete batch designs for further study. The selection was based on exposure to high temperature for long periods, without any attempt to produce the thermal shock and abrasive conditions of the jet exhaust. The second phase involved the use of a laboratory small-scale burner that produced a jet of hot gases in the temperature and velocity ranges of typical aircraft engines. The effects of this burner-jet were compared with those of an actual jet engine during the development of the laboratory jet apparatus, and the latter adjusted to improve the correlation between results from the two sources. This second phase was concerned chiefly with whether or not various concretes spalled and if their resistance to spalling imporved with age under regulated ambient temperature and humidity. The third phase of study involved more concentration on the mechanism of spalling and the effects of variables on spalling tendency. Of particular interest was the question whether spalling was due largely to thermal stresses or to internal steam pressure, or to a combination of these factors. Other factors such as dimensional and phase changes in some aggregates were considered also.

Although most of the specimens were prepared at the National Bureau of Standards, a significant number of samples of concretes poured at various Naval Air Stations were provided for check tests. Conferences were held between representatives of the sponsor and of NBS periodically to review progress and modify goals. The Technical Requirements for the concretes were developed progressively during the study. Comparatively few changes were made in the individual requirements, once each had been added. The sponsor was provided regular progress reports, containing detailed information and results. Therefore, no attempt will be made to give more than a general review of the most significant work done in this report. A partial indexing of subjects in the program is given in the Appendix.

The description of the work is divided according to the phases mentioned in an earlier paragrpah. The phases overlapped chronologically, with phase one work, such as investigation of additional aggregates, continuing throughout the study to some extent.

2. SPECIMENS

The specimens in the study included samples of aggregates, cements, and concretes. In addition to the measurements and tests peculiar to the impingement of jet exhaust - high temperature, thermal shock, etc. - other measurements and tests were made for the characterization of the specimens in terms of their properties. These data were used throughout the study not only for understanding the relationships between spalling and physical and chemical properties but, also, for a check on the uniformity among lots of nominally identical materials or nominally identical batches of concretes.

2.1 Materials

2.1.1 Aggregates

Fifteen different aggregates, both natural and man-made, were included in the study and are listed in Table 1. Samples of the aggregates were subjected to various tests. Since most of the latter are well known, they are not described, but are listed, with identification of the applicable standard test method, in Table 2. The results of these characterization tests are given in Table 3.

2.1.2 Cements

Three different cements were included in the study and are listed in Table 1. The characterization tests to which samples of the cements were subjected, like those for the aggregates, are listed and identified in Table 2.

2.2 Concretes

From the several batches of concrete, samples were taken for the preparation of specimens, supplementary to those intended for high temperature or jet-impingement exposure. These supplementary specimens were used for measurements of the concretes' characteristics and to determine the degree of compliance with requirements established by the sponsor. The measured characteristics are listed in Table 2: the technical requirements were: (1) air content 4.5 percent ± 1.5 percent, (2) cement content not over 10 bags per yard, (3) compressive and flexural strength to be measured at 28 days, (4) water and air content to be constant from batch to batch, (5) ratio of fine to coarse aggregate to be per BuY&D Specification 45Ya, (6) gradation of aggregates and fineness moduli to be per BuY&D Specification 45Ya, (7) flexural strength 600 to 650 psi, (8) slump to be 2 in., (9) specimen preparation and curing per ASTM C-192, (10) certain exceptions for lightweight aggregate concretes.

Some experimental batches were made at various mix proportions, for a particular cement-aggregate pairing, in order to determine the most desirable mix design. Such determination was based, usually on supplementary or characterization tests, e.g., flexural strength. The design for a mix was established, either by tests as above or by accepted principles, before batches were prepared from which jet-impingement specimens were prepared.

2.2.1 Specimen Preparation

The specimens were taken, prepared, or fabricated by the procedures given in a standard test method, when one was applicable. Of the tests made on aggregates and cements, only high temperature and jet-impingement were not standard. Aggregates were placed in a wire mesh container for exposure to the jet; cements were prepared as cast blocks of neat cement paste.

Concrete specimens were prepared in groups. In the earliest part of the study only a small mixer was available. As a result, a complete set of specimens of a given design mix could not be cast from a single batch. Larger mixers became available later, permitting elimination of this source of possible variation.

The numbers, sizes, and shapes of specimens from a single batch varied through the study, having been determined by the particular tests being made or the instrumentation employed. The programs of conditioning for the specimens were nearly all identical through their first seven days, but there were several variations in the periods beyond seven days.

The aggregates, coarse and fine separately, were soaked in water overnight, drained and weighed just before mixing, and mixed for roughly one minute. Some water was added, then the cement and air entraining agent followed by the rest of the water. The batch was then mixed for an additional three minutes, discharged from the mixer, and the specimens cast as quickly as feasible, while exercising due care. The specimens were struck off, allowed to develop initial set, and then either steel troweled or broomed. They were covered with wet burlap or a vapor-proof cover, or both, until removed from the forms at about 24 hours. The specimens were weighed and placed in the "fog room," a room maintained at 73°F and 100 percent relative humidity. The latter was attained by a continuous water spray, so the atmosphere in the room was permeated with fine water droplets -- that is, a fog.

In some instances, particularly the development of an optimum mix design for a particular cement-aggregate combination, slump tests were made after the normal mixing time, additional water put in the mixer, and mixing continued.

The periods during which the specimens remained in the fog room varied from six days up. The conditioning varied after removal from the fog room also. The variations are described in the sections of this report dealing with the different phases of the study.

3. HIGH TEMPERATURE-LONG TIME STUDIES, PHASE 1

Concretes made from combinations of the various cements and aggregates were exposed to elevated temperature and subjected to subsequent tests. The exposures were not intended to duplicate jet exhaust conditions. On the contrary, the specimen's temperature was raised from room temperature, at a moderate rate, and held at a high level for up to several hours [a/]. Cooling rates were also moderate so that the specimens were subjected to comparatively little thermal shock. The flow of hot gases across the surface of the specimen was only that resulting from convection air currents within the test apparatus, and was not measured.

