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REVIEW OF DATA ON THE

SHRINKAGE OF CONCRETE MASONRY

By

C. C. Fishburn

At the request of
Office of the Chief of Engineers
Department of the Army

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

June 25, 1953 10.1

Department of the Army
Office of the Chief of Engineers
(Attn: Mr. H. B. Zackrison, Chief
Engineering Division,
Military Construction)
Washington 25, D. C.

Subject: Shrinkage of Concrete Masonry
your file ENGES

Gentlemen:

This refers to your letter of July 30, 1952, regarding a review of reports covering the concrete masonry investigations made by the Research Foundation, University of Toledo. Six copies of this review are enclosed.

Very truly yours,

C. C. F.
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Materials Engineer
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Encl. (6)

CCFishburn:ew

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Review of Data on the Shrinkage of Concrete Masonry

1. INTRODUCTION

This report reviews data on the drying shrinkage and the effects of temperature changes on the shrinkage of concrete masonry walls and units, and on the shrinkage cracking of restrained concrete masonry walls. Particular attention was given to the reports, listed below, which were prepared by the Research Foundation of the University of Toledo, Ohio.

"Volume Changes of Blocks and Wallettes," by J. K. Selden, et al [1] 1/.
"Relation of Shrinkage to Moisture Content in Concrete Blocks," by G. L. Kalousek, et al [2] .
"Welded Wire Mesh for Horizontal Mortar Joint Reinforcing," by J. K. Selden and W. G. Rohr [3] .

Pertinent data from other sources also were reviewed.

It may be noted that the restrained walls tested at the Research Foundation were restrained at the ends only, and those tests did not represent the more common conditions of restraint, along the base of the concrete masonry wall.

2. VOLUME CHANGES IN CONCRETE MASONRY UNITS

2.1 Coefficient of Thermal Expansion

Values of the coefficients of thermal expansion for concrete masonry units and for two lightweight aggregate concretes were obtained from three sources, [1] , Wendt and Woodworth [4] and Petersen [5] and are listed in Table 1.

The data, Table 1, indicate that the coefficient of thermal expansion was dependent upon the kind of aggregate and the amount of cement used in the concrete. A study of data obtained from the Research Foundation [1] indicated that the kind of curing given the concrete masonry units did not have an important effect on the coefficient of thermal expansion. Concrete masonry units made of cinder aggregate concrete had the least thermal expansion; sand and gravel aggregate units had the greatest. The thermal expansion of the sand and gravel aggregate units was about double that of the cinder units.

1/ The numbers refer to the references listed at the end of this report.

Data on the bars of shale and slag aggregate concretes [5] are included to indicate the effects of the cement factor on the coefficient of thermal expansion. It is unlikely that the use of an air-entraining agent had an important effect on the value of the thermal coefficient.

In general, the coefficients of thermal expansion were approximately as listed in the following table:

Kind of aggregate	Coefficient of thermal expansion 10^{-6} /F°
Sand and gravel	5.2
Crushed limestone	5.0
Expanded slag	4.8
Pumice	4.1
Expanded shale	4.0
Cinders	2.6

2.2 Drying Shrinkage of Concrete Masonry Units

Values of the drying shrinkage, from a saturated condition, of concrete masonry units was obtained from four different sources, and are listed in Table 2. Although not complete, the data include values of the cement factor, compressive strength, method of curing, method of drying, and the moisture content of the unit. The moisture contents are the moisture retained in the units, in terms of the total moisture loss on drying from a saturated condition at 73°F to a dry condition in a ventilated oven at 220°F. Data on the shrinkage observed from a second wetting and drying are included in the Table, for some units.

The two most important factors affecting the drying shrinkage of concrete masonry units were the kind of curing of the units and the kind of aggregates used in them. As may be noted, Table 2, units cured in high-pressure steam at a pressure of 125 to 140 lb/in.^{2} shrank about one-half as much on drying from a saturated condition as did units cured at atmospheric pressure, with or without steam. For like methods of curing and drying, the units containing heavy aggregates such as sand and gravel shrank less than did units containing lighter aggregates.

In general, there was no great difference between the shrinkages of similar units cured at atmospheric pressure, with high-temperature steam, low-temperature steam or in moist air.

As indicated in Table 2, reference 2, there was a progressive shortening of concrete masonry units with wetting and drying. The shortening was not as great for high-pressure steam-cured units as for units cured by other methods.

The data obtained from the Progress Report of ACI Committee 716, [6] , give the effects on shrinkage of three methods of drying saturated high-pressure steam-cured units. For the Rapid Method, the units were dried in a ventilated oven at 220°F. In the British Method (similar to British Standards No. 824), the units were dried to constant weight over a saturated solution of calcium chloride at 120°F. In the Reference Method, the units were dried to constant weight over a saturated solution of sodium hydroxide at 73°F.

The relative humidity over the sodium hydroxide solution was about 8 percent. The drying conditions to which the units were subjected in both the British and the Reference Methods probably equalled or exceeded the most dry conditions that would be found in service. Even so, the shrinkages obtained by the Rapid Method of drying were about double those obtained by either the British or the Reference Methods and are far greater than the shrinkages to be expected in the field. There was little difference between theshrinkages of like units dried by the British and Reference Methods and there was not much difference between the shrinkage of units dried by those methods and the shrinkage of similar units dried in air at 73°F and 25 percent relative humidity. The data, [6] , also show that the shrinkages of high-pressure steam-cured units of like composition and method of drying, but made at different plants, may have a considerable range in values. These differences in shrinkage may be attributed, in most part, to differences in the technique and procedures used to cure the units at the different plants.

The range and the approximate average values of the shrinkage of concrete masonry units, showing the effects of curing and drying methods are listed in the following Table: In this Table, the units have been divided into two classes, one for heavy-weight aggregate concrete (such as sand and gravel) weighing more than 100 lb per cu ft of concrete and the other for lightweight aggregate concretes weighing 100 lb per cu ft or less.

