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In analyzing fire test data it has been customary to assume that for concrete masonry units of different geometries but made from the same mix a fire endurance versus equivalent thickness plot on log-log paper is approximately a straight line. It has since been proved (1) that this assumption is not necessarily correct, yet one can expect that this practice of correlating fire test data will go on for some time to come. It is of some practical importance, therefore, to have a simple test method available for the reasonably accurate assessment of the equivalent thickness of hollow masonry units.

The "Standard" Method

The equivalent thickness of a concrete masonry unit is defined as

$$\lambda = \frac{V}{F} \tag{1}$$

where

λ = equivalent thickness of masonry unit, ft

V = "net" volume of the unit, ft^3

F = surface area to be exposed to fire, ft^2.

The "net" volume of the unit is interpreted as the volume that is formed by the visible surfaces of the concrete, and which, therefore, includes not only the concrete itself, but also the air and water in the pores of the concrete.

Owing to the usually complex geometry of the cavities in hollow masonry units, the direct calculation of the net volume is often very laborious. It became customary, therefore, to determine the net volume with the aid of an experimental technique described in ASTM Designation C140 (2). The use of this technique has also been advocated in Supplement No. 2 to the National Building Code of Canada (3).

By now it is well known, however, that the experimental method described in ASTM C140 (referred to hereafter as the "standard" method) is inaccurate and often grossly misleading, especially if it is applied to lightweight concrete units. To understand the difficulties, it may be advisable to re-examine the essence of the method.

ASTM C140 offers the following formula for the calculation of the bulk density of the concrete:

$$\rho_D^* = \frac{W_{AD}}{W_{ASD} - W_{WS}} \rho_w \tag{2}$$

where

ρ_D^* = "standard" bulk density of concrete in air-dry condition, determined according to the standard method, lb/ft^3

ρ_w = density of water = 62.4 lb/ft^3

W_{AD} = weight of masonry unit in air, in air-dry condition, lb

W_{WS} = weight of masonry unit in water, in "saturated" condition, lb

W_{ASD} = weight of masonry unit in air, in "saturated-then-drained" condition, lb.

According to the standard method the "saturated" condition is obtained by having the masonry unit completely submerged in water at room temperature for 24 hr. If the unit is then lifted out from the water and is allowed to drain freely for 1 min, while the surface water is removed with a cloth, the "saturated-then-drained" condition is obtained.

To test the validity of Eq. (2), the following expressions of W's will be utilized:

$$W_{AD} = V\rho_D \tag{3}$$

$$W_{ASD} = V\rho_{SD} \tag{4}$$

$$W_{WS} = V(\rho_S - \rho_w) \tag{5}$$

where

ρ_D = actual bulk density of concrete in air dry condition, lb/ft^3

ρ_{SD} = average bulk density of concrete in "saturated-then-drained" condition, lb/ft^3

ρ_S = average bulk density of concrete in "saturated" condition, lb/ft^3.

By substituting expressions of W's from Eqs. (3), (4), and (5) into Eq. (2), one obtains

$$\rho_D^* = \frac{\rho_D}{1 - (\rho_S - \rho_{SD})/\rho_w} . \tag{6}$$

From this equation it is obvious that $\rho_D^* = \rho_D$ only in that particular case when $\rho_{SD} = \rho_S$, i.e. when the drainage following the saturation takes place from the surfaces of the concrete only.

Experience has shown, however, that in the case of lightweight concrete (or any other materials of sufficiently rough pore structure) in addition to the "surface water" a certain portion of the "pore water" (i.e. the water that has penetrated into the pores during the 24-hr saturation period) is also given off as the masonry unit is removed from the water, especially from within the pores in the surface regions. It is obvious, therefore, that for lightweight masonry units $\rho_S > \rho_{SD}$ and, owing to the larger surface to volume ratios, the difference between ρ_S and ρ_{SD} is greater for hollow units than for solid units.

One can now define a "standard" net volume, V*, which is expressed with the aid of ρ_D^* instead of ρ_D as

$$V^* = \frac{W_{AD}}{\rho_D^*} . \tag{7}$$

Also, analogously to Eq. (1), a "standard" equivalent thickness, λ^*, can be defined as

$$\lambda^* = \frac{V^*}{F} = \frac{W_{AD}}{\rho_D^* F} . \tag{8}$$

By substituting the expression of ρ_D^* from Eq. (2), Eq. (8) can be rewritten as

$$\lambda^* = \frac{1}{F} \cdot \frac{W_{ASD} - W_{WS}}{\rho_w} . \tag{9}$$

Furthermore, by combining Eqs. (1), (4), (5), and (9) one finally obtains

$$\frac{\lambda^*}{\lambda} = 1 - \frac{\rho_S - \rho_{SD}}{\rho_w} . \tag{10}$$

From this equation it is clear that for lightweight concrete masonry units, since $\rho_{SD} < \rho_S$, λ^* is always less than λ, in other words, the equivalent thickness determined according to the standard method is always smaller than the actual equivalent thickness that can be obtained by calculations based on the geometry of the units.