[a/] See report 1817

3.1 Materials

The three cements and the several aggregates previously mentioned and listed in Table 1 were used in this first phase of the study.

3.2 Batch Design Studies

The designs of concrete batches prepared in Phase 1 were based on (a) information obtained in a literature search, or (b) tests of specimens made from trial batches of the concretes to determine the adequacy of their properties in relation to the minimum technical requirements.

3.3 Selected Concretes

Specimens were prepared from various batches based on the design mixes deemed suitable for further study. The specimens were of sizes and shapes appropriate for various measurements during heating or following heating and cooling. These included specimens for compressive and flexural strength, expansion, weight loss on heating, etc.

A summary of the specimens, tests and results obtained is given in Table 4; they are described indetail in the various progress reports, numbered NBS Report 1362 through NBS Report 4502. As indicated earlier, there was some overlapping in the last few reports in this group with initial information on Phase 2 contained in some of them. On the basis of the results obtained, various cement aggregates and cement aggregate combinations (concretes) were selected for examination in Phase 2.

Relatively few concretes made from Phase 1 aggregates met the applicable technical requirements. For example, only sintered slag aggregate concretes and calcined flint clay aggregate concretes of all three cements exhibited acceptable flexural strengths. Similar results were achieved for second mixes employing bluestone and brick aggregates. Considered in terms of cement, only for concretes made with portland cement did the majority exhibit satisfactory flexural strength.

4. JET-IMPINGEMENT STUDIES - PHASE 2

4.1 Apparatus

An apparatus was developed to deliver hot gases in the temperature range of 600 to 1200 F at velocities of the order of 1200 feet per second. The combustion chamber was designed in cooperation with the Combustion Controls Section of the National Bureau of Standards. It is illustrated in a drawing in Figure 1 and by photograph in Figure 2.

Early experiments with specimens indicated that the optimum distance from the tip of the burner to the specimen was 3 inches. Temperature distribution on the surface and at a depth of 1/4 inch below the surface of a specimen was observed, and velocity of gas flow over the surface at various distances from the center of the specimen was also measured. These early experiments indicated that the combustion chamber needed to be operated at a temperature of approximately 1400 F in order to obtain impinging gas temperatures of 1200 F. Air and fuel pressures and flow rates were determined in order to obtain the desired operating and experimental conditions. Figure 3 is a plot of temperature as a function of distance from the center of the test area and as a function of elapsed time, both on the face and 1/4 inch below the face of the test panel. The velocities of the impinging gases at several points on the surface of the test panel were calculated from impact pressure in open-ended tubes. The formula used was $V = ((2g)(P_i - P_o)/\rho)^{1/2}$, where V equals velocity in ft/sec, g equals the gravitation constant in ft/sec^2, P_o equals static pressure in $pounds\text{-}mass/ft^2$ (atmospheric pressure), P_i equals impact pressure in $pounds\text{-}mass/ft^2$, and ρ equals density in pounds $mass/ft^3$. The impact tubes were placed at different angles to the surface as well as different distances from the center of the surface, but the calculated velocitites seemed to depend primarily on the location of the tubes rather than on the angle of placement.

When the velocity and distance from the center of the test area were plotted for several tests, the patterns obtained were quite similar. The velocity at the center ranged from 1100 to 1200 ft per second; at one inch from center, from 900 to 950 fps; at two inches from center, from 650 to 700 fps; and at three inches from the center, from 200 to 350 fps. The test panels used during this initial study of the apparatus were cured under wet conditions for a least a month and then dried thoroughly before being subjected to the test. Little or no damage to the specimens was observed.

Following the development and check-out of the above described apparatus a number of specimens were prepared for test in the apparatus, with similar specimens being prepared and shipped to the Naval Civil Engineering Laboratory, Port Hueneme, California, where they were subjected to the exhaust from a mounted jet aircraft engine. On the basis of the correlation obtained between the results from the exposure to the actual jet-engine exhaust and that from the exposure to the laboratory apparatus, final adjustments were made in the apparatus. This was followed by an additional small group of correlation specimens between the apparatus and the actual jet-engine exhaust.

In the late stages of Phase 2, apparatus designed for performance of the pyrometric cone equivalent test was used as a simulation of the thermal shock effect of the jet apparatus to simplify the connection of detection apparatus, thermocouples, etc. However, this arrangement was not found to be more convenient than the jet apparatus and the simulation was discontinued.

4.2 Tests of Materials

Samples of selected aggregates plus samples of hardened neat cement paste were exposed to the laboratory jet apparatus. The performance of these materials was evaluated in further selecting materials for use in concretes to be exposed to the jet-impingement apparatus.

4.3 Tests of Concretes

The main part of the study was concerned with tests of concrete specimens prepared for jet-impingement exposure, or for supplementary characterization tests as described before.

4.3.1 Specimens

Specimens for the jet-impingement test were prepared primarily in 18-inch square by 6-inch thick sizes. Some specimens were prepared in the same area but of lesser thicknesses. In the late stages of this phase the specimen size and configuration were modified somewhat (also in Phase 3, particularly for purposes of investigating the mechanism of spalling, which will be described later). Specimens were prepared in this later stage using cylindrical forms, as a convenience, rather than the square forms. They were prepared in 12-inch diameters, and 3-inch diameters, and in thicknesses of 6 and 2 inches. In addition to the jet-impingement specimens, others were prepared for measure of expansion and contraction during curing, for thermal expansion or dilatometry experiments, for air permeability measurements, and for flexural and shear strength measurements. In addition, specimens were cut from the 18-inch square by 6-inch-thick jet-impingement specimens for flexural or compressive strength measurements after the specimens had been exposed to the jet; beams designed for flexural strength tests were exposed to jet impingement prior to test. Reduction in flexural strength, as a result of jet impingement was significant in most instances, ranging from 20 to 65 percent of the strength of comparable specimens not exposed to the jet. However, the mechanism related to loss of flexural strength was shown to be drying shrinkage rather than jet-induced damage. Compressive strength measurements were made on ends of beams previously broken in flexure or shear.