Range of Shrinkage Values

A. Units weighing over 100 lb/cu ft of concrete

	High-pressure steam cured		Other methods of cure	
	Rapid Method of drying	Other drying methods	Rapid Method of drying	Other drying methods
	percent	percent	percent	percent
Maximum	0.042	0.025	--	0.033
Minimum	.018	.013	--	.027
Average	.028	.016	--	.030

B. Units weighing over 100 lb or less, per cu ft of concrete

	High-pressure steam cured		Other methods of cure	
	Rapid Method of drying	Other drying methods	Rapid Method of drying	Other drying methods
	percent	percent	percent	percent
Maximum	0.051	0.032	--	0.072
Minimum	.036	.018	--	.040
Average	.040	.023	--	.051

3. DRYING SHRINKAGE OF WALLS AND PANELS

3.1 Walls built of saturated units

Data on the extensibility of restrained walls and on the drying shrinkage of unrestrained wall specimens, built of saturated units, at the Research Foundation [1] are listed in Table 3. Nearly 40 walls, 8-in. thick, 5 courses high and 9 ft long, were dried to moisture equilibrium with air at 73°F and 25 percent relative humidity. About half of the wall specimens were constructed and supported on small plates and rollers and were free to shrink without restraint. The other walls were similarly supported but were restrained from shrinking by steel frames fastened at the ends of each of the five courses.

The data, Table 3, are erratic and not much dependence may be placed on the values for extensibility. The data indicate that the free shrinkage of the unrestrained walls was slightly greater than the free shrinkage observed for the units. This may be due, in part, to the drier condition of the walls at the end of the tests.

With the exception of the sand and gravel aggregate walls, the restrained walls cracked at average moisture contents greater than the minimum observed for the unrestrained walls, of like aggregates. The restrained walls of sand and gravel aggregates cracked at moisture contents equal to or less than those contents observed for the free, unrestrained walls. The first cracks were said to have occurred in the vertical joint of a course. As these cracks extended vertically they passed through the units immediately above and below the vertical joint. Both the free shrinkage of unrestrained walls and the extensibility of restrained walls built of high-pressure steam-cured units were about 60 percent of the values for the walls built of high-temperature steam-cured units. This ratio (60 percent) corresponds closely with the relation between the shrinkage of units cured by the two methods.

The ratio of the extensibility of restrained walls to the free shrinkage of similar walls of like units was highest for walls built of sand and gravel aggregate blocks and was dependent upon the moisture content, at first crack in the restrained walls. The moisture content, when dry, of unrestrained walls built of high-pressure steam-cured units averaged about 70 percent of the values for similar walls built of high-temperature steam-cured units. Similarly the moisture content at first crack in the high-pressure-cured restrained walls was less than that for the high-temperature-cured restrained walls.

3.2 Walls built of dry units

Data on the free shrinkage and the extensibility of five walls built of dry units at the Research Foundation, [1] are listed in Table 4. Two aggregates, cinders, and sand and gravel, and two curing methods, using high pressure and high-temperature steam, were represented. Before building the walls, the units had been dried to moisture equilibrium in air at 73°F and 70 percent relative humidity. After construction, the walls were dried to moisture equilibrium with air at 73°F and 25 percent relative humidity.

The data, Table 4, show that the free shrinkage of the walls greatly exceeded that of the units. At least some of the difference may be attributed to a moisture increase of the units due to their being placed in contact with wet mortar when laid in the walls. Like those in Table 3, the data in Table 4 are erratic and too much dependence should not be placed on the values for extensibility.

Neither of the two walls built of high-pressure steam-cured units cracked on drying, whereas two of those walls built of high-temperature steam-cured units did crack on drying. It may be noted that, irrespective of the aggregate, the free shrinkage of dry high-pressure steam-cured units and walls was small and averaged less than 0.010 percent.

3.3 Early tests of wall panels

Some measurements of the drying shrinkage of concrete masonry were made about 1930 by P. M. Woodworth and W. D. M. Allen. These tests are reported by Allen [7] and [8] and by Woodworth [9] . Data from the unrestrained shrinkage in the vertical direction of wall panels composed of nine moisture cured units, are given in Table 5. The panels were built of sand and gravel, cinder, and expanded shale units that had been moist cured in air at 70°F and 100 percent relative humidity for two days. After curing and prior to placing in the panels, the units were stored in laboratory air for periods ranging between zero to 88 days. The measurements on the panels were begun within one-half hour after their completion. The tests were conducted in rooms without humidity control.

The data, Table 5, show the effects, on shrinkage, of drying the units before laying them in the wall. The shrinkage of panels built of air-dried units were 25 to 35 percent of the shrinkages of panels built of saturated units. The shrinkages of the panels built of saturated units were higher than the shrinkage of unrestrained walls built of high-temperature-cured units of similar aggregates, see Tables 3 and 5.

3.4 Walls with joint reinforcement

The drying shrinkage and the extensibility of some walls containing joint reinforcement and built of high-temperature-cured units are listed in Table 6. The walls were built and tested at the Research Foundation [1] . Two walls were built of saturated sand and gravel aggregate units and two walls were built of saturated expanded shale aggregate units. The walls were dried to equilibrium with air at 73°F and 25 percent relative humidity. The joint reinforcement consisted of two plain 3/16-in. diameter cold drawn longitudinal wires held 6 in. apart with transverse No. 9 cross wires welded at 16-in. centers. The yield point of the longitudinal wire was 70,000 lb/in.^{2}. One wall of each aggregate contained reinforcement in every joint; the others were reinforced in half of the joints.