The obviously absurd finding that, for solid lightweight units, the "standard" equivalent thickness invariably turns out to be smaller than the actual thickness has long puzzled the manufacturers of masonry units. Another, even more disturbing fact, however, has not yet been clearly realized, namely that at identical values of V/F the λ^*/λ ratio is less for hollow units than that for solid units (because of the larger surface to volume ratios) and it generally varies with the geometry.

To illustrate the inadequacy of the standard method in determining the equivalent thickness, some results of a simple test are reproduced in this Note. This test was performed on a solid concrete unit made with expanded slag aggregates. The following dimensions were noted:

thickness:	5.625 in. = 0.4687 ft
breadth:	7.561 in. = 0.6301 ft
length:	15.625 in. = 1.3021 ft

Hence

$$V = 0.4687 \times 0.6301 \times 1.3021 = 0.3845 \text{ ft}^3$$

$$F = 0.6301 \times 1.3021 = 0.8305 \text{ ft}^2$$

and, naturally, the true equivalent thickness is equal to the thickness,

$$\lambda = 0.4687 \text{ ft.}$$

The weight of the unit in air, in air-dry condition, was measured as

$$W_{AD} = 36.96 \text{ lb;}$$

therefore the actual bulk density of the concrete is

$$\rho_D = 36.96/0.3845 = 96.12 \text{ lb/ft}^3 .$$

The weight of the unit in water in a saturated condition was found to be

$$W_{WS} = 19.14 \text{ lb.}$$

After measuring W_{WS} the unit was lifted out from the water bath and its weight in air was noted at 10-sec intervals as the drainage went on. This information is denoted by $\overline{W}_{ASD}$ and is reproduced in Table I. (According to the definition of the "saturated-then-drained" condition obviously $\overline{W}_{ASD}$ at 60 sec is equal to W_{ASD}.)

To point out the absurdity of the standard method, calculated values of $\bar{\rho}^*_D$ and $\bar{\lambda}^*$ (obtained with the aid of Eqs. (2) and (9), respectively, using values of $\overline{W}_{ASD}$ for W_{ASD}) are also included in the table. The data clearly indicate that the drainage occurs mainly from within the pores and that this kind of drainage is significant enough even during the first 10 sec to completely falsify the values of ρ_D and λ . (The correct values of these were calculated earlier.) As the time lapsed, the values of $\bar{\rho}^*_D$ and $\bar{\lambda}$ yielded by this test deteriorated further and in the standard "saturated-then-drained" condition (i.e. 60 sec. after the removal of the specimen from the water) the "standard" bulk density of the concrete was found to be 10.7 per cent higher and the "standard" equivalent thickness 9.7 per cent lower than the correct values.

The Recommended Method

The difficulties presented by the standard method can clearly be avoided if steps are taken to prevent the measuring liquid from penetrating into the pores of the concrete masonry unit. This can be achieved either by (a) covering the surface of the unit with some impermeable coating or by (b) using, instead of water, some other liquid that does not enter the pores.

The first of these techniques is not very convenient. It is difficult to apply the coating material to form a reliably continuous layer. Even small invisible imperfections in the continuity of the coat may markedly falsify the test result.

The use of a non-penetrating liquid seems to be more promising. Mercury would be suitable for this purpose because, owing to its high contact angle with concrete, it enters only the largest surface pores. Unfortunately, its toxicity and high cost make its use prohibitive.

Instead of real liquids it would therefore seem to be more convenient to use some bulk granular solid consisting of particles of high sphericity. Naturally, any such a "pseudo-liquid" must have a fairly well reproducible density, at least at some specified conditions.

In the authors' laboratory, No. 10 lead shot is used for measuring the volume of cavities in concrete masonry units. In filling the cavities with lead shot, three procedures were investigated: "scooping," "pouring" and "tamping." As one might expect, scooping resulted in the least dense and tamping in the densest packing of the shot. Nevertheless, the differences in the bulk densities with these three kinds of application were not large. Typically, the bulk density with scooping was about 1 per cent lower and that with tamping 2 to 4 per cent higher than with pouring.

It is somewhat more disturbing, however, that the bulk density also depends on the shape of the containing walls. In the vicinity of the walls the particles are less densely packed, so that the average bulk density decreases with increasing surface-to-volume ratio for the container (or cavity masonry units). Typically, as the surface-to-volume ratio decreased from 30 ft^2/ft^3 to 15 ft^2/ft^3, the bulk density of the lead shot increased from 400 to 435 lb/ft^3 when using the pouring technique.