4.3.2 Instrumentation

The specimens for jet-impingement were not all instrumented for all measurements. However, the following instrumentation was used in many of the specimens: For temperature, thermocouples were placed in the forms prior to casting in such a way that they would be embedded in the concrete at the exposed surface, at depths of 1/8, 1/4, 3/8, 1/2, 1 1/2, and 3 inches from that surface of the 6-inch-thick specimens; and at the surface, 1/8, 1/4, 3/8, 1/2 and 1 inch from the exposed surface of the 2-inch-thick specimens.

Open-ended tubes, either brass or stainless steel, were embedded in the concrete with the open ends approximately 1/2 inch from the center of the specimen, and at depths of 1/2, 1 1/2, and 3 inches in 6-inch-thick specimens, and at depths of 1/2 and 1 inch in 2-inch-thick specimens. Appropriate pressure transducers were attached to the ends of the tubes outside the concrete specimen, after the tubes had been filled with a hydraulic fluid, and measurements were made of pressures developed within the concretes during the jet exposure. As a check on these measurements, in some specimens similar tubes were placed but with the embedded end sealed. Thermocouples were attached to the outer surfaces of these tubes, both open ended and sealed, in order to get appropriate temperature measurements.

Sensers for determining the state of drying were embedded in some specimens. These were of two types: The first type was a conventional hygrometer placed in a cavity previously formed in the specimen; the second type senser was a pair of coated wires embedded in concrete, with the ends of the wires bare and spaced a known distance apart. These sensers were used to measure the electrical resistance across the gap between the wires periodically. The results were interpreted in terms of the shape of a curve of electrical resistance versus age or electrical conductance versus age. The specimens were taken to have reached or closely approached equilibrium moisture content when the curves showed little or no change in resistance or conductance with increased age.

4.4 Specimen Conditioning

Concrete specimens were cast in forms and as soon as an initial set was obtained they were covered with burlap and wet, or covered with a vapor-resistant building paper, or both. Ordinarily specimens were removed from the forms approximatley 24 hours after fabrication and placed immediately in a storage room kept at 100 percent relative humidity. Following placement in the above-described fog room, various programs of conditioning were followed in various parts of the study. These will be described in more detail with the appropriate parts. In some instances, a single specimen from a group would be removed and subjected to the appropriate tests, and the other specimens continued in the conditioning program for additional periods, as deemed advisable from the results obtained with the initial specimen. In other programs all specimens from a group, usually three, would be tested within a period of a day or two, in order to get a more nearly statistical indication of the range of results to be expected under any given condition. In Phase 3 of the overall study, large groups of specimens were prepared so that several specimens prepared from the same batch could be subjected to various programs of conditioning, ranging from continuation in the fog room until day of test, to artificial drying at temperatures believed safe for drying, in that they would remove moisture without affecting the basic strength of the concrete. In this part of the study these companion specimens conditioned under various programs were tested at the same age in order to determine the effect of those variables.

4.5 Permeability

Appreciable effort was made to investigate the interrelation, if any, between concrete permeability and resistance to jet impingement. It seemed probable that permeability would be a controlling factor in the escape of steam from within the concrete, and therefore, on the development of internal steam pressure. The permeabilities of several specimens were measured, investigating variables such as aggregate, type of surface (floated, steel, troweled, broomed, and sawed), conditioning, and placement by the vacuum process. Specimens prepared from similar batches were subjected to jet impingement. Initially there appeared to be a general trend that higher permeability was accompanied by increased resistance to the jet. However, continued study along this line was inconclusive. It became evident that permeability is greatly affected by variables associated with surfaces and conditioning. Also, the time required to reach steady-state air flow through the concrete specimens, necessary for permeability measurement, was several orders of magnitude greater than the time-of-jet-test within which spalling started. Although it is probable that spalling under the jet is related to permeability, it is the permeability of the thin surface layer under surge conditions. No feasible technique was apparent for measuring this characteristic on representative specimens.

5. MECHANISM OF SPALLING - PHASE 3

This part of the study was aimed at investigating certain variables believed to have an affect on the spalling of concrete, in an attempt to learn more about the basic mechanism involved and the factors affecting the tendency of the concrete to spall.

5.1 Size Variation

Variations in lateral dimensions, primarily radius of specimens prepared in cylindrical forms, were made to determine if possible the effects of resistance to thermal expansion, provided by the outer, cooler portions of the concrete, to the central most severly heated portion of the specimen. For specimens of less the 12-inch diameter, a collar of lightweight, very low strength, cementitious (lightweight aggregate) material was cast around the basic concrete specimen so that the flow pattern of hot gases and the temperature distribution over the face of the specimen would be a nearly as possible the same as that over the equivalent portion of the full 12-inch diameter concrete specimen.

Variation in thickness was made partly in relation to the effects of resistance to thermal stresses, but also partly to vary the resistance to penetration of steam, developed in the concrete, deeper into the mass of concrete and away from the exposed surface. Preliminary to the preparation of these specimens in the conduct of this particular part of the study, specimens had been subjected to steam pressure for long periods of time in an attempt to measure pressures developed within the concrete and the tendency for steam or liquid water to be forced through the mass of the concrete under the effect of high surface temperature and resulting pressure developed in the contained moisture in the concrete.

5.2 Moisture Content

The effect of moisture content on the spalling behavior of the concrete was observed by preparing specimens in large numbers from a single batch and dividing them into several groups, each group being subjected to a different conditioning program, but all groups tested at the same age, thereby hopefully eliminating the effect of variation in strength resulting from different ages. As described briefly in a preceding section, these specimens were initially placed in the fog room, but following periods from 2 to 4 weeks one group of specimens was removed and placed in 73°F, 50% relative humidity atmosphere and allowed to tend to equilibrium moisture content in that ambient. Other specimens, those in a second group, were kept in the fog room until the appropriate age for testing. Specimens in the third group were kept in the fog room until data taken on those in the first group indicated that equilibrium was very nearly approached. Then specimens in the third group were placed in ovens and heated at a temperature of 105 to 110°C. During this period measurements were made by the electrical resistance-type moisture probes previously described, and the data analyzed to determine when the specimens had, in fact, been dried thoroughly.