The data, Tables 3 and 6, indicate that the use of joint reinforcement slightly reduced the free shrinkage of the unrestrained walls. The indicated reductions in free shrinkage are listed in the following Table:

Kind of Aggregate	Curing	Number of joints reinforced percent	Reduction in free shrinkage percent
Sand and gravel	H.T.	50	0
Sand and gravel	H.T.	100	6
Expanded shale	H.T.	50	7
Expanded shale	H.T.	100	11

The extensibility of the restrained walls was not greatly affected by the use of joint reinforcing. However, the moisture content at first crack of the reinforced wall of expanded shale aggregate units was much lower than the moisture content at first crack of an unreinforced shale aggregate wall. It was stated that the width and visibility of cracks in walls built of high-temperature-cured block were reduced by the use of reinforcing. However, the width of cracks in the reinforced high-temperature walls was greater than the width of cracks in unreinforced walls built of high-pressure steam-cured units and, regardless of curing, in unreinforced walls built of dry units.

With all joints reinforced, the steel area in the joint reinforcement was equivalent to 0.25 percent of the minimum cross sectional area of blocks. Assuming the steel carries the tensile load at a section where a crack occurs, the steel stress would be about 400 times the average tensile stress on the section. Since the average tensile stress on the minimum section at failure of the sand and gravel aggregate block walls was about 220 lb/in.^{2} and since the stress in the expanded shale wall with 50 percent joint reinforcement was 130 lb/in.^{2}, the yield point of the steel (70,000 lb/in.^{2}) would have been exceeded in at least three of the four restrained walls if there had been no slip of the mortar on the reinforcement.

Further data, not reported in Table 6, were obtained on tests of four, high-temperature steam-cured cinder aggregate walls. The tests were sponsored by Adrian Peerless, Inc., Adrian, Michigan, and were made by the Research Foundation [3] . The walls were built of saturated units and were dried to equilibrium with air at 73°F and 30 percent relative humidity. Two walls were not reinforced, one wall was reinforced in the top and the bottom bed joints, and one was reinforced in every bed joint. The joint reinforcement was Adrian Peerless Crimped Wire Wall-Lok, consisting of two 3/16-in. diameter crimped longitudinal wires with No. 9 cross wires welded at 16-in. centers. One of the two unreinforced walls was not restrained against shrinkage. The other three walls were restrained, presumably in a similar manner to the restrained walls previously described [1] .

Illustrations in the report on tests of the high-temperature steam-cured, cinder-aggregate block walls, sponsored by Adrian Peerless, Inc., showed the importance of adequate joint reinforcing. The free shrinkage of the unreinforced, unrestrained wall on drying from saturation to equilibrium with air at 73°F and 30 percent relative humidity was 0.061 percent, which agrees well with the 0.069 percent shrinkage of a similar wall dried to equilibrium in air at 25 percent relative humidity (Table 3). The unreinforced but restrained wall of this series, wall C, had a single vertical crack extending through blocks and head joints. The maximum width of this crack was 0.048 in. Reinforcement of the top and bottom joints in a restrained wall, wall B, resulted in a single vertical crack through blocks and head joints. This crack had a maximum width of 0.028 in. at the center course and the maximum width of cracks in the reinforced courses was 0.020 in. The total number of cracks in the restrained walls reinforced in every joint, wall A, was increased over the number of cracks in the other walls, walls B and C, but the size of the cracks was reduced, and there was no vertical crack extending through all five courses. The maximum width of cracks was 0.008 in. The relative widths of the maximum-sized cracks in walls A, B, and C, taking wall C as 100 percent, was respectively 17, 58, and 100 percent. It was stated that the crimped joint reinforcing was much more effective in controlling the width of the cracks than the plain wire reinforcing previously tested.

4. DISCUSSION OF TEST DATA

4.1 Limitations on moisture content of the units

Specifications for concrete masonry units usually limit the moisture content of the units on delivery. If the moisture content is to be limited, the question arises as to what the limits should be. It may be presumed that the drying shrinkage of the masonry may be held to a practical minimum if the blocks, on delivery, are dry enough to be in moisture equilibrium with air at the average temperature and relative humidity to which the masonry will be exposed. Even so, it is likely that some volume changes due to changes in moisture content will occur, particularly if there is a high seasonal fluctuation in relative humidity. Some aid to the solving of this problem may be obtained from the data in Table 7, which lists the shrinkage of masonry units from moisture contents of 100, 40, 30, and 20 percent to equilibrium at different relative humidities. Information on the moisture content of the units when in equilibrium at different relative humidities is listed in Table 8.

The data in Tables 7 and 8 were obtained from an interpolation of the shrinkage curves contained in test reports of the Research Foundation, [1] and [2] . The concrete masonry units represented and tested in these two investigations may have been similar but were not necessarily alike. The values obtained [2] were for blocks which had been resaturated and dried for the second time. The values for shrinkage and moisture content were slightly increased on the second cycle of wetting and drying.

It has been noted (Table 2, [6]) that units of like compositions but made at different plants using high-pressure steam, show a wide variation in shrinkage values. While complete data in Tables 7 and 8 were not available for all the different units represented in the two Research Foundation [1] and [2] , investigations, the data for similar units that can be compared are in fair agreement and appear to be consistent. The moisture contents at different relative humidities are consistently higher for the high-temperature-cured units than for the high-pressure-cured units (see Table 8). From Table 7, it may be noted that at moisture contents of 100, 40, and 30 percent moisture contents, the shrinkages of the high-pressure steam-cured units is consistently less than the shrinkages of the high-temperature units. This advantage is much lessened at moisture contents of 20 percent. In general, the shrinkage of the high-temperature units at 20 percent of moisture content is approximately equal to the shrinkage of the high-pressure units at 30 percent moisture content. It follows that the rate of loss in potential shrinkage of the high-temperature units is greatest at moisture losses from 100- to 40- and 30- percent moisture content. It is important, therefore, that any limitations on the moisture content of high-temperature units be rigidly enforced; wetting of such units just prior to laying may be inadvisable.

