INVESTIGATION OF THE MOISTURE-VOLUME STABILITY OF CONCRETE MASONRY UNITS

By Joseph J. Shideler

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by JOSEPH J. SHIDELER*

SYNOPSIS

This report describes the results obtained in an investigation of the volume stability of high temperature moist-air cured concrete masonry units that were exposed to various simulated job-site and service moisture conditions. It includes length and weight change data on block subjected to these conditions, the moisture content of block in equilibrium with several relative humidity levels, and indicates the sensitivity of block to variations in relative humidity. Compressive strength, absorption and other data are included. Preliminary tests to determine the length and weight change of block kiln dried to equilibrium with 50 per cent and 10 per cent relative humidity as determined by a "Moisture-Humidity Indicator", developed by Carl A. Menzel, and then stored at these relative humidities are described. A limited exploratory study to determine the effect of carbonation on the length and weight change of concrete block also is discussed. Conclusions given at the end of the paper summarize the test data and indicate a method of reducing the cracking in concrete masonry — first adequately cure the block, then condition the block by a process of carbonation and drying so that they are approximately in volume equilibrium with the average relative humidity of the service condition and keep them dry until they are laid.

INTRODUCTION

The drying shrinkage of concrete masonry units has been recognized as a problem in building construction for many years.[1] Various specifications have been written in attempts to reduce the amount of free water in the block and thus reduce the total amount of drying shrinkage and cracking in masonry walls. Concrete shrinks as it dries, so it appears that solution of the shrinkage cracking problem lies in some method of permitting the shrinkage to take place before the units are incorporated in a structure.

Supposedly, block are adequately dry and shrunk when their moisture content approximates the moisture condition eventually attained in the wall under average service conditions. The moisture content of a concrete masonry wall exposed to the atmosphere is closely related to the relative humidity. The problem of the manufacturer is then one of drying block to a moisture content which is in equilibrium at the relative humidity of the service condition. Since atmospheric humidity is continuously changing, the moisture content of concrete is similarly affected and is constantly varying in an attempt to remain in balance with variations in the relative humidity of the air. This poses a problem for the manufacturer, and the practical approach appears to be one of providing block

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that are dried to a moisture level in equilibrium with a relative humidity at least as low as the average for the particular location and service involved.

A study of the effect of job-site storage conditions on the volume stability of block has also been needed to determine how quickly the block expand when exposed to a heavy rain, or if protected from the rain how sensitive they are to transitory but very high relative humidity conditions, fog for example, from which protection is difficult. Suppose that the block manufacturer delivers units that are dried to moisture equilibrium with the average humidity level of a particular locality, but before the block can be laid in the wall a period of damp weather is encountered with humidities well over the average level. Would the effort of the block producer to provide the contractor with dry block be for naught, or would the block, once dried, resist regaining air-borne moisture? Would kiln drying to a moisture content as low as 10 per cent of total absorption provide a dimensionally contracted condition that would be largely irreversible, thus making the block insensitive to subsequent moisture exposures?

To provide some answers to these questions, a series of tests was undertaken to determine the rate and amount of length and weight change of block exposed to various moisture conditions. High temperature moist-air cured block, dried to various moisture contents in the kiln, were stored in a fog room for 24 hours, immersed in water until saturated, dried to equilibrium, progressively, with 80, 60, 30 and 10 per cent relative humidity and then remoistened by a reversal of this sequence. Companion block were moved directly from the kiln to a controlled atmosphere room without exposure to fog or immersion. Weight and length measurements were taken at frequent intervals throughout the tests.

The test series was directed to several particular objectives:

1. To determine the moisture content of the block when they became stable at several humidity levels, with the thought that block could then be kiln dried to the moisture content required for equilibrium with the average relative humidity for any given service exposure.

2. To determine the effect of partial drying of concrete masonry units on their subsequent moisture-volume change and the possibilities of partial drying for producing a more volume-stable unit.

3. To determine the length and weight change of the block between various relative humidity levels in order to provide a basis for a better understanding of the effects of humidity changes, particularly those occurring rapidly.

4. To determine whether carbonation in addition to moisture loss could account for certain length and weight changes observed in the block.

5. To obtain experience and data in the application of a new instrument which was developed for quickly ascertaining the moisture content of concrete block in terms of equilibrium relative humidity. Specifically, it was desired to determine whether block

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brought to the equilibrium relative humidity indicated by this Moisture-Humidity Indicator would be stable during subsequent storage at the indicated relative humidity. The relationship between the moisture content of a block, expressed as per cent of total absorption, and the corresponding equilibrium relative humidity as indicated by the Moisture-Humidity Indicator also was desired.

TEST PROCEDURE

Manufacture and Curing of Block

Four aggregates were used which are common in concrete block manufacture and which represent a wide range of physical properties. These aggregates were sand and gravel, expanded slag, expanded shale,* and pumice. Cinders were used in a few block for carbonation tests only. A blend of equal parts of four commercial Type I cement was used throughout the tests. Concrete mixing, molding and curing procedures were established that produced compressive strengths at 72 hours after molding averaging 1300 psi for the sand and gravel, 1000 psi for the expanded shale, and 700 psi for the expanded slag and pumice units. A deviation of $\pm$ 100 psi from these average compressive strength values for individual units was allowed. Compressive strength tests were made in accordance with ASTM Designation C140-52. The yields resulting from these mixes in blocks per sack of cement were: sand and gravel, 25.8; expanded slag, 22.5; expanded shale, 25.9; and pumice, 19.5. Complete mix data are given in Table 1.

The concrete was mixed in a 9 cu. ft. multiblade paddle type mixer similar to the larger models used in commercial plants. Standard 8 by 8 by 16-in. block (3-oval core, 42 per cent core area) were molded in a commercial single unit machine which vibrated and compacted the concrete under pressure. The molded block were immediately placed in a kiln and subjected to an 18-hour curing cycle. The cycle consisted of holding the block at room temperature for 2 hours, then raising the kiln temperature to 160°F at 40°F per hour, maintaining 160°F for 13 hours, and cooling for one hour with doors and vents open. During the cycle, the temperature and moisture were maintained by the injection of live steam. For tests requiring additional drying, the moist air was exhausted from the kiln, and radiators and a unit heater provided a drying temperature of 180° to 200°F until the block reached the required moisture level.

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*The expanded shale aggregate used for the first three mixes in this study was a sintered product. As the supply of this aggregate was exhausted, another expanded shale, a rotary kiln product, was used for the block kiln dried to a moisture content of 10 per cent of total absorption. Block containing the sintered aggregate had a moisture content of 28 per cent of total absorption after 7 hours of kiln drying. Block containing the aggregate produced in a rotary kiln had a moisture content of about 50 per cent of total absorption after 8 hours of kiln drying. Due to the differences in the aggregate and in the block only data obtained on block containing the sintered expanded shale are reported.

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To study the effect on volume stability of rapid drying in the kiln, test units were kiln dried to four different moisture contents. The moisture content of block removed from the kiln without exposure to a drying period was usually 50 to 65 per cent of the total 24-hour absorption. From this initial moisture content block were dried to three selected lower moisture contents of approximately 40, 25 and 10 per cent of total absorption. A hanger connected to a weighing scale on the roof of the kiln provided the means for ascertaining the weight change of block during curing and drying.

A total of 864 block was made and tested in this program. This does not include a considerable number used for preliminary work. At least three units were made for each test condition.

Length Change Instrumentation

After the block had been removed from the kiln, bronze plugs were set in the block to be used for length change measurements. Figure Ia shows these plugs installed in the block, with the plugs drilled to receive the conically-shaped points of a 10-inch Whittemore strain gage. Figure Ib shows the Whittemore gage being used to obtain a length measurement, and also shows the type of masonry unit used in these tests.

Storage Facilities

A laboratory fog room equipped with compressed air water atomizers and thermostatically controlled at 73°F was used for the fog exposure sequence. The water immersion operation was performed in a large, rectangular tank provided with water circulating and temperature control equipment for maintaining the water bath at 73°F. Figure Ic shows a portion of the controlled atmosphere room and the method of storing the test block in the room during their exposure to the several humidities. The air conditioning plant which serves the room provides for controlled air temperature at any desired setting from 60 to 80°F and relative humidity at any setting from 10 to 90 per cent. Although the volume of air handled per minute by the air conditioning plant was, at the lower humidity settings, about equal to the volume of the room, the air distribution and pick-up was such that air movement within the room was barely discernible.

Organization of Tests

Details of the testing plan for the various series and groups of block are shown in Table 2. All of the block were divided into two major categories according to the exposure, Series A and B. Each series (A and B) was further divided into four groups according to the degree of kiln drying. Group 1 had no kiln drying; Group 2 was to be dried to 40 per cent of the total absorption; Groups 3 and 4 were to be dried to 25 and 10 per cent, respectively.

Series A block were first stored on a rack in the fog room for 24 hours while covered with a waterproof tarpaulin that extended almost to the floor and protected the block from precipitated moisture but allowed some circulation of air at 100 per cent relative humidity. This treatment simulated a job exposure of block pro-
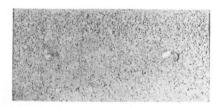
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Fig. 1a. Bronze plugs installed in block and drilled
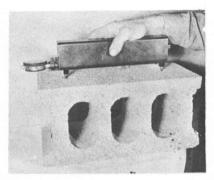to receive tips of the strain gage.

Fig. 1b. Whittemore Strain Gage used to obtain length change
measurement on the block.

Fig. 1c. Interior view of controlled atmosphere room
showing method of storing block.

tected from heavy rain, but exposed to high humidity. These block were then immersed in water for 4½ days to provide a saturated condition similar to that obtained by direct exposure to a series of very hard rains. During each of these tests, several measurements were made during the first few hours to determine the volume-sensitivity of the block as they absorbed water. After this period of immersion, the "A" series block were placed in the controlled atmosphere room set at 80 per cent relative humidity and 73°F.

The "B" series block were provided to obtain data on the moisture-volume stability of concrete block which had not been subjected to external moisture influences such as fog and rain. Thus, this allotment of block was taken directly from the kiln and placed in the controlled atmosphere room at 80 per cent relative humidity. In planning the program, it was at first considered that the desired information might be obtained from the tests performed on the Series A block. However, the effect of the moist room exposures and water immersion on further hydration of the cement raised questions which warranted the separate series, Series B.

Both series of block, therefore, were exposed to the same humidity cycle beginning at 80 per cent. Weight and length changes were measured frequently until the block had become stable at this relative humidity. The relative humidity was then changed to 60, 30 and 10 per cent as equilibrium was established at each level. The moisture content of the block were then increased by raising the relative humidity to 30, 60 and 80 per cent and finally immersing the block in water until they were saturated. The purpose of this single humidity cycle was to determine the moisture content of the block when they were in equilibrium with a certain relative humidity and to determine the corresponding weight and length changes.

Since all block were stored in the same controlled atmosphere room, the humidity level was not changed until all had reached equilibrium. The pumice block required a longer period of time to reach equilibrium than the other block and so controlled the total time of exposure. The pumice block required 8 months to reach equilibrium at the first 80 per cent relative humidity level, 5 months at 60 per cent relative humidity and 3 to 4 months for each of the other levels. The humidity cycle required a total of 29 months.

Compressive Strength

Compressive strength tests were made on block from each series (A and B) for each initial kiln drying condition at ages of 3 and 28 days and at the end of each humidity level. The strength specimens were capped with a cement-plaster mixture and tested in accordance with ASTM Designation C140-52.