The data observed in determining the effect of moisture content were both the pressure and temperature data. The effect of the variation in moisture content was noted in its effect on pressure observed within the specimens, and on the severity of the thermal gradients observed near the exposed surface of the specimen.

5.3 Results

The highest pressures, ranging up as high as 750 psi, were observed in fairly dense concretes that were tested following a long period of aging in the fog room but no aging in other atmospheres. Specimens conditioned for a short time in the fog room, followed by natural drying, showed comparatively low pressures, in many cases no pressure being observed. Finally the majority of specimens conditioned by thorough artificial drying at temperatures of 105 to 110°C showed no observable pressure development during the jet-impingement test.

The effects of wide variation in moisture content on the observed temperatures and temperature gradients were not as extreme as those observed on pressure but were nonetheless quite real. The very wet specimens showed steeper temperature gradients near the surface until the jet-impingement test had progressed to the point at which the surface concrete was dried under the effect of the jet. Lower temperatures were observed at appreciable depths, such as 1 inch to 3 inches from the surface, than were observed with the dried specimens at corresponding times during the test.

The results of the tests designed to investigate the affect of variation in resistance to thermal expansion stresses showed that specimens of the smaller diameters tended to spall less than companion specimens of greater diameters following the same conditioning program, thereby substantiating the belief that spalling is at least partly due to stresses built up in the concrete by differential heating and thereby differential tendency to expand thermally.

Analysis of the results obtained with specimens designed to investigate the effect of variation in moisture content also indicated that spalling is at least partially the result of the effects of moisture content. Those specimens tested following drying in temperatures of 105 to 110°C in no case spalled, and in all but a very few cases did not even show minor hairline cracking of the surface following jet exposure. Those specimens tested after final conditioning in normal drying (73°F, 50% relative humidity) showed a noticeable but comparatively little amount of spalling. Some individual specimens conditioned to this program did not spall at all. Finally, specimens tested after aging strictly in the fog room in most cases spalled, and spalled appreciably. This spalling was quite violent and continued over an extended portion of the total test period. This is in contrast to those specimens which spalled following so-called normal drying, which ordinarily spalled within the first minute of the test and did not spall thereafter.

6. MINIMAL CONDITIONING

In view of the finding on the importance of conditioning (as affecting moisture content), a brief study was made of possible ways to minimize the time required for conditioning. Two methods of artificial drying were studied: vacuum and elevated temperature.

On vacuum drying, several groups of specimens were placed in a chamber and kept at low absolute pressures--one-half an atmosphere for one group, and below 10mm Hg for the others. All the specimens had been kept in the fog room for 28 days before being placed in the partial vacuum. The vapor pressure of water is about 21mm Hg at the laboratory temperature. The state of dryness of some specimens was measured by electrical resistance elements already mentioned. Specimens kept at one-half an atmosphere pressure for four weeks had essentially the same strength (flexural and compressive) and slightly higher moisture content than companion specimens kept an equal time in air at 73°F, 50 percent relative humidity, and free atmospheric pressure--so-called "normal drying." Other specimens kept at pressures below the vapor pressure so water for long periods reached moisture contents of the same order of magnitude as achieved in oven-drying while having strengths essentially equal to those of companion specimens kept at "normal drying" conditions. This required several months. During the first 28 days, electrical resistance measurements indicated they were drying more slowly than the companion specimens. Generally, the results indicate that drying equal to oven-drying can be achieved by vacuum, but only over long periods for concrete. Shorter periods should be expected for materials of greater permeability or lower moisture content. The technique would be particularly useful for materials that can not be heated much above room temperature.

The minimum combination of fog-room curing and oven-drying was sought. The criterion was that there be no significant effect on flexural or compressive strength while achieving high resistance to jet impingement. For each set of specimens subjected to oven-drying, a companion set was kept in the fog room and tested for strength at the same time as those oven-dried. A third set, restricted to flexural and compressive strength specimens, was placed in normal drying. The conditioning programs examined ranged from 14 days in the fog room, followed by 28 days in an oven kept at 105 to 110°C, down to 7 days in the fog room, followed by 7 days oven-drying. Most of the specimens were of diabase aggregate concrete, but a set of blast furnace slag aggregate concrete specimens was put through the minimum periods. None of the oven-dried specimens spalled under jet impingement, but all the fog room specimens did. With one exception, the strengths (averages of three specimens) of the oven-dried specimens were lower, but only slightly so, than those of the fog-room specimens. The difference is considered to be statistically real but not of engineering importance. Therefore, resistance to jet-induced spalling appears feasible by short periods of wet curing, followed by short periods at 105 to 110°C.

7. SPECIMENS FROM OUTSIDE NBS

Over the final portion of Phase 2 and much of Phase 3, the Bureau of Yards and Docks required contractors to submit samples (3, each 18 by 18 by 6 in.) cast at the same time, and from the same batches used to pave trafficways at various air facilities under the jurisdiction of Bu Y&D. These specimens had been sealed in damp sawdust by the contractors. They were removed from this packing, placed in the fog room until 28 days after casting, and then dried in air at 73 F/50%rh. The specimens had not been instrumented, so the decision as to the appropriate age for testing the first specimen in each group was based on the shape of the curve obtained by plotting data from periodic weighing. Each specimen from a group of three was subjected to the jet-impingement at a different age; the results from the first in a group being used, with the weight-loss data, as an indicator toward the additional conditioning periods for the other two. The specimens were cut into beams 18 by 6 by 6 in. following jet-impingement exposure, and data obtained on flexural strength, compressive strength, moisture content, etc.

The results obtained from the above were included in the periodic reports to Bu Y&D. A table summarizing all such test data (except for one set submitted late,(see NBSR 7780) appeared in report NBSR 7486.