4.2 Steel Joint Reinforcement

In general, the effects of steel joint-reinforcement were as follows:

a) Slightly reduce the free shrinkage of unrestrained walls.

b) Increase the number but reduce the maximum width of cracks in restrained walls.

c) Reduce the number of cracks in the blocks relative to the number of cracks in the head joints of restrained walls.

These effects were most pronounced when the longitudinal wires were deformed and had a high bonding efficiency. Information on the maximum width of cracks in restrained walls, two of which contained crimped wire joint reinforcement, is given below for 5-course test walls of high-temperature cinder aggregate blocks dried from a saturated condition to equilibrium at 30 percent relative humidity.

Amount of joint reinforcement	Total number of separate vertical cracks	Maximum width of crack	
		Vertical joint	block
		in.	in.
None	1	0.048	0.040
Top and bottom courses	3	0.028	.020
Every joint	6	0.012	.008

For the wall reinforced in the top and bottom joint only, the maximum width of crack (0.028 in.) was in the center course. The width of this crack was nearly 50 percent greater than the maximum width of cracks in the reinforced courses. It follows, so far as these tests are concerned, that where dependence is placed on joint reinforcement to reduce crack width, the reinforcement should be placed in every joint or in alternate joints. It is unlikely that bond beams, spaced 12 to 15 courses apart, vertically, will prevent the formation of large shrinkage cracks near midheight between the bond beams in walls without openings.

Attempts were made to formulate rational methods for determining the amount of reinforcement needed in concrete masonry walls to avoid the likelihood of yielding of the steel, and for estimating the probable widths of cracks under various conditions. These methods are needed. If there is yielding of the reinforcement, it occurs at cracks, permitting them to widen unduly and thereby diminishing the value of the reinforcement. Provided there is no yielding of the steel, the widths of the cracks in reinforced masonry depend chiefly upon the slip of the reinforcement in the masonry. However, the amount of slip depends upon many factors, and adequate test data on the various factors are not yet available.

Although reliable methods for designing reinforcement can not be formulated until more test data become available, it may be helpful to consider some of the factors. For simiplicity, it will be assumed that a long wall is prevented from shortening longitudinally by end anchorages and that it is not restrained otherwise. First consideration will be limited to the central portion sufficiently remote from the ends to be unaffected by any irregularities there. As shrinkage of the wall material occurs, the wall is subjected to longitudinal tensile stresses. If the shrinkage proceeds until the longitudinal tensile strength is exceeded, a crack forms. Ordinarily the crack will be vertical or nearly so. If the wall does not contain longitudinal reinforcement, the cracking would relieve the stresses completely; in reinforced walls the shrinkage stresses would be decreased somewhat and the longitudinal force (summation of the longitudinal stresses in a vertical plane) at the crack would be borne by the reinforcement.

For the idealized conditions assumed, a single crack would relieve the stresses in a non-reinforced wall, and additional shrinkage would increase the crack size but would not produce more cracks. In a reinforced wall, further shrinkage would tend to increase the tensile stresses until the tensile strength of the masonry is again exceeded, if there is no yielding of the reinforcement; and a second crack forms, and so on. The maximum stresses in the reinforcement and the masonry occur just before the appearance of each new crack. Then, as the total tensile force in the reinforcement equals approximately:

$A_s f_s = A_w f_t$, in which

A_s = cross sectional area of steel bars or wires, in a vertical section of the wall, sq in.

f_s = tensile stress in the reinforcement at a crack, psi

A_w = gross area of wall in a vertical section, sq in.

f_t = tensile strength of the masonry (gross area), psi

$p = \frac{A_s}{A_w}$, and, solving for f_s gives:

$$f_s = f_t/p \text{ , in which} \qquad (1)$$

p = ratio of cross sectional area of the reinforcement to that of the masonry wall.

As it is obviously undesirable for the reinforcement to undergo appreciable yielding, f_s should not exceed the yield strength Y of the reinforcement. Therefore one criterion of design should be

$$p \geqq \frac{f_t}{Y} \qquad (2)$$

As previously mentioned, the basic data needed for an analysis of widths of cracks are not available. Therefore, a pretentious theoretical analysis is not warranted. However, for the simple case considered in the foregoing it will be further assumed that the imaginary wall is reinforced with conventional smooth 3/16-in. diameter wire in some of the horizontal joints. The relation between the slip at the loaded end of such wire and the stress on that end is indicated in plotted data [3] and may be estimated by the empirical relation

$$S = \frac{f_s^2}{2 \times 10^{11}} \text{ , in which}$$

S = slip at a crack, inch, and (3)

f_s is given by equation (1). Substituting from equation (1) and noting that the maximum width of the cracks equals twice the slip of reinforcement at a crack,

$$W = 2S = \frac{f_t^2}{p^2 \times 10^{11}} \text{, in which} \qquad (4)$$

W = maximum width of the cracks, inch.

For example, assuming a tensile strength (gross area) of the masonry of 30 lb/in.^{2} and reinforcement consisting of two 3/16-in. diameter wires in every joint, the ratio of reinforcement area to gross cross sectional area of the masonry "p" would be about 0.0009 and the maximum width of crack would be about 0.011 in. (equation 4). For reinforcement in every other joint the value of "p" would be halved and the maximum crack width would be 0.045 in.

4.3 Summary and Conclusions

The coefficients of thermal expansion of concrete masonry units ranged from about 5.2 by 10^{-6} per 1°F for heavy aggregate sand and gravel units to about 2.6 by 10^{-6} per 1°F for lightweight units made of cinder aggregate.

The drying shrinkage of saturated concrete masonry units was affected by the kind of aggregates, the kind of curing and the method, or degree, of drying the units. Units made of concrete weighing more than 100 lb per cu ft (of concrete) shrank much less than did units made of concretes weighing 100 lb or less per cu ft.