Moisture Content and Absorption Tests

The "initial" moisture content of the block was determined at the time of removal from the kiln. The block used for moisture content and absorption data were immediately weighed, then immersed in water for 24 hours and oven dried to constant weight.

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Procedures and computations were in accordance with ASTM Designation C140-52. An attempt was made to dry the block in the kiln to moisture contents of approximately 40, 25 and 10 per cent of the 24-hour absorption, but the moisture content of some of the block departed from the desired values. The moisture contents of pumice block, in particular, were as much as 15 percentage points above the desired values. The actual moisture contents at the time of removal from the kiln are given in Table 2, together with the group number and kiln drying time required to produce the indicated moisture content. Five to seven hours of drying were required to produce a moisture content of 25 per cent in the slag, shale, and sand and gravel block, while 26 hours of drying were required to produce the same moisture content in the pumice block. Thus, the pumice block required a drying period about four times as long as block containing the other aggregates.

Moisture content and absorption tests were also made at 28 days and at the equilibrium condition with each of the relative humidity levels, with the exception that complete tests were not made at the first 80 and 60 per cent levels. A different set of block was used for these tests at each age, and these are referred to as the "absorption block". The moisture contents of block at each humidity level were also computed from the equilibrium weights and the final saturated and dry weights of the block used for the weight and length change measurements. These values are referred to as the moisture contents of the "volume-stability blocks", and were computed to obtain an estimate of the moisture content of the block at the first two humidity levels.

Moisture-Humidity Indicator Tests

A device which provides a rapid indication of the moisture content of concrete block in terms of equilibrium relative humidity was developed by Carl A. Menzel,[2] Concrete Technical Problems Consultant, P.C.A. This "Moisture-Humidity Indicator" consists of a ten-gallon metal container having a vapor-tight lid, a blower to circulate the air within the container, and a hygrometer to indicate the relative humidity. One-half of a concrete block is broken into small pieces and placed in a wire basket inside the metal container. Within the sealed container an interchange of moisture occurs between the pieces of concrete block and the enclosed air until an approximate balance is attained between the moisture in the concrete and the relative humidity of the air. It has been assumed that companion block will be volume-stable at this indicated relative humidity, as presumably there is no tendency to gain or lose moisture.

The special group of block used for these Moisture-Humidity Indicator tests were kiln dried to a moisture content of about 30 per cent of total absorption. Inserts for length change measurements were then installed in some of the block and drying was continued in an oven at 200-215°F. About every two hours a block was removed from the oven and cooled to 73°F. Half of this block

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was then broken into small pieces and placed in the apparatus for equilibrium relative humidity measurements. The other half was weighed and used to determine the corresponding moisture content. Three block were removed from the oven when the meter indicated a moisture content in equilibrium with 50 per cent relative humidity. These block were cooled, weighed and measured, and stored at 50 per cent relative humidity. Additional tests were made on the block in the oven to determine the equilibrium relative humidity at several moisture contents. When the block had dried to a moisture content estimated to be in equilibrium with 10 per cent relative humidity, the remaining block were removed from the oven, cooled, measured, and sealed in a drum containing a sodium hydroxide solution to maintain a relative humidity of 10 per cent.

Carbonation

The test procedure used to study the effect of carbonation is briefly described in the section discussing these test results.

Supplemental Series C and D

During the long period of time required for the Series A and B block to reach shrinkage equilibrium at the various humidity levels the cement continued to hydrate. It was thought that possibly this additional hydration would tend to decrease the ultimate shrinkage at the various levels of drying as compared with freshly-made block. Accordingly, new block were made of sand and gravel and expanded slag aggregates for each level of drying. None of these block were given any drying in the kiln. The "D" series block were placed directly in the humidity cycle, while the "C" series block were saturated prior to exposure to the humidity cycle. Comparisons of the total shrinkage for each level of drying, and the time required to reach equilibrium with various humidities for the freshly-made block of C and D series were made with the corresponding values for the Series A and B block. Details of the testing plan for the C and D series are given in Table 2.

TEST RESULTS AND DISCUSSION

Strength

All strength values are given in Table 3 and are plotted in Figure 2. The strength of the sand and gravel block during exposure to the humidity cycle increased from 1320 psi at 3 days to 1680 psi at 28 days, and to 2150 psi at age 2 years. The expanded shale and expanded slag block showed an increase in strength of about 500 psi between ages of 3 and 28 days with little gain thereafter. The pumice block had a strength of 770 psi at age 3 days, 920 psi at 28 days and showed no strength gain at later ages.

Additional block were given 14 days fog curing at 73°F followed by 14 days air drying at 73°F and 50 per cent relative humidity. These reference block show that the compressive strengths of the Group 4 concretes were generally about 200 psi lower than the Group 1 concretes at age 28 days. When this correction was applied to the "A" and "B" series block, there was no significant difference in
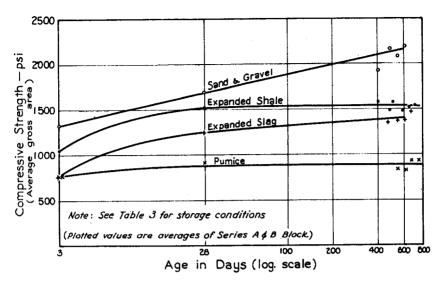
Fig. 2 — Compressive Strength of Concrete Block

the strength of block due to the different amounts of kiln drying. The sand and gravel "A" series block had higher strengths at 28 days than the "B" series block, but at the later ages there was little difference between the two series. The strength of the "A" series block was essentially the same as the "B" series block at all ages for the lightweight aggregate block. Thus, the 4½ days immersion period had no significant effect on the compressive strength of the block as compared to the storage at 80 per cent relative humidity.

Length Change

B Series

A summary of the length change data for sand and gravel block, "B" series is given in Figure 3a. The bottom curve shows the drying shrinkage of block with no kiln drying and initial moisture content of 55 per cent of total absorption. The top curve shows the drying shrinkage of block that were kiln dried to a moisture content of 17 per cent of total absorption. The intermediate curves are for block dried to 25 and 43 per cent of total absorption. When stored at 60 per cent relative humidity the block kiln dried to 43 and 17 per cent of total absorption had 87 per cent and 74 per cent as much shrinkage, respectively, as the block with no drying. When stored at 10 per cent relative humidity, the block dried to 43 and 17 per cent of total absorption had 93 and 81 per cent as much shrinkage, respectively, as the block with no drying. When these block were saturated at the end of the humidity cycle, they recovered about 50 per cent of the maximum drying shrinkage.

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Corresponding data are shown for expanded slag, expanded shale, and pumice aggregate block in Figures 3b, 3c, and 3d. Pumice block showed considerably more length change than other block under the various conditions. At 60 per cent relative humidity the pumice block dried to 55 and 22 per cent of total absorption had 76 and 48 per cent as much drying shrinkage as the block that had no kiln drying. At 10 per cent relative humidity the block dried to 55 and 22 per cent of total absorption had 82 and 62 per cent as much shrinkage as the block that had no kiln drying. Drying block to about 25 per cent of total absorption produced a substantial decrease in the amount of shrinkage obtained to equilibrium with 60 per cent relative humidity as compared to block given no kiln drying. This decrease amounted to 16 per cent for sand-and-gravel block, 31 per cent for expanded slag, 27 per cent for expanded shale and 52 per cent for pumice block.

Fig. 3 – Summary of Length Change Data for Concrete Block
Subjected to Varied Relative Humidities

SAND AND GRAVEL BLOCK, 'B' Series

o — No kiln drying (55% of total absorption)
• ---- Kiln dried to 43%   "   "   "
+ ---- Kiln dried to 25%   "   "   "
x —·—Kiln dried to 17%   "   "   "

Fig. 3a

EXPANDED SLAG BLOCK, 'B' Series

—— o No kiln drying (56% of total absorption)
········ Kiln dried to 42% " "   "
----+ Kiln dried to 29% " "   "
—— x Kiln dried to 6% " "   "

Fig. 3 b

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Fig. 3c

Fig. 3d
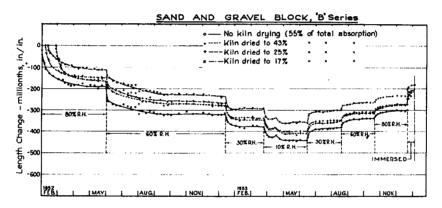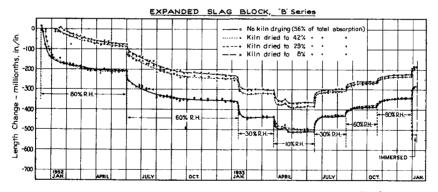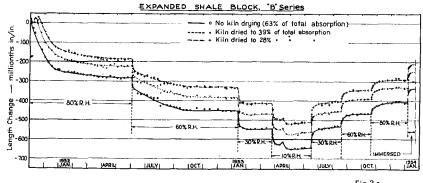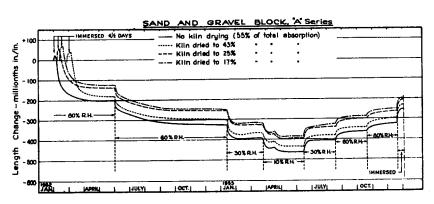
The pumice block dried to 22 and 36 per cent of total absorption showed a considerable expansion when first exposed to 80 per cent relative humidity. This would seem to indicate that these block were dried below the equilibrium moisture content for 80 per cent relative humidity. However, after a few days these block began to shrink and after several weeks showed net shrinkage values. This behavior will be discussed later in this report.

Minor variations in the plotted points occur in Figures 3a, 3b, 3c and 3d on the same day for all block. These variations are due to fluctuations in the controlled conditions and to interruptions in the controlling equipment. The most apparent deviation occurred in April 1953 when the equipment controlling the 10 per cent relative humidity atmosphere was inoperative for about five days. The long exposure at 60 per cent relative humidity was due to the fact that new equipment was being installed to provide the lower humidity levels.

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A Series

A summary of the length change data for sand and gravel block, "A" series, is shown in Figure 4a. Upon immersion these block showed a maximum length increase of about 70 millionths in. per in. During the subsequent storage in the humidity cycle, the length changes were very similar to the "B" series block, which had not been saturated. This is shown by a comparison of Figures 3a and 4a. The curves in Figure 4b for the expanded slag block, "A" series, are very similar to those for the "B" series block, but indicate about 10 per cent greater shrinkage. Values in Table 4 indicate that for all aggregates the "A" series block showed greater shrinkage than the "B" series block. Figures 4c and 4d show the length changes of the expanded shale and pumice block. (Note that the length change scale for the pumice, Figure 4d, is only half that used for the other aggregates.) Due to the similarity of Figures 3 and 4 plotted points are shown only on Figure 3.