8. ACKNOWLEDGMENTS

The findings summarized and referred to inthis report are based on the work of many people during the period 1951 to 1964. Principal contributors include: R. A. Heindl, W. L. Pendergast, Dr. B. Foster, S. Zerfos, C. Tuma, L. Mong, R. A. Clevenger, and E. Tratner. Numerous others contributed to a lesser extent.

TABLE 1. MATERIALS

The following lists the materials used as the major constituents of the concretes studied in this program. Some of the concretes submitted from various Naval Air Facilities contained materials not listed below. The letter-symbols were used in the progress reports to indicate batch constituents. Those for cements are used in part B.3 of the Index to this report.

Phase 1

Cements

L Lumnite (high alumina)
Z Portland pozzolan
P Portland

Aggregates

B Brick, medium dense
BS Bluestone (limestone)
C Calcined flint clay
H Haydite (expanded shale)
K Kenlite (expanded shale)
L Lelite (expanded shale)
O Olivine
P Pumice
R Rocklite (coated expanded shale)
RC Raw flint clay
SS Sintered slag
W Waylite (expanded slag)
WM White Marsh (siliceous)

Phase 2

Cements

A Alcoa (high alumina)
P Portland

Aggregates

B Brick, medium dense
BF Blast furnace slag
Di Diabase

Phase 3

Cements

P Portland

Aggregates

BF Blast furnace slag
V Volcanite[a/]
Di Diabase

[a/] Submitted by Naval facility

TABLE 2. CHARACTERIZATION TESTS

These tests were made on the aggregates, cements, or concretes to identify their general characteristics.

Aggregates	Cements	
Sieve analysis ASTM C117; C33; BY&D 45Ya	Chemical analysis ASTM C114	Mix a/
Bulk specific gravity ASTM C127; C128	Bulk specific gravity ASTM C188	Air content ASTM C138; C231
Water absorption ASTM C127; C128	Compressive strength ASTM C39	Slump ASTM C143
Crushing strength BuReclamation MLR C385	Air content ASTM C138; C231	Compressive strength ASTM C39
Abrasion (Los Angeles ASTM C131; C3	Expansion (autoclave)	Flexural strength ASTM C78
Unit weight ASTM C29	Thermal dilation	Youngs modulus, dynamic G. Pickett, ASTM Proc. 1945 NBS RP 1252
Petrographid	PCE ASTM C24	Abrasion
	Water content change	Shrinkage
	Modulus of elasticity, Youngs, dynamic G. Pickett, ASTM Proc. 1954; NBS RP 1252	Weight Loss
		Thermal dilation
		Air permeability
		Thermal conductivity Pentane apparatus
		Shear strength
		Refractoriness (PCE) ASTM C24
		Freezing-thawing ASTM C290

a/ Designed

Table 3. Properties of Aggregates

Aggregate Type	Aggregate Name	Size	Unit Weight Loose	Unit Weight Jigged	Bulk Specific Gravity	Fineness	Water Absorption	Crushing Strength, Compaction of: 1 in.	2 in.	3 in.	Abrasion
			lb/cu ft	lb/cu ft	lb/cu ft		%	psi	psi	psi	%
Limestone	Bluestone							a/			21.3
		Coarse	83.6	98.0	2.74	6.73	0.24				
		Fine	99.8	113.0	2.64	3.28	1.06				
Brick	Brick										27.0
		Coarse	61.4	71.9	2.26	6.77	8.93				
		Medium	60.5	70.3	2.27	5.75	9.60				
		Fine	80.1	91.9	2.37	3.08	6.10				
Clay, Calcined	Clay, Calcined							3930	>41030		41.3
		Coarse	87.7	101.7	2.65	5.60	0.90				
		Fine	89.4	101.3	2.65	4.49	0.80				
Clay, Raw	Clay, Raw							778	13074	>40682	23.5
		Coarse	86.0	101.5	2.52	5.55	4.76				
		Fine	80.9	95.0	2.50	4.50	5.03				
Olivine	Olivine										59.7
		Coarse	124.8	146.7	2.97	5.29	3.20				
		Fine	114.4	130.5	3.09	2.08	1.00				
Pumice	Pumice							396	1563	6465	
		Coarse	29.2	32.1	1.26	6.18	39.00				
		Fine	38.6	43.9	1.43	4.01	44.80				
Shale, Expanded	Haydite							1535	13863	>41062	
		Coarse	53.8	62.1	1.66	6.16	11.28				
		Fine	68.1	97.5	2.08	2.45	8.61				
Shale, Expanded	Kenlite										30.5
		Coarse			1.34		8.30				
		Fine			1.75		12.30				
Shale, Expanded	Lelite							561	3244	>39824	
		Coarse	42.4	47.9	1.65	6.46	8.42				
		Fine	63.9	73.1	2.09	2.48	5.50				

Table 3. (continued)

Shale, Exp. coated	Rocklite							2780	28299	41026	25.1
		Coarse	47.7	52.0	1.32	7.21	10.54				
		< 9/16	51.3	57.0	1.65	6.39	10.22				
		< 5/16	55.3	61.9	1.81	5.54	17.80				
		Fine	66.3	73.3	1.97	3.48	17.10				
Siliceous	White Marsh										40.5
		Coarse	101.1	110.9	2.64	6.88	0.30				
		Fine	100.4	112.0	2.63	2.82	0.30				
Slag, Ex-panded	Waylite							264	943	8450	
		Coarse	33.2	39.4	1.68	5.80	17.10				
		Fine	60.4	72.2	2.38	2.16	2.61				
Slag, Sin-tered	Slag, Sin-tered										67.5
		Coarse			1.83		9.20				
		Fine			2.72		0.80				
		Coarse[b/]			2.16		3.86				45.3
		Fine[b/]			2.49		3.18				
Diabase[c/]	New York										13.7
		Coarse			2.85		1.18				
		Fine			2.78		1.70				
	Virginia										25.9
		Coarse			2.96	6.35	0.60				
		Fine			2.87	3.06	1.54				
Slag, Blast Furnace[c/]											34.5
		Coarse	73.2	73.1	2.19	7.37	2.19				
		Fine	92.4	95.1	2.73	2.96	3.66				

a/ Available equipment not adequate to achieve 1-in. compaction.

b/ A second shipment.

c/ Phase II aggregates; included for comparison.