Units cured with high-pressure-steam at 120 to 140 psi shrank much less on drying than did units cured at atmospheric pressure by other methods. Other things being equal, there was little difference between the drying shrinkages of units cured at atmospheric pressure in air, in low-temperature (120°F) steam and in high temperature (170°F) steam.

The drying of saturated units in a ventilated oven at 220°F (Rapid Method of drying) produced a much greater shrinkage of the units than did drying them in an oven over a saturated solution of calcium chloride at 122°F (British Method) or drying in a drum over a saturated solution of sodium hydroxide at 73°F (Reference Method). There was little difference between the shrinkages of like units dried by the British and the Reference Methods and there was not much difference between the shrinkage of units dried by these methods and the shrinkage of similar units dried in air at 73°F and 25 percent relative humidity. Regardless of the kind of aggregate, the shrinkage of high-pressure-steam cured units dried by the Rapid Method was nearly twice (175 percent) as much as the average shrinkage of similar units dried by the other three methods. The exposure, in the Reference Method, to a relative humidity of 8 percent represents an extreme of drying that would hardly be expected in service. For specification purposes, the Rapid Method of Measuring shrinkage is a practical one, but it should be remembered that the shrinkages obtained by this method are far in excess of the shrinkage that may occur under the most severe service conditions.

Walls restrained at the ends and supported on a series of rollers cracked when the longitudinal shrinkage exceeded the extensibility of the masonry. Cracks were formed in restrained walls built of saturated units when the walls were dried to moisture equilibrium with air at 73°F and 25 percent relative humidity. Some walls built of units dried to equilibrium at 73°F and 70 percent relative humidity did not crack on drying to 25 percent relative humidity. The first cracks in restrained walls occurred at the vertical joints between units. These cracks then extended into the unit above and below the cracked head joint. None of the restrained test walls were restrained along the supporting base and it may be noted that walls restrained along the base may crack even though the shrinkage is less than the extensibility of the masonry.

Steel joint reinforcement slighly reduced the free shrinkage of unrestrained walls, increased the number but greatly reduced the size of cracks in restrained walls and tended to reduce the number of cracks in the units. These effects were most pronounced when the longitudinal reinforcing wires were crimped. Regardless of how a concrete masonry wall may be restrained against shrinkage and provided the blocks are laid dry enough to prevent excessive shrinkage, it is possible that the proper use of joint reinforcement will reduce the size of cracks to a satisfactory minimum.

Drying of sand and gravel aggregate units to a 30 percent moisture content was roughly equivalent to placing them in moisture equilibrium with air at 73°F and about 75 percent relative humidity. This appears to be a satisfactory and practical limit for those parts of the country where the mean annual relative humidity is somewhat below 75 percent. For example, the mean annual relative humidity at Washington, D. C., is about 65 percent. Units made of lightweight aggregates contained 20 to 25 percent moisture when in equilibrium at 70 per-
64 cent relative humidity. For very dry locations and for special exposure conditions, the blocks may be dried to less than 30 percent of moisture content.

at the mean annual temp. of 55.5°F

References

1. "Volume Change Characteristics of Blocks and Wallettes," J. K. Selden, et al, Research Foundation, University of Toledo, Ohio, (April 1952).

2. "Relation of Shrinkage to Moisture Content in Concrete Blocks," G. L. Kalousek, et al, by Research Foundation, University of Toledo, Ohio, (April 1952).

3. "Welded Wire Mesh for Horizontal Joint Reinforcing," J. K. Selden and W. G. Rohr, Research Foundation, University of Toledo, Ohio, (December 1952).

4. "Tests on Concrete Masonry Units Using Tamping and Vibration Molding Methods," K. F. Wendt and P. F. Woodworth, American Concrete Institute 36-121 (1940).

5. "Properties of Some Lightweight Aggregate Concretes With and Without an Air-Entraining Admixture," Perry H. Petersen, NBS Report BMS 112.

6. "Physical Properties of High-Pressure Steam-Cured Concrete Block." Progress Report of ACI Committee 716 - Journal, American Concrete Institute, April 1953, page 745.

7. "Shrinkage Measurements of Concrete Masonry," W. D. M. Allen, American Concrete Institute 26, page 699 (1930).

8. "Shrinkage Measurements of Concrete Block Masonry," W. D. M. Allen, American Concrete Institute 28, page 177 (1932).

9. Some Tests of Concrete Masonry Units Cured with High-Pressure Steam, P. M. Woodworth, American Concrete Institute 26, page 504 (1930).

Table 1. Coefficients of thermal expansion

Source of data, reference No. a/	Kind of test specimen	Kind of aggregate	Cement factor: bags per cu yd	Cement factor: blocks per bag	Compressive strength 28 days	Coefficient of thermal expansion	Temperature range: Low	Temperature range: High
					lb/in.^{2}	$10^{-6}/°F$	°F	°F
1	Hollow concrete masonry units	Sand and gravel	--	--	--	5.2	73	143
		Cinders	--	--	--	3.1		
		Expanded shale	--	--	--	4.3		
		Expanded slag	--	--	--	4.6		
		Pumice	--	--	--	4.1		
4	Hollow concrete masonry units	Sand and gravel	--	17-34	3800 to 1600	5.2	-7	125
		Crushed limestone	--	18-35	1940 to 720	5.0		
		Cinders	--	18-35	1680 to 700	2.2		
		Expanded shale	--	16-33	1450 to 1150	3.6		
		Expanded slag	--	16-34	1220 to 580	4.5		
5	Bars (1.5- by 1.5- by 9-in.)	Expanded shale	3.0	--	480	3.6	14	104
		Expanded shale	5.4	--	1730	4.1		
		Expanded shale	9.9	--	5720	4.5		
		Expanded slag	4.4	--	590	5.1		
		Expanded slag	6.9	--	1510	5.5		
		Expanded slag	11.0	--	3380	6.2		

a/ Reference 1. Volume change characteristics of blocks and wallettes "Research Foundation, Univ. of Toledo, Ohio
Reference 4. "Tests on Concrete Masonry Units using tamping and vibration molding methods," K. F. Wendt and P. F. Woodworth, Proc. Am. Conc. Inst. 36-121 (1940)
Reference 5. Properties of Some Lightweight Aggregate Concretes With and Without an Air-Entraining Admixture, N.B.S. Report BMS 112,