Fig. 4 - Summary of Length Change Data for Concrete Block
Subjected to Varied Relative Humidities

Fig. 4a

Fig. 4b

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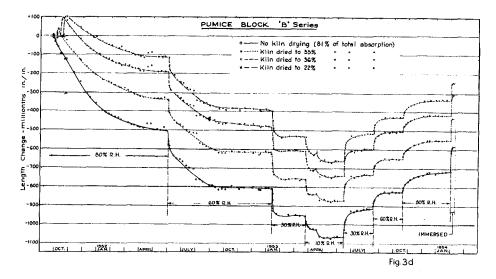
Fig. 4c

Fig. 4d

Fig. 4e

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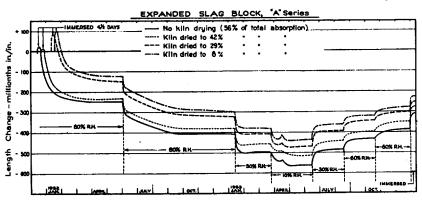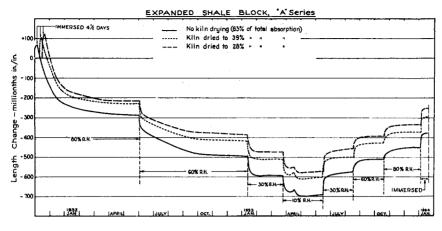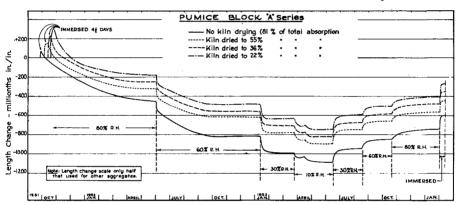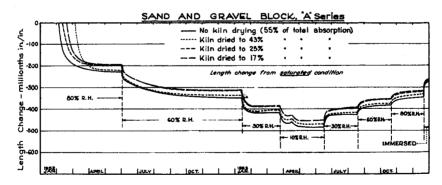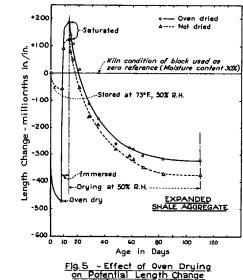
Figure 4e shows the length change of sand and gravel block, "A" series, using the saturated length as the zero reference. These curves show the drying shrinkage that could be expected if the block are allowed to become saturated prior to use. Kiln drying had very little effect on the moisture-volume stability of the block. Similar curves were obtained for the other aggregates, and all showed the same trends. The shrinkage at 10 per cent relative humidity of block kiln dried to the lowest value of total absorption and then saturated was within 11 per cent of the shrinkage of block that were given no kiln drying. This was true for all aggregates. These curves also show that after resaturation at the end of the cycle, the block had recovered less than half the maximum drying shrinkage. Although the initial kiln drying had only very minor effect on the volume-stability of the block, the long exposure to the relative humidity cycle apparently had a very marked effect in stabilizing the block.

As kiln drying the block to a moisture content as low as 10 per cent seemed to have little effect on the potential volume changes of the block, an auxiliary test was performed to determine whether oven drying the block would improve volume stability. Block from one run were removed from the·kiln at a moisture content of 30 per cent. One-half of these were immediately placed in an oven at 210°F and brought to an oven dry condition. All block were then immersed in water four days and then stored in a room at 50 per cent relative humidity. The shrinkage of the oven dried block was identical to the shrinkage of block dried to 30 per cent of total absorption, using the saturated condition as a zero reference. This emphasizes the fact that drying the block does not produce a volume-stable unit, and kiln drying the block is of exceedingly small value if the block are allowed to get wet prior to use (Figure 5).

Fig. 5 – Effect of Oven Drying
on Potential Length Change
of Concrete Block

Comparison of A and B Series

The length change of block stored under the various conditions are summarized in Table 4. All of these values were computed from the initial length of the block measured immediately after they had been removed from the kiln and cooled to 73°F. Figure 6 summarizes some of the more important variations of drying shrinkage as affected by the curing and storage conditions. For each aggregate the bottom curve is for block that were given no kiln drying and were then immersed (A-1 block) and dried from the saturated condition, which was used as the initial length. The curve next to the bottom shows the drying shrinkage from a saturated condition of block that were initially kiln dried to 25 per cent of total absorption. The curve next to the top is for block that were given no kiln drying but were not resaturated (B-1 block). The top curve is for block dried to 25 per cent of total absorption and kept dry.

Some numerical comparisons of drying shrinkage values taken from Figure 6 are summarized in Table 5. The upper portion of this table compares the drying shrinkage of block stored under various conditions to the drying shrinkage of block which were given no kiln drying and were then immersed. The lower part of this table compares block within the B series, which were kiln dried to 40 and 25 per cent of total absorption, to block which were given no kiln drying (B-1 block). Comparisons are shown at 60 and 10 per cent relative humidity. These two values of relative humidity were used because the average relative humidity over a large part of the nation is about 60 per cent and the relative humidity in heated buildings often approaches 10 per cent.

Considerable differences in drying shrinkage were obtained during the 80 per cent relative humidity storage. However, this storage brought the cement gel to a common moisture level in all block containing one aggregate so that these block showed almost identical length changes at each of the various humidity levels below 80 per cent relative humidity. For example, the pumice block B-1 shrank 5 times as much as the B-4 block at 80 per cent relative humidity, but at the 60 per cent relative humidity, there was very little difference in the shrinkage of the B-1 and B-4 block. The length changes of block between the various humidity levels are given in Table 6.

Moisture Content

One of the main purposes of this investigation was to obtain a relationship between the moisture content of the block and the ambient relative humidity at the various equilibrium levels. This relationship is shown in Figure 7 as determined from the absorption block. Values for the individual series and groups are given in Table 7. Block brought to equilibrium with 60 per cent relative humidity during the drying portion of the humidity cycle had moisture contents between 12 and 21 per cent of total absorption, de-
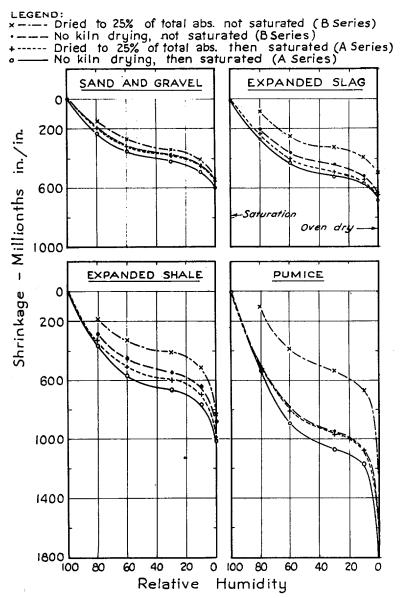
Fig. 6 - Comparison of Shrinkage of
Concrete Block for Different Initial Curing Conditions
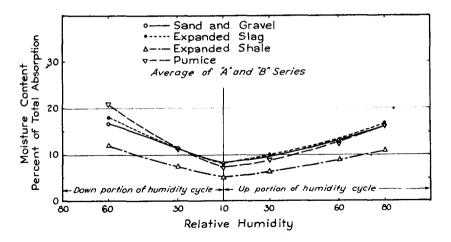
Fig. 7 – Moisture Content of Block in Equilibrium
With Various Relative Humidities
(Absorption Block)

pending on the aggregate. At 10 per cent relative humidity the moisture content was between 5 and 8 per cent of total absorption. The moisture content at each humidity level of block used for length measurements was also computed at the end of the test, by using the final saturated and dry weights and the equilibrium weights at each humidity level (Figure 8 and Table 8). These values check those obtained with the absorption block during the remoistening portion of the test, but are about 5 per cent lower than for the absorption block at the first 60 percent relative humidity level. This is probably due to the fact that the oven dry weight of block gradually increased during the long exposure to the humidity cycle (see Table 9).

The original thought in the preparation of these curves was that they would be useful in determining the moisture content to which a block should be dried in order to be in equilibrium at a certain humidity, i.e., a sand and gravel block should be dried to a moisture content of 17 per cent of total absorption, (see Figure 7) in order to show a minimum volume change at 60 per cent relative humidity. The relationship shown in Figure 7 holds for block that have been stored under relatively constant conditions for several months, but, as will be shown later, rapidly drying a freshly cured block to a point indicated on the figure for a particular aggregate will not necessarily produce a volume-stable block at the corresponding relative humidity. This is primarily due to the effects of carbonation and will be discussed later in the report.

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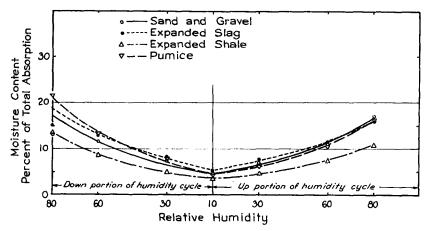
Fig. 8   Moisture Content of Block in Equilibrium
With Varied Relative Humidities
(Volume Stability Block)

Length vs. Weight Change

Very interesting curves are obtained when the length changes
of the block are plotted against the weight changes. Figure 9a pre-
sents the length-change weight-change relationship for sand and
gravel block. These curves are for "B" series block dried to various
initial moisture contents and then subjected to the humidity cycle.
When stored at 80 per cent relative humidity, block given no kiln
drying (curve 1) showed shrinkage and weight loss, then showed a
gain in weight, but continued to shrink. When the relative humidity
was lowered to 60 per cent, these block shrank and lost weight,
then gained weight while continuing to shrink. At relative humidities
of 30 and 10 per cent the block lost weight and continued to shrink.
The minimum weight of these block at 80 and 30 per cent relative
humidity was essentially constant, but the block shrank about 300
millionths between these two conditions. As a block can show con-
siderable shrinkage without a change in weight, a determination of
the moisture content of a freshly cured block is not necessarily an
indication of its potential shrinkage.

Curves 2 and 3 show similar data for the block kiln dried to 43
and 25 per cent of total absorption. The block dried to 17 per cent
of total absorption actually gained almost 0.4 pound per block dur-
ing storage at 80 per cent relative humidity, but also shrank about
110 millionths during this time (curve 4). These block continued to
shrink at 60 per cent relative humidity but showed an additional
small gain in weight. At 30 and 10 per cent relative humidity they
continued to shrink and lose weight. At the end of the 10 per cent
relative humidity storage, the block showed a drying shrinkage of
about 360 millionths with a gain in weight of 0.2 pounds from the
kiln condition.

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Figure 7 indicates that a freshly made sand and gravel block dried rapidly to 17 per cent of total absorption would be in equilibrium with about 60 per cent relative humidity. However, the block dried to 17 per cent of total absorption shrank 230 millionths before they were in volume-equilibrium with 60 per cent relative humidity.

Curve 5, Figure 9a shows the length-change weight-change relationship for the average of the "A" series block from a saturated condition. The first 1.4 pounds of water lost from the saturated block produced little drying shrinkage. About 80 per cent of the shrinkage of these initially saturated block was accompanied by a loss in weight of the last 0.4 pound.

These curves of Figure 9a are of a rather unusual appearance but similar curves for mortar bars showing shrinkage with weight loss, then continued shrinkage with weight gain are shown in Figure 19 of a report "PCA Long-Time Study of Cement Performance," U.S. Bureau of Reclamation, Materials Laboratory report No. C-345,[3] (March 1947). Data reported by C. A. Menzel[4] also showed weight gain of neat cement-silica specimens while they continued to shrink at 35 per cent relative humidity. This type of curve appears to be associated only with concrete specimens that are relatively porous or that have not been adequately cured, and as will be shown later is due to carbonation.