Table 4. Aggregates, Phase I, by Properties of Concretes Made Therefrom.

Aggregate	Cement a/	Proportions By Weight, Cement: Coarse:Fine	Compressive Strength	Flexural Strength	Modulus of Elasticity	Abrasion		Properties After 5 Hrs. at 1000 C: Compressive Strength	Flexural Strength	Modulus of Elasticity	Abrasion		Weight Loss	Linear Shrinkage
						Weight of Dust	Depth of Wear				Weight of Dust	Depth of Wear		
			psi	psi	$lb/in.^2 \times 10^6$	gm	in.	psi	psi	$lb/in.^2 \times 10^6$	gm	in.	%	%
Pumice	P	1:1:0.5	1470		.714			85						4.940
	Z	1:1.0.5	1255		.749			95						2.080
	L	1:1:0.5	560		.535									
Haydite	P	1:1.7:1.9	1750		2.340			290		.527				-.383
	Z	1:1.7:1.9	2000		2.080			240		.434				-.500
	L	1:1.7:1.9	2145		2.090			310		.509				-.499
Waylite	P	1:0.9:1.5	1535		1.542	140.8		68						-.780
	Z	1:0.9:1.5	1420		1.399	67.2		122						-.540
	L	1:0.9:1.5	1660		1.663	203.6		303						-.850
Rocklite	P	1:2.0:1.9	2110		2.109	100.3		445		.707	448.8			.370
	Z	1:2.0:1.9	2770		1.877	51.4		515		.755	583.0			.240
	L	1:2.0:1.9	2350		1.839	110.6		515		.619	522.3			.310
	P	1:1.01:0.73	5305	605	2.641	3.50	.0019		0				16.41	-.718
	Z	1:1.00:0.64	5010	585	2.717	3.20	.0021		65	NG	NG	NG	17.71	-.094
	L	1:0.97:0.72	3090	375	2.773	37.05	.0119		180	NG	NG	NG	14.86	.119
Olivine	P	1:0.55:3.24	4240	484	5.962	66.9								
	Z	1:0.58:3.24	4205	425	4.653	45.5			145	0.972	351.8		6.92	0.55
	L	1:0.55:3.24	5890	378	5.627	82.5								
	P	1:3.50:1.50	4740	665	7.195	18.15	.0051		70	1.063	616.0	.1138	7.51	0.15
	Z	1:3.45:1.54	5320	700	6.870	66.50	.0157		150	1.119	378.0	.0691	7.91	0.31
	L	1:3.16:2.11	4300	620	6.822	28.65	.0056		110	.883	432.0	.0756	7.53	-0.04

Table 4. (continued)

Bluestone	P	1:1.55:1.72	4000	420	5.471	14.9		0	0					
	Z	1:1.43:1.59	4620	405	4.876	15.2		0	0					
	L	1:3.01:1.34	5030	810	6.160	20.0			15				37.25	-1.42
	P	1:3.33:1.57	3605	680	5.872	11.5			10				37.45	-1.35
	Z	1:3.16:1.45	5925	965	6.119	9.1			8				33.01	-2.06
Brick	P	1:3.12:1.47	4430	685	5.280	16.60	.0047		125	1.610	501.0	.1159	8.24	0.10
	Z	1:1.52:0.99	4890	395	2.911	15.7			140	.734	68.0		9.80	0.21
	L	1:1.45:0.95	5300	300	2.819	26.3			151	.560	59.5		12.11	0.08
	Z	1:2.79:1.27	7790	820	5.598	4.30	.0023		155	1.918	351.5	.0725	9.00	0.12
	L	1:2.11:1.53	6940	665	5.590	43.25	.0115		290	1.505	230.0	.0511	12.27	0.10
Brick & Sand	P	1:2.72:1.28	4640	790	5.520	15.60	.0074		80	1.083	441.0	.0913	9.23	-.05
Clay, Raw	P	1:1.24:1.56	4010	238	3.426									
	Z	1:1.24:1.56	3400	269	3.125									
Clay, Cal-cined	P	1:3.02:1.42	4420	705	6.535	19.75	.0069		95	1.152	1198.8	.2360	7.950	.273
	Z	1:2.97:1.35	5570	840	6.528	4.65	.0032		150	1.408	479.0	.0910	8.337	.246
	L	1:2.66:1.77	5750	740	6.692	35.25	.0100		130	1.393	400.0	.0830	8.316	.074
Clay, Cal-cined & Sand	P	1:2.84:1.33	5810	800	6.298	8.55	.0040		60	.784	1361.0	.2610	7.50	.05
Siliceous	P	1:3.57:1.95	3080	540	5.199				10	.103			8.20	-0.24
	Z	1:1.59:2.26	4440	426	4.450	52.9								
	L	1:3.58:1.93	3435	490					20	.071	593		10.85	-0.41
	Z	1:3.58:1.94	4290	640	5.510				10	.092			8.29	-3.79
Slag, Sin-tered	P	1:1.38:1.57	5595	795	4.697	35.40	.0113		130	1.194	572.0	.1166	13.54	.475
	Z	1:1.58:1.52	6445	725	4.536	20.80	.0067		80	.576	678.0	.1509	13.91	.390
	L	1:1.31:1.31	7220	670	4.750	58.85	.0171		145	1.534	382.0	.0753	14.69	-.442
Kenlite	P	1:0.99:0.73	5405	670	2.976	21.35	.0084		115	.768	NG	NG	17.75	.724
	Z	1:0.76:0.95	5860	635	3.069	10.25	.0075		75	.750	NG	NG	18.28	.374
	L	1:0.91:0.74	5790	555	3.160	33.00	.0091		190	1.248	NG	NG	15.45	.325

