Model for Evaluating Essential Volume Parameters During Drying of Wet Clay

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Abstract: Model for evaluating essential volume parameters during drying of wet clays has been derived. The clays were prepared using three different grain sizes; <100µm, 100-300µm and 300-1000 µm and fired to a temperature of 1200^{0}C for 18hrs. The derived model;

$$V_o = \left(\frac{V}{e^{(x+\gamma)}}\right)$$

is dependent on the total volume of clay body before drying, the expansion factor and the volume fraction of water removed following the drying process. The expansion factor which forms part the model was found to depend significantly on the grain size of clay materials, clay mineralogy and the water expansion coefficient.
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1. Introduction

Reed (1988) described firing as having three stages through which it proceeds; preliminary reactions which include binder burnout, elimination of gaseous product of decomposition and oxidation, sintering as well as cooling which may include thermal and chemical annealing. Several works (Barsoum,1997;Viewey and Larrly,1978;Keey, 1978) have been carried out on shrinkage of clay during drying. In all these works, porosity has been shown to influence the swelling and shrinkage behaviour of clay products of different geometry. It has been reported (Reed,1988) that drying occurs in three stages; increasing rate, constant and decreasing rate. He pointed out that during the increasing rate; evaporation rate is higher than evaporating surface hence more water is lost. At constant rate, the evaporation rate and evaporation surface are constant. He posited that shrinkage occurs at this stage. Keey (1978) also in a similar study suggested that at this stage, free water is removed between the particles and the inter-particle separation decreases, resulting in shrinkage. During the decreasing rate, particles make contacts as water is removed, which causes shrinkage to cease.

Model for calculating the volume shrinkage resulting from the initial air-drying of wet clay has been derived (Nwoye, 2008). The model;

$$\theta = \gamma^3 - 3\gamma^2 + 3\gamma \qquad (1)$$

calculates the volume shrinkage when the value of dried shrinkage γ, experienced during air-drying of wet clays is known. The model was found to be third-order polynomial in nature. Olokoro clay was found to have the highest shrinkage during the air drying condition, followed by Ukpor clay while Otamiri clay has the lowest shrinkage. Volume shrinkage was discovered to increase with increase in dried shrinkage until maximum volume shrinkage was reached, hence a direct relationship.

Nwoye et al. (2008) derived a model for the evaluation of overall volume shrinkage in molded clay products (from initial air-drying stage to completion of firing at a temperature of 1200^{0}C). It was observed that the overall volume shrinkage values predicted by the model were in agreement with those calculated using conventional equations. The model;

$$S_T = \alpha^3+\gamma^3-3(\alpha^2+\gamma^2)+3(\alpha+\gamma) \qquad (2)$$

depends on direct values of the dried γ and fired shrinkage α for its precision. Overall volume shrinkage was found to increase with increase in dried and fired shrinkages until overall volume shrinkage reaches maximum.

Nwoye (2009a) derived a model for calculating the quantity of water lost by evaporation during oven drying of clay at 90^{0}C. The model;

$$\gamma = \exp[(\ln t)^{1.0638} - 2.9206] \qquad (3)$$

indicated that the quantity of evaporated water, γ during the drying process is dependent on the drying time t, the evaporating surface being constant. The validity of the model was found to be rooted in the expression $(\text{Log}\beta + \ln\gamma)^N = \ln t$.

Model for predictive analysis of the quantity of water evaporated during the primary-stage processing of a bioceramic material sourced from kaolin has been derived by Nwoye (2009b). The model;

$$\alpha = e^{(\ln t/2.1992)} \qquad (4)$$

shows that the quantity of water α, evaporated at 110^0C, during the drying process is also dependent on the drying time t, where the evaporating surface is constant. It was found that the validity of the model is rooted on the expression $(\ln t/\ln\alpha)^N = \text{Log}\beta$ where both sides of the expression are correspondingly approximately equal to 3. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value was found to be less than 22% which is quite within the acceptable deviation range of experimental results.