For the cavities of concrete masonry units 20 ft^2/ft^3 can be regarded as a characteristic value. The bulk density corresponding to this value is about 415 lb/ft^3 (when the shot is poured).

The way of measuring the volume of cavities in a masonry unit is shown in Figure 1. If there are some end cavities, the gross volume of the unit is adjusted into a rectangular parallelepiped by the use of two pieces of plywood. This specimen assembly is then placed in a plastic pan on a scale. All cavities within the parallelepiped are filled with lead shot. The weight of the filling material, W_f (lb) is recorded. The total volume of the cavities, V_c (ft^3) is obtained as

$$V_c = W_f/\rho_f \qquad (11)$$

where ρ_f is the appropriate bulk density of the filling material in lb/ft^3.

The equivalent thickness is

$$\lambda = \frac{V_p - V_c}{F} \qquad (12)$$

where V_p is the volume of the rectangular parallelepiped in ft^3.

It was found that cavity volume measurements performed with the use of this technique are reproducible within 1 per cent.

References

1. Harmathy, T. Z. Thermal Performance of Concrete Masonry Walls in Fire. ASTM Spec. Techn. Publ. 464, 1970, p. 209.

2. Tentative Methods of Sampling and Testing Concrete Masonry Units. ASTM Designation C140-65T, ASTM Standards, Vol. 12, 1966.

3. Fire Performance Ratings, 1965. Supplement No. 2 to the National Building Code of Canada, p. 6.

ADDENDUM

It has been suggested recently that the techniques described in ASTM Designation D 1556-64 and D 2167-66 (ASTM Standards, Vol. II, 1970) concerning the in-situ measurement of soil density might also be successfully used in measuring the volume of cavities in concrete masonry units.

TABLE I

SOME RESULTS OF A TEST CONCERNING THE ACCURACY OF THE "STANDARD" METHOD

Time lapse after removal of specimen from water, sec.	Weight of wet specimen in air, $\overline{W}_{ASD}$, lb	$\bar{\rho}^*_D$, lb/ft^3	$\bar{\lambda}^*$, ft
10	41.80	101.78	0.4425
20	41.36	103.79	0.4340
30	41.14	104.83	0.4297
40	40.92	105.89	0.4253
50	40.88	106.09	0.4246
60	40.81	106.43	0.4233
120	40.70	106.97	0.4211
180	40.70	106.97	0.4211

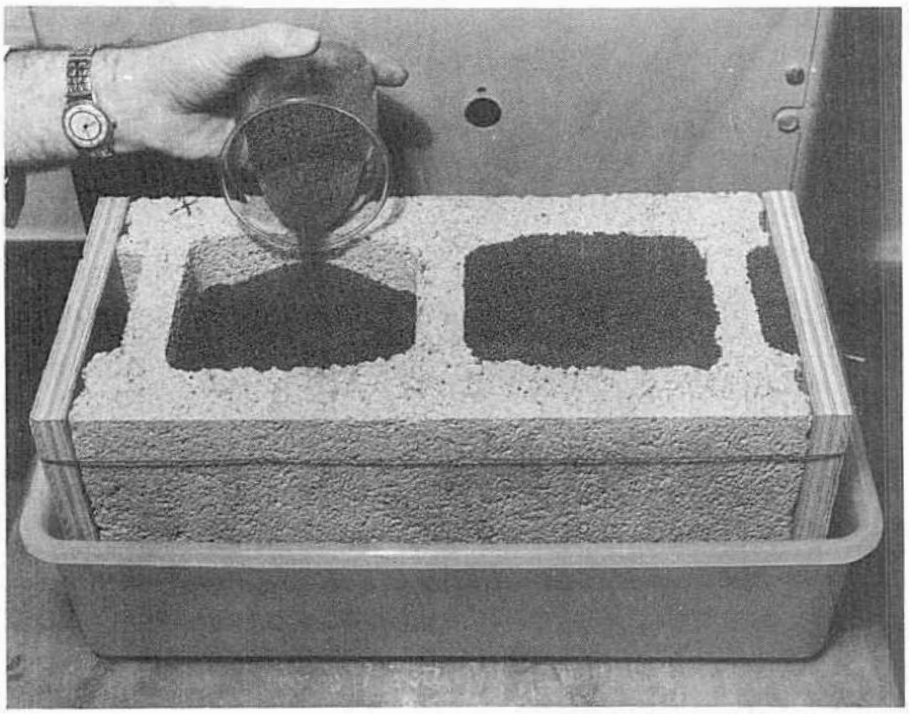

Figure 1. The use of lead shot in measuring the volume of cavities in concrete masonry units.