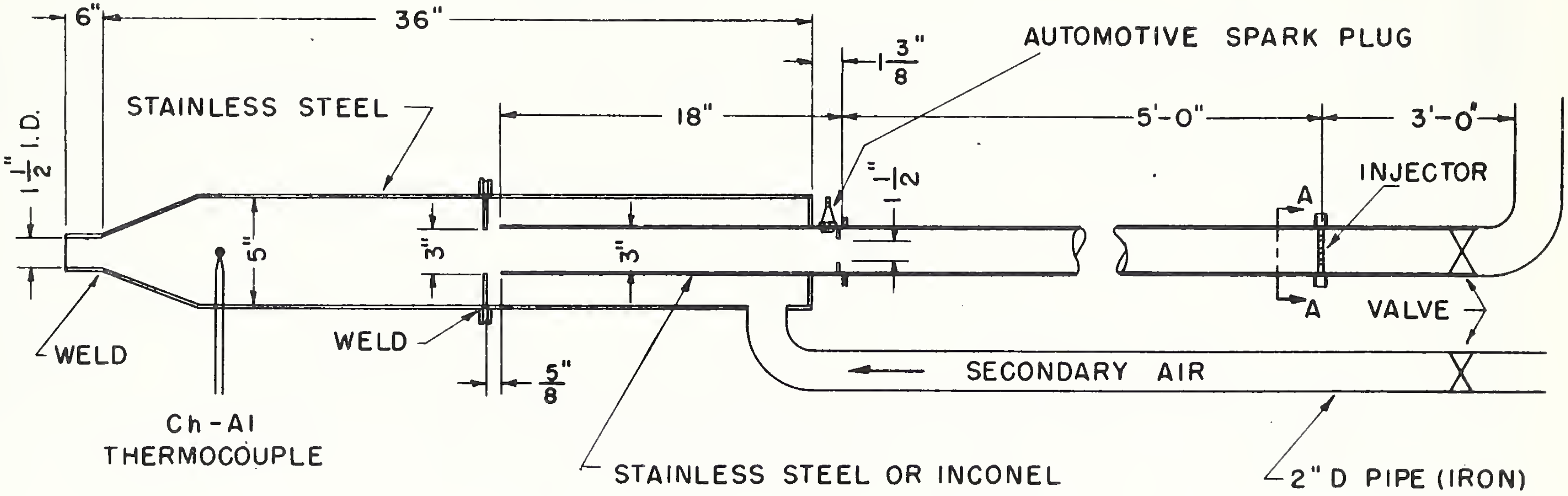

FIG. 1- COMBUSTION CHAMBER

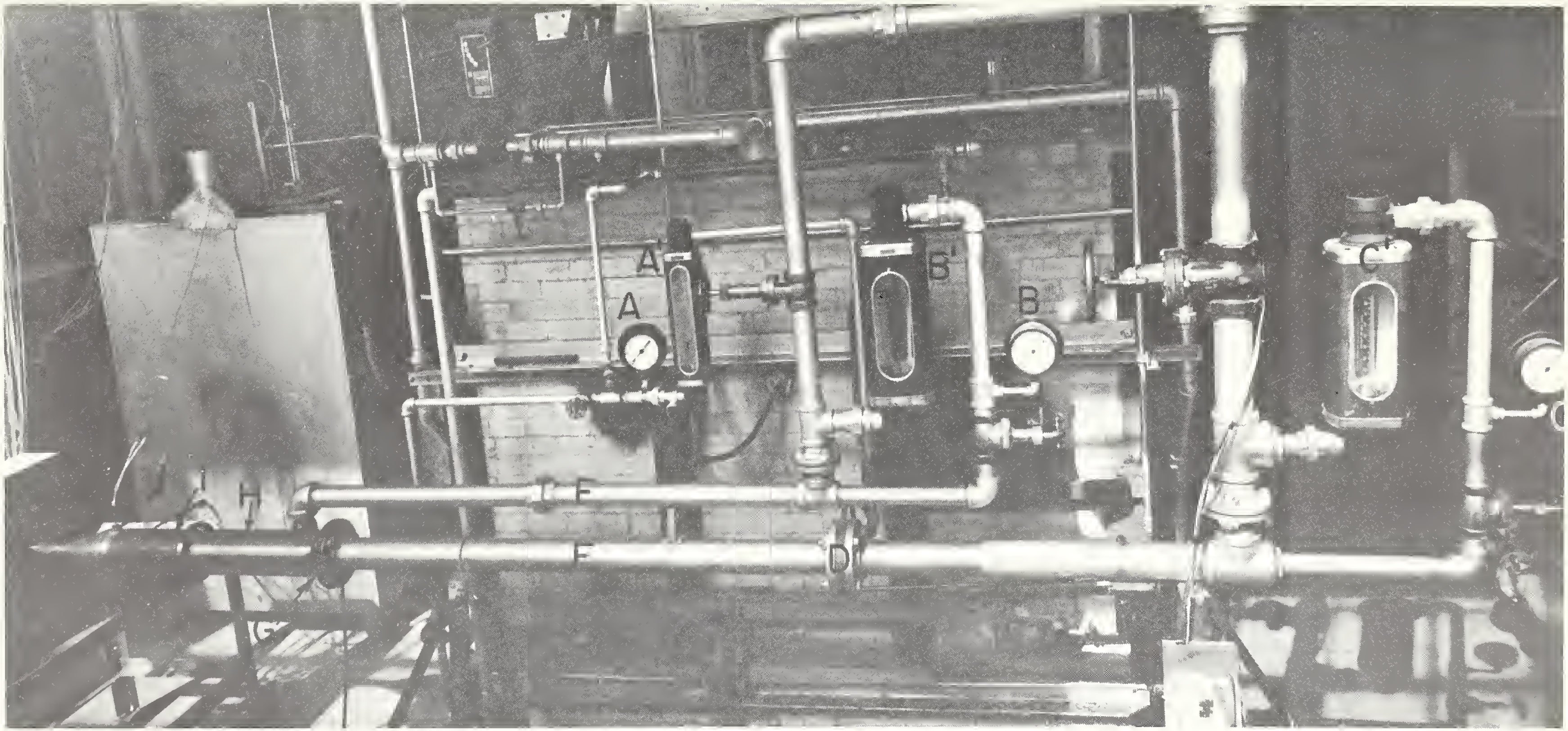

Figure 2. Combustor and Controls

A, B, C Pressure gages for fuel, secondary, and primary air; A′, B′, C′ Flow meters for fuel, secondary, and primary air; D fuel injector; E Mixing chamber, primary air and fuel; F Secondary air; G Ignition and flame retainer; H Secondary air (outer tube); combustion chamber (inner tube); I Mixing chamber, hot gas and secondary air; J Thermocouple, inserted to center line of I.