Table 2. Drying shrinkage of some concrete masonry units

Source of data reference No. a/	Kind of aggregate	Yield blocks per bag of cement	Compressive strength gross area	Method of cure b/	Kind of drying from saturation c/	Shrinkage	Moisture content when dry d/	Shrinkage on second drying	Moisture content on d/ second drying
			lb/in.^{2}			%	%	%	%
1	Sand & gravel			H.P.	25% relative humidity	0.020	11		
	do			H.T.	25% do	0.027	16		
1	Cinders			H.P.	25% do	0.023	10		
	do			H.T.	25% do	.051	12		
1	Expanded shale			H.P.	25% do	0.032	-7		
1	Pumice			H.P.	25% do	0.043	--		
2	Sand & gravel	29.7	1560	H.P.	25% relative humidity	0.013	4	.015	9
	do		680	H.T.	25% do	.029	7	.036	14
	do		955	L.T.	25% do	.033	12	.038	16
2	Cinder	23.8	830	H.P.	25% relative humidity	.016	1	.026	7
	do		730	H.T.	25% do	.040	5	.053	11
	do		780	L.T.	25% do	.055	8	.065	20
2	Expanded shale	22.6	1110	H.P.	25% relative humidity	0.020	2	.027	8
	do		930	H.T.	25% do	.049	3	.060	8
	do		830	L.T.	25% do	.040	7	.049	11
2	Expanded slag	14.3	1010	H.P.	25% relative humidity	.026	0	.032	10
	do		1500	H.T.	25% do	.040	14	.057	19
	do		1230	L.T.	25% relative humidity	.060	20	.070	23
2	Sintered shale	19.9	1250	H.P.	25% relative humidity	.024	0	.034	6
	do		1080	H.T.	25% do	.050	5	.068	11
	do		1080	L.T.	25% do	.072	9	.084	13
2	Pumice	16.9	640	H.P.	25% do	.050	2	.066	9
	do		570	H.T.	25% do	.072	6	.094	10
	do		610	L.T.	25% do	.069	10	.090	14

Table 2. Drying shrinkage of some concrete masonry units (con't.)

Source of data reference No. a/	Kind of aggregate	Yield blocks per bag of cement	Compressive strength gross area	Method of cure b/	Kind of drying from saturation c/	Shrinkage	Moisture content when dry d/	Shrinkage on second drying	Moisture content on d/ second drying
			lb/in.^{2}			%	%	%	%
6	Sand & gravel	2560	H.P.		Rapid Method	.032	0	(No values for second drying)	
		3960	H.P.		do	.042	0		
		1730	H.P.		do	.022	0		
		3780	H.P.		do	.018	0		
6	Sand & gravel	2400	H.P.		British Method	.016	-		
		-	H.P.		do	.025	-		
		1600	H.P.		do	.015	-		
		1750	H.P.		do	.015	-		
6	Sand & gravel	2550	H.P.		Reference Method	.013	-		
		3840	H.P.		do	.022	-		
		1650	H.P.		do	.014	-		
		3650	H.P.		do	.015	-		
6	Cinders	1250	H.P.		Rapid Method	.038	0		
		1130	H.P.		do	.043	0		
		1120	H.P.		do	.037	0		
		1220	H.P.		do	.051	0		
6	Cinders	1340	H.P.		British Method	.020	-		
		-	H.P.		do	.027	-		
		1120	H.P.		do	.024	-		
		1220	H.P.		do	.032	-		
6	Cinders	1280	H.P.		Reference Method	.018	-		
		1190	H.P.		do	.024	-		
		1190	H.P.		do	.021	-		
		1180	H.P.		do	.030	-		

Table 2. Drying shrinkage of some concrete masonry units (con't.)

Source of data reference No. a/	Kind of aggregate	Yield blocks per bag of cement	Compressive strength gross area	Method of cure b/	Kind of drying from saturation c/	Shrinkage	Moisture content when dry d/	Shrinkage on second drying	Moisture content on second drying d/
			lb/in.^{2}			%	%	%	%
6	Expanded clay		1440	H.P.	Rapid Method	.043	0	(No values for second drying)	
				H.P.	do	-	0		
			1080	H.P.	do	.036	0		
			1180	H.P.	do	.037	0		
6	Expanded clay		1450	H.P.	British Method	.021	-		
			-	H.P.	do	-	-		
			1010	H.P.	do	.022	-		
			1200	H.P.	do	.023	-		
6	Expanded clay		1370	H.P.	Reference Method	.019	-		
			---	H.P.	do	--	-		
			1080	H.P.	do	.020	-		
			1140	H.P.	do	.023	-		

a/Ref.1. "Volume Change Characteristics of Blocks and Wallettes." Res.Found. Univ.of Toledo.
Ref.2. "Relation of Shrinkage to Moisture Content in Concrete Blocks." Res.Found. Univ.of Toledo.
Ref.6. "Physical Properties of High-Pressure Steam-Cured Concrete Block" A.C.I.Com.716. The units were made of like materials by four different producers. Each shrinkage value is an average of values from four laboratories.

b/H.P.-High-pressure steam at pressures of 120 to 140 psi.
H.T.-High-temperature steam at 170°F and atmospheric pressure.
L.T.-Low-Temperature steam at 120°F and atmospheric pressure.

c/25% relative humidity - Drying to constant weight or length in air at 73°F and 25 percent relative humidity.
Rapid Method: Immersed in water at 73°F for 24 hr/ dried in ventilated oven at 220 to 235°F for 48 hr - cooled in tight drum at 73°F for 24 hr.
British Method: Similar to method given in British Standards No. 834. Immersed in water at 73°F for 96 hr - dried to constant weight in a closed cabinet at 122°F over saturated solution of calcium chloride.
Reference Method: Immersed in water at 73°F for 96 hr. Dried to constant weight in a closed cabinet at 73°F over a saturated solution of sodium hydroxide (equivalent to a relative humidity of about 8 percent).

d/The amount of moisture in the units in terms of the total absorption. (This is equivalent to the relative amount of moisture in the units, in terms of the total moisture loss on drying from a saturated condition of 73°F to a dry condition in a ventilated oven at 220°F.)