SAND AND GRAVEL BLOCK
"B" Series
1 - No kiln drying (55% of total absorption)
2 - Kiln dried to 43% of total abs.
3 - Kiln dried to 25% " " "
4 - Kiln dried to 17% " " "
5 - Saturated (Av. of 'A' Series)

Fig. 9a–Relationship of Weight Change to Length Change of Block Subjected to Varied Relative Humidities

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The length-change weight-change relationship for expanded slag, expanded shale, and pumice aggregate block are shown in Figures 9b, 9c and 9d. The expanded slag block (Figure 9b) dried to 8 and 29 per cent moisture content showed a gain in weight of about 0.8 pound and a shrinkage of 80 millionths during 80 per cent relative humidity storage. The block continued to shrink during storage at the lower humidity levels but showed only a very small change in weight. The pumice block dried to 22 and 36 per cent of total absorption, when exposed to 80 per cent relative humidity, first gained weight and expanded. After several days they lost this weight and expansion and later showed another weight increase while they continued to shrink. These variations in weight and length change are of considerable interest and several possible explanations have been offered including continued hydration of cement at later ages, stress conditions due to moisture gradients in the block, carbonation, and capillary tension effects.
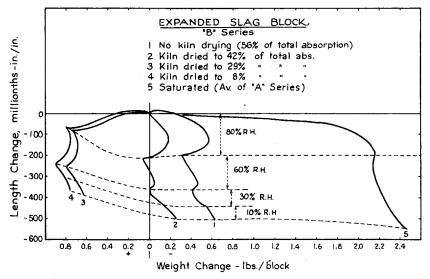
Fig. 9b- Relationship of Weight Change to Length Change of Block
Subjected to Varied Relative Humidities
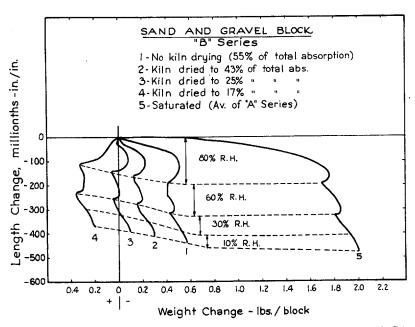
Fig. 9c–Relationship of Weight Change to Length Change of Block Subjected to Varied Relative Humidities
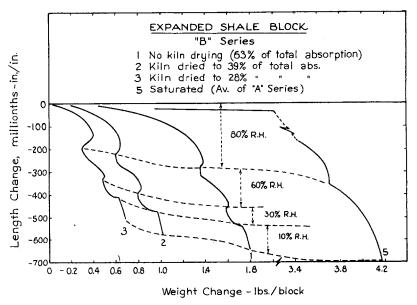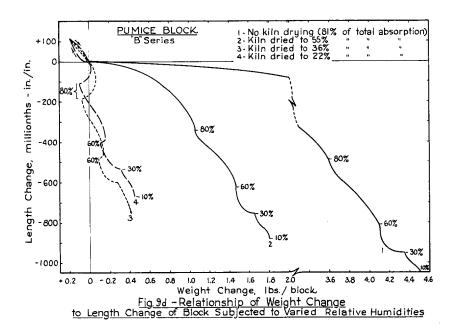
Fig. 9d –Relationship of Weight Change to Length Change of Block Subjected to Varied Relative Humidities

Carbonation

Carbonation is generally considered to be a reaction between calcium hydroxide $(Ca(OH)_2)$ released during the hydration of cement, and carbon dioxide (CO_2) in the atmosphere to produce calcium carbonate and water. In order to determine the effect of carbonation on the weight change and length change of concrete block, a few block containing different aggregates were exposed to an atmosphere of carbon dioxide. These block had been kiln dried to equilibrium with 50 per cent relative humidity as indicated by the Moisture-Humidity Indicator and were stored for several weeks in air at 50 per cent relative humidity. Very minor weight and length changes occurred during this storage. During a 4-day exposure to a high concentration of CO_2 the block shrank about 300 millionths and gained between 1.0 and 1.5 pounds in weight per block as shown by Figure 10 for expanded shale only.

Carbonation was accomplished by sealing the block in a steel drum and allowing CO_2, obtained by the sublimation of dry ice in a separate sealed container, to enter the drum through a copper tube. A water jar "bubbler" was also connected to the drum to allow air and gas to escape. A measured quantity of dry ice was used each day for four days. The relative humidity of the atmosphere in the drum was maintained at 53 per cent by the use of a magnesium nitrate solution. Weight and length measurements of the block were made each day. The quantity of dry ice added was weighed and the weight of the humidity controlling solution also was determined.

The following tabulation presents the data obtained during the test:

	Wt. Gained By Block per day (lbs.)				Wt. Gain By Sol. (lbs)
Date	Shale	Slag	Cinders	Total	
6-25	—	—	0.80	0.80	—
6-26	0.30	0.37	0.04	0.71	0.05
6-27	0.64	1.03	0.16	1.83	0.14
6-28	0.09	0.10	0.03	0.22	0.02
6-29	0.03	0.02	0.02	0.07	0.02
	1.06	1.52	1.05	3.63	0.23

During subsequent air storage for 14 days at 50 per cent relative humidity the three block lost a total of 0.32 pounds of water (Figure 10 for expanded shale only). It may be assumed then that the three block gained 3.31 pounds due to carbonation and that all of the water produced by the reaction was lost to the atmosphere. The three blocks contained a total of about 14.7 pounds of cement. If the reaction were entirely between CO_2 and $Ca(OH)_2$ the quantities involved in a weight increase of 3.31 pounds would be as follows:
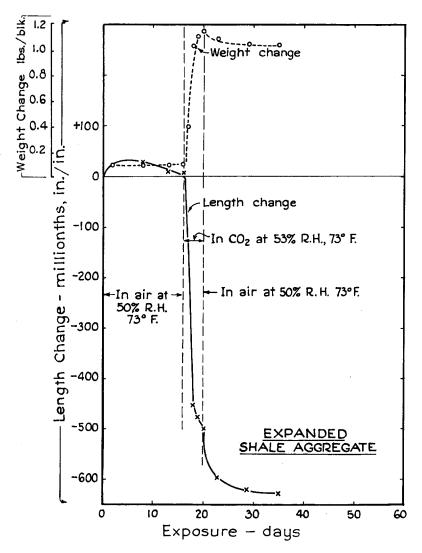
Fig. 10 – Effect of Carbonation on Length Change and Weight Change of Concrete Block

Reaction, $Ca(OH)_2 + CO_2$ ————————— $CaCO_3 + H_2O$
Mol. wts., 74 $+ 44$ ————————— 100 $+ 18$
Actual
wts., lbs. 9.42 $+ 5.61$ ————————— 12.73 $+ 2.30$

This quantity of $Ca(OH)_2$ is considerably larger than that normally released during hydration, and thus indicates that the CO_2 also reacted in some other way.

During 4 days exposure to CO_2 shrinkages of block containing the various aggregates were: shale 510 millionths, slag 422 millionths, and cinders 423 millionths. These block shrank an additional 100 to 250 millionths during the next two weeks at 50 per cent relative humidity. These later shrinkages were probably due to continued carbonation and water loss. During a 3-day exposure to CO_2 sand and gravel block shrank 220 millionths and pumice block shrank 650 millionths.

An attempt was made to carbonate several block at 11 per cent relative humidity. A lithium chloride solution was used to control the relative humidity within the drum. During a 24-hour exposure to CO_2 the relative humidity increased to about 17 per cent, each block expanded about 30 millionths and showed a very small increase in weight. This indicates that carbonation does not take place at this low humidity, or at least the reaction is very minor compared to that occurring at 50 per cent relative humidity.

Several references on carbonation are to be found in the literature, but few of them discuss shrinkage. A patent was issued to J. L. Rowland[5] in 1868 for "Improvement in the Manufacture of Artificial Stone" by curing with carbonic acid gas. One of the few references to shrinkage is in a Report of the Building Research Board[6] (1931) and the data are discussed further by F. M. Lea and C. H. Desch[7] (1935). They report that 1:3 mortar prisms, ¼ in. thick, exposed to a high concentration of CO_2 showed about 10 times as much shrinkage as companion prisms in air.

Yashichi Yoshida[8] (1937) showed that small neat cement specimens exhibited carbonation to the extent that the combined CO_2 equaled 25 per cent of the weight of the cement at the end of one year storage in air at 50 per cent relative humidity. At 95 per cent relative humidity the combined CO_2 equaled 8 per cent of the weight of cement, and in fog storage 3.5 per cent. He also observed weight gain and continued shrinkage during prolonged storage at 50 per cent relative humidity. He did not determine the effect of CO_2 on shrinkage other than the fact that . . . "the one paste in which carbonation was greatest exhibited by far the greatest shrinkage."

S. L. Meyers[9] (1949) carbonated 2-in. cubes under 150 psi pressure for 25 days and showed that the CO_2 reacted with the $Ca(OH)_2$ and that it also must have attacked one or more of the calcium compounds in the hydrated cement, and reacted with the calcium released. This process of carbonation increased the com-

pressive strength from 4500 psi for the control specimen to 8425 psi for the carbonated specimen, the tensile strength from 470 to 765 psi and the modulus of elasticity from 3.8×10^6 to 5.5×10^6 psi. Carbonated specimens showed only 30 to 40 per cent as much volume change under wetting and drying conditions as control specimens. Carbonation also increased the density of the cement paste. He suggests that, since carbonation appears to reduce volume change and improves hardness, strength, and impermeability, concrete products might be improved by carbonation after an initial curing period.

Weber and Mathei[10] (1941) reported poor results in CO_2 treatment of freshly molded products, but good results for treatment begun after one day or more of normal curing.

A curing process has been patented by A. L. Nugey[11] (1951) in which block are carbonated during a 2- or 8-hour curing and drying period. The principal claim is that hardening of the block is accelerated. Patents have been issued in England[12] in 1947 and Russia[13] in 1950 covering the use of CO_2 in curing of concrete and concrete products. Increased compressive strength is claimed.

Blakey and Leber[14] recently reported (1954) that mortar specimens stored in an atmosphere of CO_2 immediately after demolding showed less shrinkage than specimens stored in air at 65 per cent relative humidity. If the specimens were allowed to dry prior to exposure to CO_2 instead of a reduction in shrinkage, the shrinkage was greatly increased.

These tests and references to carbonation then suggest a reasonable explanation for the shape of the curves obtained in Figures 9a, b, c, and d. For curve 1, Figure 9a, the initial weight loss was due to a loss of water from the aggregate, capillaries, and cement gel.[15] The initial shrinkage was undoubtedly due to the loss of water by the cement gel, and for sand and gravel block this was the controlling factor at early ages. Carbonation, causing weight gain and shrinkage, was also occurring during this time but was obscured by the rapid drying. After losing weight for about three weeks at 80 per cent relative humidity, the sand and gravel block begun to slowly gain weight. The gain in weight indicates that carbonation was in progress and contributing to the shrinkage although the shrinkage due to drying and to carbonation cannot be separated. For very long exposures the shrinkage due to carbonation is a significant factor.

When the relative humidity was changed to 60 per cent, the rate of drying exceeded the rate of weight gain due to carbonation and the block lost weight. After several weeks the rate of carbonation became the greater and the block began to slowly gain weight.

Curve 4 of Figure 9a shows that the block dried to a moisture content of 17 per cent showed a continual gain in weight at 80 per cent relative humidity. The data in Figure 7 indicate that the block were drier than required for equilibrium at 80 per cent relative humidity and hence no shrinkage should be expected. The gain in weight is due to the combined effects of carbonation and moisture

absorbed by the drier portions of the block. The shrinkage caused by carbonation is greater than the expansion caused by the absorption of water, and the net length change is shrinkage. When the relative humidity of the atmosphere was decreased to 60 per cent, the aggregate and the cement gel of the block lost moisture to the atmosphere until the block were in equilibrium with the lower relative humidity. This moisture loss caused the block to lose weight and shrink, but after a few days the weight gain due to carbonation equaled and exceeded the water loss and the block again gained weight while continuing to shrink. This shrinkage is due both to carbonation and water loss, but the two effects could not be quantitatively separated. In the 30 and 10 per cent relative humidity atmosphere the block continued to lose weight and shrink due almost entirely to water loss from the cement gel. Carbonation appeared to be of little consequence at these low humidities.