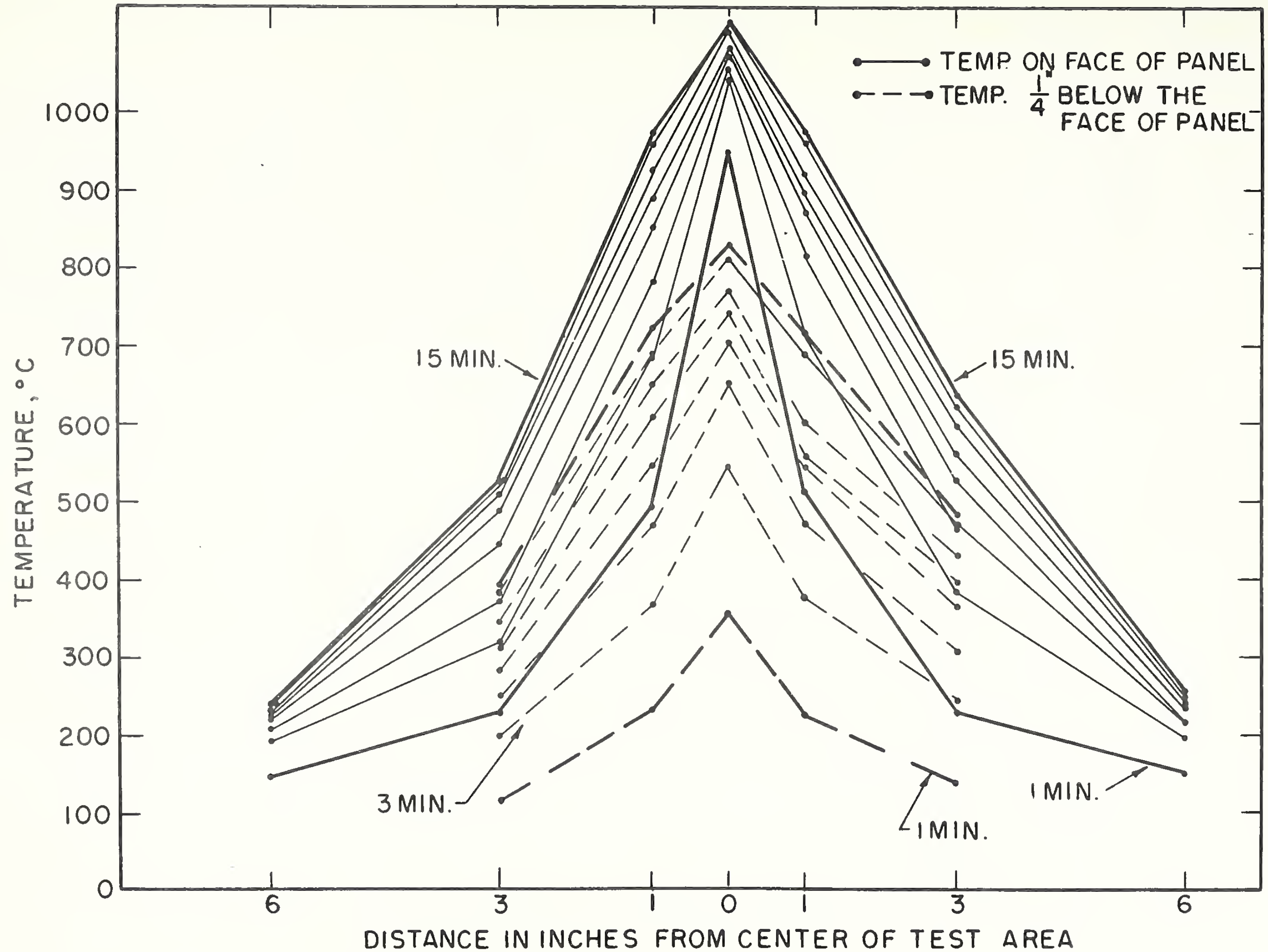

Figure 3. Curves, for times of 2 min intervals, obtained by plotting temperature and distance from center.

INDEX TO PROGRESS REPORTS

This is an index to the progress reports made to the sponsor, the Bureau of Yards and Docks, throughout this study. It is not an index to this summary report. Since most of the progress reports were of modest length, the references are by report number (NBS Report No.) without page numbers.

The index is in two parts. Part A is by subjects discussed in the text or to information conveyed by illustrations. Part B is to information, primarily numerical data, given in tables.

Part A - Subject Index

Part B - Tables

The multitude of tables in the progress reports made this part highly desirable. It is organized as follows:

Sections B.1, B.2, and B.3, respectively, identify reports having tables on aggregates, cements, or concretes. Sections B.4, B.5, B.6, and B.7 give information as to the properties, test results, or other data headings for aggregates, cements and concretes. Those for concretes are divided between Phase 1 and the remainder of the study. In order to determine which reports have, for example, strength of diabase-portland cement concrete, the reader looks at B.3, B.6, and B.7. Without such organization, the index would be much longer.

Finally, Section B.8 locates some data related more to the experimental method than to the particular specimens. Section B.9 relates to specimens sent in from several air facilities, Naval and Marine, of interest to the Bureau of Yards and Docks.

B.3 Concretes (by aggregate; properties, test results, etc.) - underlined reports include jet-impingement data. Symbols after report numbers indicate cements used.

B.4 Aggregate Properties

1/ For topping over base concrete

B.7 Concrete Properties - Phase 2

1/ Topping over base concrete

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