Table 3. Shrinkage of walls built of saturated units.[a]

Kind of aggregate	Kind of curing	Units[b]		Unrestrained walls		Restrained walls		Ratio of extensibility to free shrinkage of:	
		Free shrinkage	Moisture content [c]	Free shrinkage	Moisture content [c]	Extensibility at first crack	Moisture content at first crack [c]	Units	Walls
		%	%	%	%	%	%	%	%
Sand and gravel	H.P.	0.020	12	0.023	9	0.019	9	95	83
	H.T.	.027	17	.033	14	.023	12	85	70
Cinder	H.P.	.023	11	.047	6	.029	10	126	62
	H.T.	.051	13	.069	9	.053	12	104	77
Expanded shale	H.P.	.032	7	.034	7	.022	18	69	65
	H.T.	.049[d]	3	.055	9	.032	25	65	58
Expanded slag	H.P.	.026[d]	0	.029	14	.012	43	46	43
	H.T.	.040[d]	14	.060	20	.026	40	65	44

a/ Walls were built and tested at the Research Foundation, Univ. of Toledo, Ohio, see reference 1. After construction, the walls were dried to moisture equilibrium with air at 73°F and 25 percent relative humidity.

b/ See table 2 for additional data on physical properties of units.

c/ The amount of moisture in the units in terms of the total absorption, see footnote "d," table 2.

d/ Data taken from table 2, reference 2. These blocks were similar but not necessarily the same as those used in the walls.

Table 4. Shrinkage of walls built of dry units[a]

Kind of aggregate	Kind of curing	Units[b]		Unrestrained walls		Restrained walls		Ratio of extensibility to free shrinkage of	
		Free shrinkage	Moisture content[c]	Free shrinkage	Moisture content[c]	Extensibility at first crack	Moisture content[c]	Units	Walls
		%	%	%	%	%	%	%	%
Sand and gravel	H.P.	0.005	12	0.009	8	0.006[d]	8	--	--
Sand and gravel	H.T.	.007[e]	17	.023	12	.017[d]	11	--	--
Cinders	H.P.	.009	11	.012	6	.009[d]	25	--	--
Cinders	H.T.	.021	13	.045	12	.041	12	195	91

a/ Built and tested at the Research Foundation, University of Toledo, Ohio, see reference 1. When laid, the blocks were in moisture equilibrium with air at 73°F and 70 percent relative humidity. After their construction, the walls were dried to moisture equilibrium with air at 73°F and 25 percent relative humidity.

b/ See table 2 for additional data on physical properties of the units.

c/ Amount of moisture in units in terms of the total absorption, see footnote "d" table 2.

d/ Elongation per unit of length caused by stress; wall did not crack.

e/ The shrinkage for similar sand and gravel block, table 1, reference 2 was 0.011 percent.

Table 5. Other tests of shrinkage of wall panels.[a]

Kind of aggregate	No. of units per sack	Compressive strength of units at 28 days, gross area	Curing period: Moist cured[b]	Curing period: Air storage	Age of units when laid	Moisture content of units when laid[c]	Age of wall at end of shrinkage test	Shrinkage of wall at end of test
		lb/in.^{2}	day	day	day	percent	day	percent
Sand and gravel	22	1400	2	0	2	100	365	0.050
do	22	1400	2	5	7	60	365	.030
do	22	1400	2	26	28	21	365	.018
do	22	1400	2	88	90	16	365	.018
Cinder	17	690	2	0	2	100	365	.077
do	17	690	2	5	7	40	365	.080
do	17	690	2	26	28	19	365	.037
do	17	690	2	88	90	19	365	.028
Expanded shale	20	990	2	0	2	100	365	.057
do	20	990	2	5	7	38	365	.042
do	20	990	2	26	28	25	365	.030
do	20	990	2	88	90	15	365	.015

a/ Free shrinkage in a vertical direction of panels containing nine 8- by 8- by 16-in. units, superimposed one over another. After laying, the panels were dried in laboratory air at temperatures of 69 to 82°F and at an average relative humidity of 53 percent.

b/ Units were moist cured in air at 70°F and 100 percent relative humidity for 48 hr after molding. They were then stored in laboratory air until laid in the panels.

c/ Units were considered to be in a saturated condition at the end of the moist curing. The moisture contents are listed as a percentage of the saturated condition.

Table 6. Shrinkage of walls reinforced at the joints.[a]

Kind of aggregate	Kind of curing	Units		Number of joints reinforced	Unrestrained walls		Restrained walls		Ratio of extensibility to free shrinkage of:	
		Free shrinkage	Moisture content[b]		Free shrinkage	Moisture content[b]	Extensibility at first crack	Moisture[b] content at first crack	Blocks	Walls
		percent	percent	percent	percent	percent	percent	percent	percent	percent
Sand and gravel	H.T.	0.027	17	50	0.033	17	0.022	14	81	67
Sand and gravel	H.T.	.027	17	100	.031	16	.021	14	78	68
Expanded shale	H.T.	.049[c]	3	50	.051	9	.035	14	71	68
Expanded shale	H.T.	.049	3	100	.049	9	.026	18	53	53

a/ Built and tested at the Research Foundation, Univ. of Toledo, Ohio. The walls were built of saturated units and were dried to moisture equilibrium with air at 73°F and 25 percent relative humidity.
b/ Amount of moisture in units in terms of the total absorption. (See footnote d, Table 2).
c/ Values taken from table 2, reference 2. These blocks were similar but not necessarily the same as those used in the walls.