In order to determine the extent of carbonation that had taken place during the long humidity cycle storage, some of the block. were broken and tested with phenolphthalein. This test showed that there was no $Ca(OH)_2$ present in the block, and thus indicated that it had been converted to $CaCO_3$.

The shapes of any of the curves in Figure 9a through 9d are thus determined by the rates at which the aggregate, capillaries and cement gel gain or lose water, by the rate of carbonation at a particular time and by the restraint imposed by the various aggregates.[16]

A set of block that had been carbonated by exposure to a high concentration of CO_2 and a set of companion block that were not carbonated were exposed to alternate cycles of wetting and drying at 50 per cent relative humidity. The carbonated block showed about half as much length change as the uncarbonated block as shown in Figure 11. Although the block were initially dried to equilibrium with 50 per cent relative humidity, the uncarbonated block showed a very marked shrinkage below this initial length during the subsequent drying cycles and a large portion of this shrinkage is attributed to continuing carbonation.

The data indicate that carbonation was active at 60 and 80 per cent relative humidity but not at 10 per cent. The rate of carbonation at various humidity levels needs further study. However, if block were carbonated prior to use this long-time shrinkage might be eliminated. Carbonation of the block should be accomplished after the block have been adequately cured, and before the block are dried to a moisture content so low that carbonation would not be effective. It would seem, then, that carbonation might most effectively be accomplished about midway in the drying cycle.

Such a procedure should be carefully investigated to determine whether carbonation would have a detrimental effect on strength, impermeability, or weathering resistance. The economic feasibility, methods, and proper time for carbonation also need study.
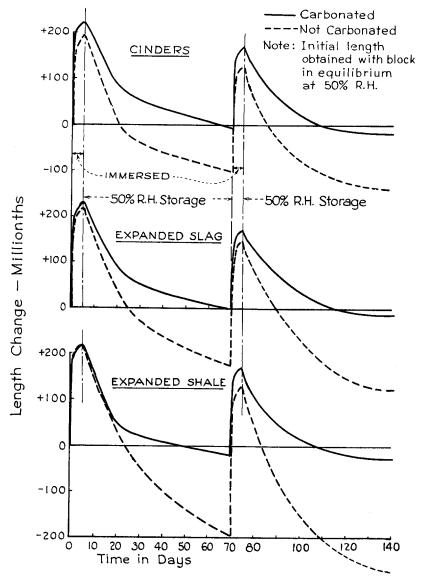
Fig. II - Effect of Carbonation on Length Change of Block Under Wetting and Drying Conditions

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Moisture-Humidity Indicator Tests

A principal thought behind this study of the moisture-volume stability of block was that block should be dried to a condition in equilibrium with the relative humidity of the service condition. C. A. Menzel has proposed a method for determining the relative humidity at which a block will be in equilibrium, but the Moisture-Humidity Indicator developed by Menzel was not available until the study was well under way. An additional series of tests is in progress in which block are kiln dried to 50 per cent relative humidity, as indicated by the Moisture-Humidity Indicator. and then stored at this humidity for several weeks. Additional block containing five different aggregates were made for this particular series of tests. A limited amount of data are now available and are shown in Figure 12. The block containing cinders and shale aggregates showed a small initial expansion and then a slight shrinkage accompanied by a small gain in weight. The particular block containing the slag aggregate were apparently not as dry as the companion block measured in the Moisture-Humidity Indicator, as indicated by the shrinkage occurring during the first few days of exposure at 50 per cent relative humidity. The slow gain in weight of all of the block indicates that carbonation is in progress and this accounts for the small but continuing shrinkage.

In order to determine the extent of carbonation a corner was broken from the block and tested with phenolphthalein. This test indicated that carbonation had progressed about one-half inch in from the surface of the blocks containing cinders and expanded shale, and about one-quarter inch into the block containing expanded slag. This test was made when the block were between 60 and 90 days old. The slag block contained more cement and appeared to be more dense thus retarding the entrance of CO_2.

Some block were also dried until they were judged to be in equilibrium with 10 per cent relative humidity and were given prolonged storage at this humidity. For some tests the indicated relative humidities departed considerably from the desired value. This was due primarily to a lack of knowledge of the drying characteristics of the block under this drying condition and to differences between companion block. The length and weight changes of these block have been minor, as shown in Figure 13. These block were also tested with phenolphthalein, and the total absence of carbonation was indicated.

The relationship between the moisture content of the block expressed as per cent of the 24-hour absorption and the equilibrium relative humidity as indicated by the Moisture-Humidity Indicator is shown in Figure 14. The curves occupy a relatively narrow band considering the wide range of physical properties of the aggregates and block. These curves indicate that in general block should be dried to a moisture content of about 15 per cent of the 24-hour absorption to be in equilibrium with 60 per cent relative humidity, and a moisture content of about 3 per cent of the 24-hour absorption to be in equilibrium with 10 per cent relative humidity. These values

SYMBOL	AGGREGATE	Dried to Indicated R.H.(%)*	Moisture Content %
• — —	Sand & Gravel	65	13.3
× ········	Expanded Slag	50	13.0
△ — — —	" Shale	40	11.0
□ —·—·—	Pumice	59	16.5
○ ——	Cinders	53	14.1

Additional block were made for these tests

*Relative humidity as indicated by "Moisture-Humidity Indicator"

Fig. 12 - Length Change and Weight Change of Block
Kiln Dried to Equilibrium With About 50% R.H.
and Stored at 50% R.H.

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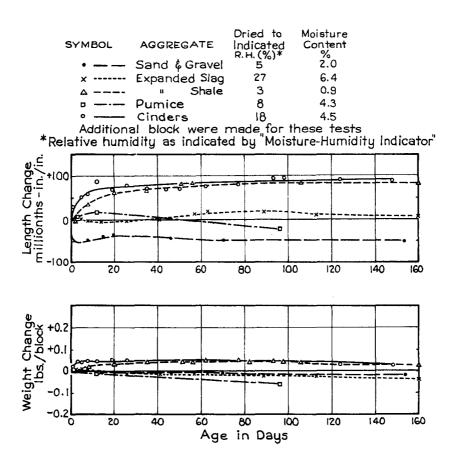
Fig. 13 – Length Change and Weight Change of Block Kiln Dried to Equilibrium With About 10% R.H. and Stored at 10% R.H.

of moisture content are slightly lower than those indicated in Figure 7.

About 85 per cent of the total absorption water is removed when block are dried to equilibrium with 60 per cent relative humidity. More than 70 per cent of the shrinkage occurring during drying from a saturated condition to equilibrium with 10 per cent relative humidity is obtained when the block are dried to equilibrium with 60 per cent relative humidity. These data then indicate that block dried to a moisture content in equilibrium with 60 per cent relative humidity (15 per cent of total absorption), and carbonated to prevent long time carbonation shrinkage, would be very satisfactory for either interior or exterior use.
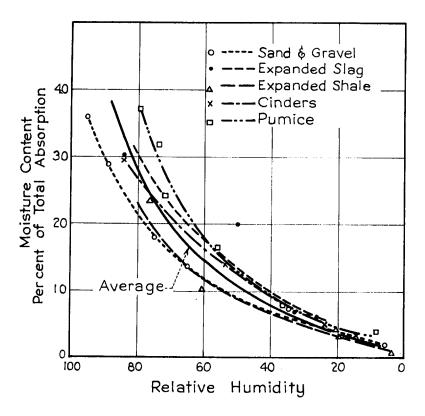
Fig. 14 — Relationship Between Moisture Content
of Block and the
Equilibrium Relative Humidity
Indicated by the Moisture-Humidity Indicator

The Moisture-Humidity Indicator is a very convenient instrument for determining whether block are dry enough for use at a particular relative humidity. If the block are not dry enough, this will be indicated in a few minutes, and satisfactory values for the equilibrium relative humidity can be obtained in about two hours. This method provided a realistic and direct measurement of the desired property of the block. The procedure outlined in ASTM Designation C140-52 requires about three days.
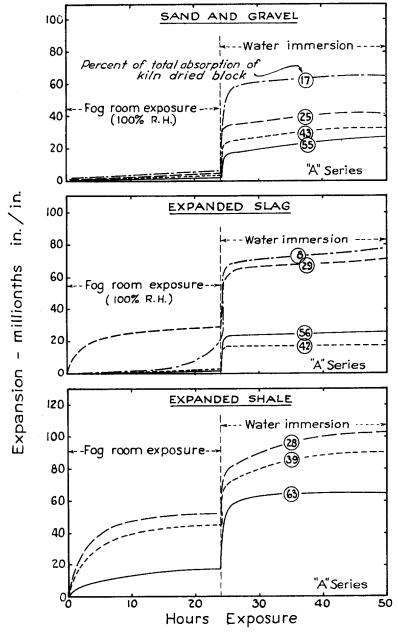
Rate of Length Change Under Various Humidity Exposures

The "A" series block were placed in the fog room and covered with a waterproof material. This cover protected them from precipitated moisture but was loose around the bottom and allowed the block to be exposed to nearly 100 per cent relative humidity. The length changes of the block during a 24-hour exposure are shown in Figures 15a and b. Sand and gravel block showed a negligible expansion, and expanded slag only a slight expansion. The shale block, kiln dried to 28 per cent of total absorption, showed an expansion of about 50 millionths, and shale block that were not dried expanded only 17 millionths. Most of this expansion took place in the first 5 hours of exposure. The pumice block showed several times as much expansion as the other block. Pumice block dried to 22 per cent of total absorption expanded 120 millionths, and block that were not kiln dried expanded only 26 millionths.
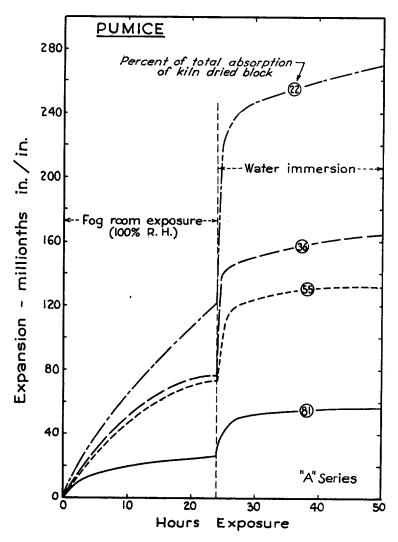
After the block had been in the fog room for 24 hours they were immersed in water. Within one hour the block had expanded between 50 and 90 per cent of the total expansion occurring during 4½ days immersion (Figures 15a and b). This rapid expansion is in contrast to the relatively slow expansion at nearly 100 per cent relative humidity. These data indicate that covering the block at the job site to protect them from rain is an effective method of reducing subsequent volume change in the block.