Table 7. Drying shrinkage of blocks from controlled moisture contents.[a]

Kind of aggregate	Initial moisture content of blocks[b]	High-pressure steam-cured units				High-temperature steam-cured units			
		Shrinkage at a relative humidity of:				Shrinkage at a relative humidity of:			
		85%	70%	50%	25%	85%	70%	50%	25%
		%	%	%	%	%	%	%	%
Sand and gravel	100	0.009 --	0.016 .008	0.019 --	0.021 .016	0.015 --	0.020 .023	0.026 --	.027 .036
	40	.003 --	.009 .004	.012 --	.013 .010	.006	.011 .011	.017 --	.018 .021
	30	0 --	.006 .002	.009 --	.011 .008	0	.005 .006	.011 --	.012 .017
	20	0 0	0 0	0 -	.002 .005	0 0	0 0	0 -	.001 .006
Cinders	100	.005 --	.015 .016	.020 -	.023 .026	.014 -	.030 .035	.044 -	.052 .053
	40	.002 --	.012 .011	.017 -	.021 .021	.009 -	.026 .020	.040 -	.047 .037
	30	.001 --	.011 .006	.016 -	.020 .016	.006 -	.022 .012	.037 -	.044 .030
	20	0 --	0 .002	.004 --	.008 .012	0 0	0.12 0	.027 -	.033 .018

a/ Shrinkage of blocks from given moisture content at 73°F to equilibrium in air at given relative humidity. Blocks were tested at the Research Foundation, see references 1 and 2, Table 1. Values in first line are for reference 1 blocks. Values in second line are for reference 2 blocks, after resaturation and drying.

b/ The amount of moisture in the units in terms of the total absorption, see footnote "d", Table 2.

Table 7. Drying shrinkage of blocks from controlled moisture contents,(con't.)[a]

Kind of aggregate	Initial moisture content of blocks[b]	High-pressure steam-cured units: Shrinkage at a relative humidity of: 85%	70%	50%	25%	High-temperature steam-cured units: Shrinkage at a relative humidity of: 85%	70%	50%	25%
		%	%	%	%	%	%	%	%
Expanded shale	100	.013	.014	.022	.032	--	--	--	--
		--	.019	.--	.028	--	.044	--	.060
	40	.006	.007	.018	.026	--	--	--	--
		--	.008	--	.018	--	.020	--	.030
	30	.004	.005	.015	.023	--	--	--	--
		--	.005	--	.014	--	.014	--	.024
	20	0	0	.006	.015	--	--	--	--
		0	0	--	.008	--	.003	--	.012
Sintered shale	100	--	--	--	--	--	--	--	--
		--	.022	--	.034	--	.047	--	.068
	40	--	--	--	--	--	--	--	--
		--	.011	--	.022	--	.022	--	.045
	30	--	--	--	--	--	--	--	--
		--	.007	--	.020	--	.018	--	.041
	20	--	--	--	--	--	--	--	--
		--	.003	--	.014	0	0	--	.021

Table 7. Drying shrinkage of blocks from controlled moisture contents, (con't.)[a]

Kind of aggregate	Initial[b] moisture content of blocks	High-pressure steam-cured units				High-temperature steam-cured units			
		Shrinkage at a relative humidity of				Shrinkage at a relative humidity of:			
		85%	70%	50%	25%	85%	70%	50%	25%
	%	%	%	%	%	%	%	%	%
Expanded slag	100	--	--	--	--	--	--	--	--
		--	.020	--	.032	--	.034	--	.057
	40	--	--	--	--	--	--	--	--
		--	.008	--	.020	--	.015	--	.036
	30	--	--	--	--	--	--	---	--
		--	.006	--	.018	0	0	--	.014
	20	--	--	--	--	--	--	--	--
		0	-	--	.011	0	0	0	0
Pumice	100	.022	.027	.039	--	--	--	--	--
		--	.047	--	.066	--	.067	--	.094
	40	.019	.024	.036	--	--	--	--	--
		--	.021	--	.039	--	.029	--	.057
	30	.006	.010	.022	.027	--	--	--	--
		--	.016	.--	.034	--	.021	--	.048
	20	0	0	0	.003	--	--	--	--
		--	.002	--	.013	0	0	--	.016

Table 8. Moisture content of units at different relative humidities.[a/]

Kind of aggregate	High-pressure-steam-cured units: Moisture content of relative humidity of: 85 percent	70 percent	50 percent	25 percent	High-temperature steam-cured units: Moisture content of relative humidity of: 85 percent	70 percent	50 percent	25 percent
	%	%	%	%	%	%	%	%
Sand and gravel	32	27	16	12	32	28	20	17
	-	23	-	7	-	23	-	12
Cinders	26	20	12	11	22	19	14	13
		15	-	6	-	22	-	11
Expanded shale	23	22	15	7	-	-	-	-
	-	21	-	6	-	20	-	7
Sintered shale	-	-	-	-	-	-	-	-
	-	16	-	6	-	22	-	11
Expanded slag	-	-	-	-	-	-	-	-
	-	20	-	10	-	34	-	20
Pumice	28	26	17	-	-	-	-	-
	-	21	-	8	-	23	-	10

a/ Units tested at the Research Foundation, Toledo, Ohio, references 1 and 2, table 1. Units were dried from saturation at 73°F to equilibrium in air at 73°F and given relative humidities. Values in first line are for reference 1 units; values in second line are for reference 2 units on resaturation and drying. The moisture contents represent the absorbed moisture in units in terms of moisture loss from saturation at 73°F to oven dry at 220°F. See footnote d, table 2.