Figure 16 illustrates how rapidly the length change of block responded to a change in relative humidity during the humidity cycle. The curves show the length change of block during the first few days after a change in relative humidity, expressed as a percentage of the total length change at each humidity level. In general, the sand and gravel respond more slowly than the lightweight aggregate block, and there appears to be a considerable difference in rate of length change depending upon the particular humidity level. The curves that show the length change when the humidity was changed from 80 to 60 per cent indicate a very slow response to humidity change. This may be due to a difference in rate of air circulation, since a new air conditioning unit was installed after the 60 per cent relative humidity tests had been in progress for several weeks. The rate of air circulation was constant at all other humidity levels.
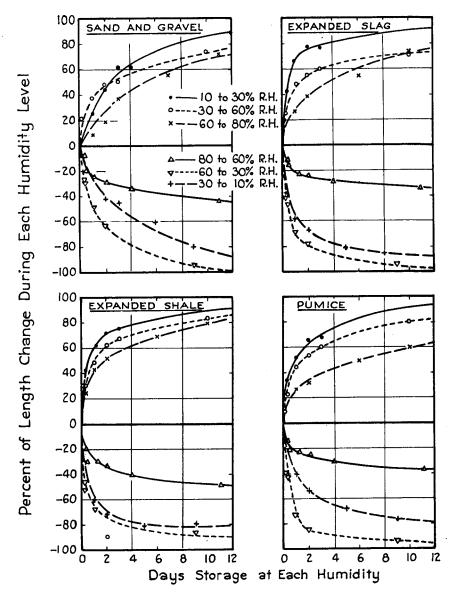
An average of the data indicates that about one-third of the total volume change due to a change in humidity occurs in 12 hours, and that nearly one-half occurs in 24 hours. The symmetry of the curves also indicates that block are approximately equally sensitive to either increasing or decreasing humidity changes. The curves in Figure 16 generally indicate a greater rate of length change than was obtained on the "A" series block given the fog room exposure (Figure 15a and b). This may be due to the fact that the covered block in the fog room were exposed to only slight air circulation, while the air in the controlled atmosphere room was completely circulated every two minutes.

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Fig. 15a – Expansion of Partially Dried Block
Under Fog Room Exposure and Water Immersion

Fig. 15b – Expansion of Partially Dried Block Under Fog Room Exposure and Water Immersion

Fig. 16 – Rate of Length Change
With Change in Relative Humidity

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C and D Series

The C and D series block (new block molded for each humidity level with no kiln drying) had very nearly the same shrinkage at 60, 30 and 10 per cent relative humidity, as shown by Figure 17. This is an anomaly, since the long-time tests showed about 30 per cent more shrinkage at 10 per cent than at 60 per cent relative humidity. The initial moisture content of the sand and gravel block for 60, 30 and 10 per cent relative humidity tests were 67, 55 and 60 per cent respectively. The initial moisture contents of the expanded slag block for these three humidity levels were 55, 47 and 61 per cent. The same mix proportions and procedures were used in making these block as were used for the long-time block, and the minor variations in weight and initial moisture contents do not explain the coincident drying shrinkage curves.

The block dried at 60 per cent relative humidity showed a small increase in weight after 22 days. This indicates that carbonation was in progress and was contributing to the shrinkage. Yoshida[8] showed that carbonation was much more active at 50 per cent relative humidity than at 95 and 100 per cent relative humidity. In the PCA laboratory carbonation was quickly accomplished at 50 per cent relative humidity but was not obtained at 10 per cent relative humidity. It may then be that the block with the least drying shrinkage (at 60 per cent relative humidity) had the greatest shrinkage due to carbonation. The block with the greatest drying shrinkage (at 10 per cent relative humidity) had the least shrinkage due to carbonation. The fact that the total shrinkage at the three humidity levels was almost identical may be a fortuitous combination of the two effects.

The shrinkage of 250 millionths for the "D" series sand and gravel block is less than the 317 millionths that was obtained on comparable block at 60 per cent relative humidity in the long-time tests. In every instance the block in the C and D series showed less shrinkage than was obtained at 60 per cent in the A and B series. This is attributed to the fact that during the very long storage at 80 per cent and 60 per cent relative humidity the shrinkage of the A and B series block was increased considerably by carbonation.

For both aggregates the weight loss to equilibrium was about twice as great for the C and D series as for the A and B series. A considerable portion, if not all, of this difference in weight loss is due to the weight gained through carbonation during the long storage of the A and B series block at high humidities. The relationship of weight change to length change for the D series block is shown in Figure 18.
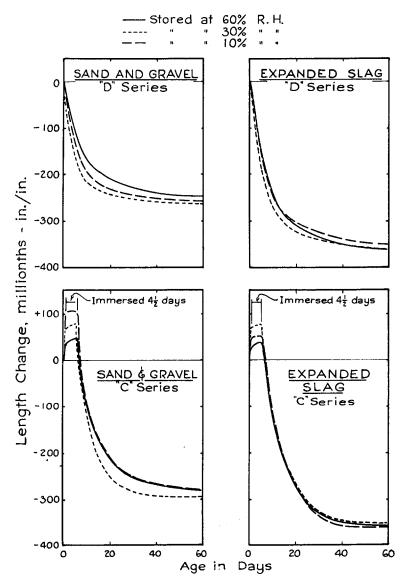
Fig. 17 – Length Change of "C" and "D" Series Block
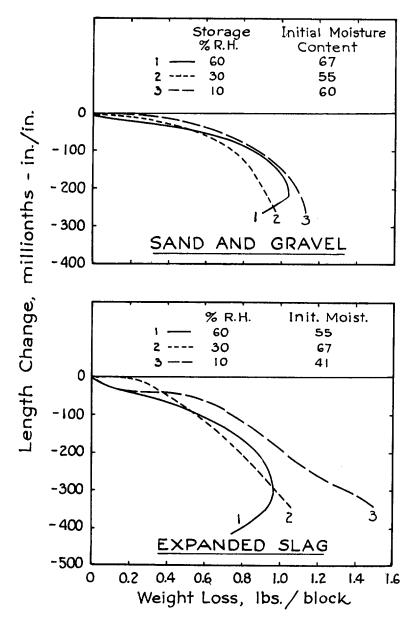
Fig. 18 – Relationship of Weight Change to Length Change of "D" Series Block

CONCLUSIONS

Shrinkage values in millionths in. per in. of "B" series block dried in the humidity cycle to equilibrium with 10 per cent relative humidity were:

	No Kiln Drying	Kiln Dried to 25% of Total Abs.
Sand and gravel	440	400
Expanded slag	510	385
Expanded shale	642	510
Pumice	1065	663

The reductions in shrinkage at 10 per cent relative humidity due to kiln drying as compared to no kiln drying were:

	Kiln Dried to 40% of Total Abs.	Kiln Dried to 25% of Total Abs.
Sand and gravel	7%	9%
Expanded slag	3%	25%
Expanded shale	13%	21%
Pumice	31%	38%

The data indicate that drying the block does not produce a volume-stable unit, and kiln drying and even oven drying the block had no significant effect in reducing drying shrinkage if the block were allowed to get wet prior to use.

Block brought to equilibrium with 60 per cent relative humidity by a long storage period at this humidity had a moisture content between 12 and 21 per cent of total absorption, depending on the aggregate. At 10 per cent relative humidity the moisture content was between 5 and 8 per cent of total absorption. However, expanded slag block kiln dried to 8 per cent of total absorption and subjected to the humidity cycle shrank 360 millionths before they were in volume equilibrium with 10 per cent relative humidity.

A very large part of the shrinkage of block dried to a moisture content lower than 20 per cent of total absorption and then subjected to the higher humidities employed in the humidity cycle was due to carbonation. The shrinkage of block that were not adequately dried was due to loss of water, primarily from the cement gel, and to carbonation.

All lightweight aggregate block brought to equilibrium with 50 per cent relative humidity shrank at least 300 millionths and gained almost a pound per block during a 24-hour exposure to a high concentration of carbon dioxide. No significant evidence of carbonation was obtained in tests made on block in equilibrium with 10 per cent relative humidity. The data obtained in the humidity cycle tests indicate that carbonation occurred and produced a relatively large shrinkage, but do not provide a direct quantitative evaluation of the shrinkage produced by carbonation under the various conditions. The gain in weight of block while they continued to shrink after several weeks storage at 80 and 60 per cent relative humidity was due mainly to carbonation.

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As carbonation causes considerable shrinkage in block, a process of carbonating the block after a period of hydration may be beneficial. Preliminary tests indicate that such a process may be used to preshrink the block prior to use and thus eliminate the prolonged shrinkage due to carbonation. The literature indicates that carbonation produces a more volume-stable unit, and improves the hardness, strength, and impermeability of · concrete. The process and effects of carbonation need much further study to determine the long-time effect on strength, weathering resistance, and volume change.

Block are volume-sensitive to changes in relative humidity. About one-third of the total volume change due to changes in humidity occurred in 12 hours and nearly one-half in 24 hours. Block are equally sensitive to an increase or decrease in humidity. However, tests indicated that covering block at the job site to protect them from rain and from rapid circulation of high humidity air was effective in reducing the volume changes of the block. All -block that were immersed in water attained within one hour as much as 50 to 90 per cent of the total expansion occurring during 4½ days of immersion.

The relationship between the moisture content of block expressed as per cent of total absorption and the equilibrium relative humidity as indicated by the Moisture-Humidity Indicator was established. This relationship shows that block kiln-dried to equilibrium with 60 per cent relative humidity would have a moisture content between 12 and 18 per cent of total absorption depending on the aggregate. Block kiln dried to a moisture content in equilibrium with 50 per cent relative humidity as indicated by the Moisture-Humidity Indicator showed a continuous length change during several months storage at this humidity which was due to carbonation. Block kiln dried to an indicated 10 per cent relative humidity showed no significant length change in storage at 10 per cent relative humidity.

These data indicate a method of reducing the cracking in concrete masonry — first adequately cure the block, then condition the block by a process of carbonation and drying so that they are approximately in volume equilibrium with the average relative humidity of the service condition. Keep the block dry until they are laid. Higher and lower humidities may then produce some volume change and stress in the block, but these will be alleviated when the relative humidity returns to normal.

Acknowledgment

Table I — Concrete Mix Data

| | Aggregate | | Concrete | |
Aggregate	Max. Size In.	Unit Wt. Dry Rodded p.c.f.	Mix Parts By Vol. Cement To Dry Rodded Aggregate	Yield Block/sk. of Cement
Sand & gravel	⅜	126.9	1:7.6	25.8
Expanded slag	½	71.4	1:7.6	22.5
Expanded shale	⅜	62.1	1:8.9	25.9
Pumice	⅜	52.1	1:5.4	19.5

Sieve Analyses of Combined Aggregate

| | Per Cent Coarser Than Sieve Indicated | | | | | | | |
Aggregate	⅜-in.	No. 4	8	16	30	50	100	F.M.
Sand & gravel	—	32	49	63	74	88	99	4.05
Expanded slag	—	7	23	40	61	79	89	3.93
Expanded shale	—	14	45	66	78	85	90	3.78
Pumice	—	20	49	66	82	90	94	4.00

Table 2

Details Relating to The Testing Plan
for Various Series and Groups of Block

Aggregate	Group No.	Moist. Cont. % of Total Abs. Planned	Moist. Cont. % of Total Abs. Actual	Drying Time Hrs.	Treatment After Removal From Kiln
SERIES A & B					
Sand and	1	No Drying	55	0	**SERIES A**
Gravel	2	40	43	3	24 hours in moist room fol-
	3	25	25	5	lowed by 4½ days water
	4	10	17	5	immersion, then stored at
Expanded	1	No Drying	56	0	80% R.H. and continued
Slag	2	40	42	2	through relative humidity
	3	25	29	7	cycle.
	4	10	8	8	
Expanded	1	No Drying	63	0	
Shale	2	40	39	4	**SERIES B**
	3	25	28	7	Stored at 80% R.H. and
Pumice	1	No Drying	81	0	continued through relative
	2	40	55	10	humidity cycle.
	3	25	36	26	
	4	10	22	33	
SERIES C					
Sand and Gravel	"60"	No Drying	67		24 hours in moist room
Expanded Slag	"60"	No Drying	55		followed by 4½ days water immersion, then stored at 60% R.H.
Sand and Gravel	"30"	No Drying	55		24 hours in moist room
Expanded Slag	"30"	No Drying	47		followed by 4½ days water immersion, then stored at 30% R.H.
Sand and Gravel	"10"	No Drying	60		24 hours in moist room
Expanded Slag	"10"	No Drying	61		followed by 4½ days water immersion, then stored at 10% R. H.
SERIES D					
Sand and Gravel	"60"	No Drying	67		Stored continuously at
Expanded Slag	"60"	No Drying	55		60% R.H.
Sand and Gravel	"30"	No Drying	55		Stored continuously at
Expanded Slag	"30"	No Drying	47		30% R.H.
Sand and Gravel	"10"	No Drying	60		Stored continuously at
Expanded Slag	"10"	No Drying	61		10% R.H.

Table 3 — Compressive Strength of Concrete Block Subjected to Varied Relative Humidities
(psi gross area)

Age Days	R.H. Group	Storage No.‡	Sand and Gravel A	B	A+B/2	Lab.*	Expanded Slag A	B	A+B/2	Lab.*	Expanded Shale A	B	A+B/2	Lab.*	Pumice A	B	A+B/2	Lab.*
3		1	—	—	1290	—	—	—	750	—	—	—	1060	—	—	—	770	—
		2	—	—	1340	—	—	—	760	—	—	—	1060	—	—	—	780	—
		3	—	—	1350	—	—	—	760	—	—	—	1030	—	—	—	750	—
		4	—	—	1310	—	—	—	750	—	—	—	—	—	—	—	780	—
		Av.	—	—	1320	—	—	—	760	—	—	—	1050	—	—	—	770	—
28	80%	1	1850	1710	1780	2490	1350	1320	1340	1320	1540	1730	1640	1370	1010	970	990	980
		2	1880	1510	1700	2650	1370	1370	1370	1300	1430	1490	1460	1210	890	880	890	820
		3	1900	1590	1750	2590	1200	1140	1170	1090	1480	1460	1470	1320	920	970	940	830
		4	1590	1400	1490	2200	1200	1060	1130	1070	—	—	1520	—	870	840	860	780
		Av.	1800	1550	1680	2480	1280	1220	1250	1200	1480	1560	1520	1300	920	920	920	850
410 to 545	30%	1	2080	2050	2060	—	—	1400	1400	—	1580	—	1580	—	960	—	960	—
		2	—	—	—	—	1340	1450	1400	—	—	1600	1600	—	—	850	850	—
		3	1930	—	1930	—	1220	—	1220	—	—	1650	1650	—	850	700	700	—
		4	—	1640	—	—	—	—	—	—	—	—	—	—	—	—	—	—
		Av.	2000	1840	1920	—	1280	1420	1350	—	1580	1630	1600	—	900	770	840	—
491 to 628	10%	1	2130	2220	2180	—	1210	1390	1300	—	1620	1730	1670	—	800	860	830	—
		2	2310	2240	2280	—	1560	1500	1530	—	1410	1660	1540	—	850	780	820	—
		3	2180	2140	2160	—	1470	1320	1400	—	1340	1420	1380	—	840	810	820	—
		4	2110	1920	2020	—	1250	1290	1270	—	—	—	—	—	770	830	800	—
		Av.	2180	2130	2160	—	1370	1370	1370	—	1460	1600	1530	—	820	820	820	—
547 to 684	30% Up	1	1980	2170	2080	—	1300	1390	1340	—	1570	1810	1690	—	1020	900	960	—
		2	2200	2180	2190	—	1530	1570	1550	—	1480	1610	1550	—	870	900	880	—
		3	2360	2060	2210	—	1310	1300	1300	—	1450	1430	1440	—	900	910	900	—
		4	1950	1770	1860	—	1320	1360	1340	—	—	—	—	—	1010	950	980	—
		Av.	2120	2040	2080	—	1360	1400	1380	—	1500	1620	1560	—	950	910	930	—
617 to 754	60% Up	1	2090	2310	2200	—	1370	1470	1420	—	1480	1750	1620	—	990	910	950	—
		2	2300	2350	2330	—	1560	1720	1640	—	1520	1580	1550	—	850	880	860	—
		3	2410	2200	2300	—	1370	1400	1380	—	1700	1420	1560	—	930	860	900	—
		4	2050	1800	1920	—	1480	1400	1440	—	—	—	—	—	1020	1000	1010	—
		Av.	2210	2160	2190	—	1450	1500	1470	—	1570	1580	1580	—	950	910	930	—

‡ Refers to initial kiln curing and drying treatment. See page 4 for discussion of curing and Table 2 for drying treatment.
* 14 days fog curing at 73° F followed by 14 day air drying at 73° F and 50 per cent relative humidity.

Table 4

Length Change of Block from Various Initial Moisture Contents to Equilibrium with Various Ambient Relative Humidities
(Millionths in./in.)

Aggregate	Series & Group No.	Initial Moisture % of Total Abs.	Satu-rated	Relative Humidity % 80	60	30	10	30	60	80	Satu-rated	Oven dry
Sand & Gravel	A-1	55	+22	202	325	390	460	405	360	320	250	555
	2	43	+40	180	298	367	435	378	340	295	227	487
	3	25	+55	137	255	325	392	337	295	260	203	495
	4	17	+70	125	247	315	384	323	285	248	195	496
	B-1	55		190	317	377	440	380	337	300	230	535
	2	43		162	277	345	410	355	315	275	215	493
	3	25		145	265	335	400	345	306	270	205	499
	4	17		110	234	290	357	300	265	232	180	474
Expanded Slag	A-1	56	+20	250	410	500	565	488	435	390	315	681
	2	42	+10	235	383	460	518	445	400	355	280	619
	3	29	+80	150	325	410	470	395	348	305	260	592
	4	8	+98	125	300	382	440	365	322	280	230	560
	B-1	56		205	358	437	510	430	387	345	290	640
	2	42		215	358	437	497	425	380	342	285	598
	3	29		83	245	320	385	309	267	232	195	493
	4	8		70	232	305	365	300	260	223	183	494
Expanded Shale	A-1	63	+70	290	500	595	695	578	512	455	380	1006
	2	39	+105	233	420	510	605	500	430	373	300	903
	3	28	+122	213	385	475	575	458	395	335	255	867
	B-1	63		282	450	545	642	532	465	405	335	886
	2	39		220	383	465	560	453	390	328	250	813
	3	28		188	328	410	510	403	340	288	210	833
Pumice	A-1	81	+65	460	830	1008	1105	960	870	753	612	1803
	2	55	+153	327	625	790	908	758	673	570	450	1629
	3	36	+235	258	560	718	835	685	594	485	360	1567
	4	22	+312	185	494	648	757	600	513	410	275	1453
	B-1	81		505	810	950	1065	915	825	715	585	1693
	2	55		335	615	760	872	733	650	550	433	1600
	3	36		190	480	610	740	595	505	417	308	1513
	4	22		110	390	535	663	515	430	333	243	1397

+ indicates expansion, all other values are shrinkage

Table 5

Shrinkage of Block Stored Under Various Conditions
Compared to Block Given No Kiln Drying and Then Saturated

Shrinkage of Block Stored at R.H. Indicated

Treatment of Block	Sand and Gravel				Expanded Slag				Expanded Shale				Pumice			
	60% *	R.H. %	10% *	R.H. %	60% *	R.H. %	10% *	R.H. %	60% *	R.H. %	10% *	R.H. %	60% *	R.H. %	10% *	R.H. %
No kiln drying and saturated (A-1)	347	100	482	100	430	100	585	100	570	100	765	100	895	100	1170	100
Kiln dried to 25% of total abs. and then saturated	310	89	447	93	405	94	550	94	507	89	697	91	806	90	1069	91
No kiln drying and not saturated (B-1)	317	91	440	91	358	83	510	87	450	79	642	84	810	90	1065	91
Kiln dried to 40% of total abs. (B-series)	277	80	410	85	358	83	497	85	383	67	560	73	480	54	740	63
Kiln dried to 25% of total abs. (B-series)	265	76	400	83	245	57	385	66	328	58	510	67	390	44	663	57
SHRINKAGE OF BLOCK DRIED TO 40 AND 25% OF TOTAL ABSORPTION COMPARED TO BLOCK GIVEN NO KILN DRYING. (B-SERIES)																
No kiln drying (B-1)	317	100	440	100	358	100	510	100	450	100	642	100	810	100	1065	100
Kiln dried to 40% of total absorption	277	87	410	93	358	100	497	97	383	85	560	87	480	59	740	69
Kiln dried to 25% of total absorption	265	84	400	91	245	69	385	75	328	73	510	79	390	48	663	62

* Drying shrinkage — millionths in./in.

Table 6

Length Change of Block Between Relative Humidity Levels During Humidity Cycle
(Millionths in./in.)

Aggregate	Series & Group No.	Initial Moisture % of Total Abs.	Sat.* to 80	80 to 60	60 to 30	30 to 10	10 to 30	30 to 60	60 to 80	80 to Sat.	Sat. to Dry
	A-1	55	−224	−123	−70	−70	+55	+45	+40	+70	−305
	2	43	−220	−118	−69	−68	+57	+38	+45	+68	−260
	3	25	−192	−118	−70	−67	+55	+43	+35	+57	−292
	4	17	−195	−123	−68	−69	+61	+38	+37	+53	−301
Sand &	Av.			−120	−69	−68	+57	+41	+39	+62	−290
Gravel	B-1	55	−190	−127	−60	−63	+60	+43	+37	+70	−305
	2	43	−162	−115	−68	−65	+55	+40	+40	+60	−278
	3	25	−145	−120	−70	−65	+55	+39	+36	+65	−294
	4	17	−110	−124	−56	−67	+57	+35	+33	+52	−294
	Av.			−122	−64	−65	+57	+39	+36	+62	−293
	A-1	56	−270	−160	−90	−65	+77	+43	+45	+75	−366
	2	42	−245	−148	−77	−58	+63	+45	+45	+75	−339
	3	29	−230	−175	−85	−60	+75	+47	+43	+45	−332
Ex-	4	8	−223	−175	−82	−58	+75	+43	+42	+50	−330
panded	Av.			−164	−84	−60	+72	+45	+44	+61	−342
Slag	B-1	56	−205	−153	−79	−73	+80	+43	+42	+55	−350
	2	42	−215	−143	−79	−60	+72	+45	+38	+57	−313
	3	29	− 83	−162	−75	−65	+76	+42	+35	+37	−298
	4	8	− 70	−162	−73	−60	+65	+40	+37	+40	−311
	Av.			−155	−77	−64	+73	+42	+38	+47	−318
	A-1	63	−360	−210	−95	−100	+117	+66	+57	+75	−626
	2	39	−338	−187	−90	− 95	+105	+70	+57	+73	−603
Ex-	3	28	−335	−172	−90	−100	+117	+63	+60	+80	−612
panded	Av.			−190	−92	− 97	+113	+66	+58	+76	−614
Shale	B-1	63	−282	−168	−95	− 97	+110	+67	+60	+70	−551
	2	39	−220	−163	−82	− 95	+108	+63	+62	+78	−563
	3	28	−188	−140	−82	−100	+107	+63	+52	+78	−623
	Av.			−157	−88	− 97	+108	+64	+58	+75	−579
	A-1	81	−525	−370	−178	− 97	+145	+90	+117	+141	−1181
	2	55	−480	−298	−165	−118	+150	+85	+103	+130	−1179
	3	36	−493	−302	−158	−117	+150	+91	+109	+125	−1207
	4	22	−497	−309	−154	−109	+157	+87	+103	+135	−1178
Pumice	Av.			−320	−164	−110	+150	+88	+108	+133	−1186
	B-1	81	−505	−305	−140	−115	+150	+90	+110	+130	−1108
	2	55	−335	−280	−145	−112	+139	+83	+100	+117	−1167
	3	36	−190	−290	−130	−130	+145	+90	+ 88	+109	−1205
	4	22	−110	−280	−145	−128	+148	+85	+ 97	+ 90	−1154
	Av.			−289	−290	−140	−121	+146	+87	+ 99	+112	−1158

* Saturation to 80% relative humidity for A series
 Kiln condition to 80% relative humidity for B series

Table 7
Moisture Content of Block in Equilibrium with Various Relative Humidities
(Computed from Absorption Block)
Per Cent of Total Absorption

Aggregate	Series & Group No.	Initial Moisture Content	Relative Humidity (%)					
			60	30	10	30	60	80
	A-1	55	19.7	13.5	8.2	10.4	12.0	16.6
	2	43	18.8	14.0	8.6	11.4	14.0	18.4
	3	25	18.9	13.7	8.5	11.2	13.8	17.9
Sand &	4	17	15.4	9.2	7.9	9.6	11.8	15.7
Gravel	Av.		18.2	12.6	8.3	10.6	12.9	17.1
	B-1	55	16.3	10.4	7.6	9.7	12.2	15.7
	2	43	16.4	11.1	8.1	10.4	13.0	16.1
	3	25	15.9	10.1	8.0	9.0	11.8	15.5
	4	17	13.4	8.5	7.0	7.6	9.3	13.0
	Av.		15.1	10.0	7.7	9.2	11.6	15.1
Average A & B			16.6	11.3	8.0	9.9	12.2	16.1
	A-1	56	21.1	14.0	8.4	10.2	12.9	19.5
	2	42	24.3	20.2	9.4	11.2	14.6	21.2
	3	29	15.6	11.2	7.7	9.1	11.9	16.2
Expanded	4	8	16.5	11.8	7.7	9.6	12.2	13.0
Slag	Av.		19.4	14.3	8.3	10.0	12.9	17.5
	B-1	56	18.7	12.5	8.0	10.7	13.6	15.1
	2	42	21.2	14.5	8.8	11.0	14.0	19.1
	3	29	13.4	9.8	6.6	8.4	10.6	13.6
	4	8	12.0	9.6	6.2	8.0	10.3	13.6
	Av.		16.3	11.6	7.4	9.5	12.1	15.4
Average A & B			17.8	13.0	7.8	9.8	12.5	16.4
	A-1	63	13.5	8.4	5.8	6.6	9.0	12.2
	2	39	12.3	7.4	5.1	6.4	8.7	10.8
Expanded	3	28	12.2	7.4	5.2	6.6	8.8	10.4
Shale	Av.		12.6	7.7	5.3	6.5	8.8	11.1
	B-1	63	12.1	7.8	5.5	6.8	9.0	11.7
	2	39	11.4	7.2	5.0	6.4	8.5	10.8
	3	28	12.4	7.7	4.9	6.3	8.6	10.0
	Av.		11.6	7.6	5.1	6.5	8.7	10.8
Average A & B			12.1	7.6	5.2	6.4	8.8	11.0
	A-1	81	22.3	14.8	7.8	10.0	13.9	18.1
	2	55	20.8	12.0	7.2	9.0	12.3	16.2
	3	36	22.3	11.9	7.4	9.4	12.8	16.6
	4	22	20.6	11.7	7.1	9.2	12.8	16.3
Pumice	Av.		21.5	12.6	7.4	9.4	13.0	16.8
	B-1	81	24.9	10.9	7.9	9.4	12.6	16.9
	2	55	22.3	9.8	6.9	8.8	12.1	15.8
	3	36	17.3	10.4	6.6	8.4	11.5	14.8
	4	22	17.0	9.4	6.4	8.2	11.8	15.1
	Av.		20.4	10.1	7.0	8.7	12.0	15.6
Average A & B			21.0	11.3	7.2	9.0	12.5	16.2

Table 8

Moisture Content of Block in Equilibrium with Various Relative Humidities (Computed from Volume Stability Block) Per Cent of Total Absorption

Aggregate	Series & Group No.	Initial Moisture Content	Relative Humidity (%)						
			80	60	30	10	30	60	80
	A-1	55	15.4	13.0	8.6	5.4	7.9	12.0	17.6
	2	43	17.1	13.2	8.7	5.5	8.2	12.4	18.4
	3	25	15.6	13.0	8.5	5.2	8.0	12.0	17.8
	4	17	12.2	11.1	5.2	4.6	6.8	10.4	15.7
Sand &	Av.		15.1	12.6	7.8	5.2	7.7	11.7	17.4
Gravel	B-1	55	11.9	11.4	7.9	4.6	6.9	10.5	15.7
	2	43	12.0	11.0	7.1	4.1	6.5	10.4	16.0
	3	25	11.5	11.0	7.0	4.2	6.5	10.2	15.5
	4	17	8.3	9.4	6.1	4.0	5.6	8.6	13.0
	Av.		10.9	10.7	7.0	4.2	6.4	9.9	15.0
	Average A & B		12.5	11.6	7.4	4.7	7.0	10.8	17.2
	A-1	56	23.7	16.3	10.6	6.9	9.7	14.0	19.5
	2	42	26.1	18.5	12.2	7.2	10.7	15.3	21.2
	3	29	15.3	12.6	8.3	5.7	7.7	11.5	16.1
	4	8	10.8	9.0	5.0	2.5	4.5	8.2	13.0
Expanded	Av.		19.0	14.1	9.0	5.6	8.2	12.2	17.4
Slag	B-1	56	13.9	11.2	6.5	3.8	6.1	10.0	15.1
	2	42	18.2	15.7	10.2	6.6	9.3	13.5	15.6
	3	29	7.7	10.1	6.8	4.9	6.5	9.6	13.6
	4	8	5.4	9.3	6.4	4.4	6.1	9.2	13.6
	Av.		11.3	11.5	7.4	4.9	7.0	10.6	14.5
	Average A & B		15.1	12.8	8.2	5.2	7.6	11.3	15.9
	A-1	63	15.4	9.5	5.6	3.7	5.1	8.0	12.2
	2	39	13.5	8.5	5.1	3.7	4.9	7.3	10.8
	3	28	13.2	8.4	4.8	3.4	4.5	7.0	10.6
Expanded	Av.		14.0	8.8	5.1	3.6	4.9	7.4	11.2
Shale	B-1	63	13.9	8.8	5.1	3.5	4.6	7.5	11.7
	2	39	12.6	8.4	5.1	3.6	4.7	7.2	10.7
	3	28	11.8	8.0	4.6	3.2	4.3	6.8	10.1
	Av.		12.8	8.4	4.9	3.4	4.5	7.2	10.8
	Average A & B		13.4	8.6	5.0	3.5	4.7	7.3	11.0
	A-1	81	29.6	16.3	9.5	4.6	6.8	11.3	18.1
	2	55	22.0	12.5	6.6	2.8	5.3	9.7	16.2
	3	36	24.7	14.1	7.8	4.2	6.2	10.4	16.6
	4	22	24.0	13.5	7.5	4.1	6.1	10.1	16.3
Pumice	Av.		25.1	14.1	7.8	3.9	6.1	10.4	16.8
	B-1	81	24.8	14.1	7.9	4.0	6.0	10.3	16.9
	2	55	21.0	12.7	7.7	4.5	6.4	11.3	15.8
	3	36	15.8	11.6	7.1	4.6	6.3	9.7	14.8
	4	22	17.1	12.3	7.6	4.6	6.4	9.9	15.1
	Av.		19.7	12.7	7.6	4.4	6.3	10.3	15.6
	Average A & B		22.4	13.4	7.7	4.2	6.2	10.4	16.2

Table 9

Absorption and Weight of Oven Dry Concrete
Before and After Humidity Cycle Storage

Aggregate	Group No.	Absorption						Weight of oven-dry concrete					
		lb./c.f.*			% of oven dry weight*			per block			lb./c.f.*		
		3 day	28 day	Final	3 day	28 day	Final	3 day	28 day	Final	3 day	28 day	Final
Sand and Gravel A & B	1	8.45	7.57	7.67	6.22	5.57	5.54	42.11	42.82	42.68	135.6	137.8	138.6
	2	7.72	7.42	7.39	5.65	5.37	5.28	42.78	42.80	43.38	137.3	138.0	140.2
	3	8.04	7.35	7.40	5.72	5.28	5.29	42.61	43.26	43.17	140.5	139.2	139.7
	4	8.52	8.18	8.17	6.34	6.00	5.94	41.75	41.96	42.31	134.9	136.5	137.4
	Av.	8.18	7.63	7.66	5.98	5.56	5.51	42.31	42.71	42.88	137.1	137.9	139.0
Expanded Slag A & B	1	12.13	10.34	10.10	12.47	10.61	10.05	28.59	28.82	29.83	97.2	97.6	100.6
	2	10.00	8.80	8.95	10.15	8.82	8.83	29.23	29.62	30.16	98.3	99.8	101.4
	3	11.75	10.37	10.53	11.89	10.42	10.33	29.04	29.83	30.19	98.7	99.5	102.0
	4	11.07	10.86	10.14	11.48	11.03	9.94	28.73	28.98	29.99	96.7	98.7	101.7
	Av.	11.24	10.09	9.95	11.49	10.22	9.79	28.90	29.31	30.04	97.7	98.9	101.4
Expanded Shale A & B	1	18.02	14.66	15.69	19.87	16.30	17.17	25.67	26.26	26.66	90.7	89.8	91.3
	2	17.90	15.30	16.53	20.90	17.20	18.22	25.36	25.97	26.41	88.9	88.9	90.7
	3	18.20	15.25	16.42	21.10	17.10	18.32	25.03	25.97	26.00	86.4	89.1	89.6
	Av.	18.04	15.07	16.21	20.62	16.87	17.90	25.35	26.07	26.36	88.7	89.3	90.5
Pumice A & B	1	25.10	14.30	15.14	36.60	20.39	21.05	19.78	20.52	20.89	68.6	70.3	72.0
	2	19.72	14.57	15.26	28.90	20.80	21.46	19.52	20.19	20.63	68.3	70.0	71.2
	3	17.30	14.11	15.18	25.70	20.18	21.18	19.58	20.46	20.76	67.3	69.9	71.6
	4	16.80	14.53	15.15	25.00	20.90	21.08	19.60	20.19	20.75	67.1	69.3	71.9
	Av.	19.73	14.38	15.18	29.05	20.59	21.19	19.62	20.34	20.76	67.8	70.0	71.7

* ASTM Designation C140-52

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