Model for quantifying the extent and magnitude of water evaporated during time dependent drying of clay has been derived (Nwoye et al.,2009). The model;

$$\gamma = \exp((\ln t/2.9206)^{1.4}) \qquad (5)$$

indicates that the quantity of evaporated water γ during the drying process (at 90^0C) is dependent on the drying time, t the evaporating surface being constant. It was found that the validity of the model is rooted in the expression $\ln\gamma = (\ln t/\text{Log}\beta)^N$ where both sides of the expression are correspondingly almost equal.

The present work is to derive a model for evaluating essential volume parameter during drying of wet clays.

2. Materials and Methods

2.1 Clay preparation

All clays (Olokoro, Ukpor, and Otamiri) used were collected in lumps from deposits. These clays were allowed to dry in air for 96 hours. Each of those clay samples were crushed and sieved to <100μm, 100-300μm and 300-1000 μm particle sizes using assembly of sieves and sieve shaker. Each sample was manually homogenized using 2% starch as binder. Samples were mixed with water (6% of the total weight of dry materials). The plastic clays from the three clay samples were kneaded using hand to expel any trapped air from the clays. The samples were moulded in a rectangular wooden mould of dimension 70mm x 17mm x 9mm for each of the clay sample.

2.2 Firing process and evaluation of essential volume parameters

These samples were dried under the laboratory temperature condition (25^0C) for 18hrs after which they were carefully packed in saw-dust to prevent them from cracking and absorbing moisture from the surrounding. These samples were then fired using electric kiln. The samples were charged at lower temperature (125^0C) after which the temperature was increased to 1200^0C. These samples were fired for 18hrs and then cooled in furnace for the same time limit.

After firing, new volumes, V_o, V_R were calculated using the new dimensions of the drying sample. The initial volume of the sample V, which is the total volume, was also calculated using the initial dimensions of the sample before drying. The values of the volume shrinkage, water removed (x) and expansion factor (γ) were also calculated. The values of the correlations between $\ln(V/V_o)$ and x were calculated using regression analysis method where $\ln(V/V_o)$ is Y axis and x, X axis.

Following experiment carried out,

V = Total volume of clay body before drying (mm^3)
V_o = Dry volume of clay body after drying (mm^3)
x = Volume fraction of water removed after drying
V_R = Volume of water removed after drying
(γ) = Expansion factor

Past report (Cooke,1988) has shown that volume shrinkage can be calculated using the formular;

$$\% \text{Vs} = \left(1-\left(1-\left(\frac{L_1 - L_2}{L_1}\right)^3\right)\right) \times 100 \qquad (6)$$

Where

L_1 = Dried length of sample after air-drying (mm)
L_2 = Fired Length (mm)
Vs = Volume shrinkage (%)

3. Model Formulation

Results of the experiment carried out in this work as shown in Tables 2-12 indicate that;

$$\ln\left(\frac{V}{V_o}\right) - x = \gamma \qquad (7)$$

Where x, γ and ln (V/V_o) from equation (7) are fractional values.

$$x = \left(\frac{V - Vo}{V}\right) \qquad (8)$$

$$V_R = V - Vo \qquad (9)$$

Evaluating equation (7), reduces it to;

$$\ln\left(\frac{V}{V_o}\right) = x + \gamma \qquad (10)$$

Taking the exponential of both sides of equation (10)

$$\left(\frac{V}{V_o}\right) = e^{(x+\gamma)} \qquad (11)$$

$$V_o = \left(\frac{V}{e^{(x+\gamma)}}\right) \qquad (12)$$

Equation (12) is the derived model

4. Boundary and Initial Conditions

Consider a rectangular shaped clay product of length 70mm, width 17mm, and breadth 9mm exposed to drying in the furnace while it was in wet condition. Initially, atmospheric levels of oxygen are assumed. Atmospheric pressure was assumed to be acting on the clay samples during the drying process (since the furnace is not air-tight). The grain sizes for the clay materials used are, <100µm, 100-300µm and 300-1000µm. Drying temperature used; 1200^0C, and drying time used; 18hrs. The boundary conditions are: atmospheric levels of oxygen at the top and bottom of the clay samples since they are dried under the atmospheric condition. No external force due to compression or tension was applied to the drying clays. The sides of the particles and the rectangular shaped clay products are taken to be symmetries. All the water in the clay body was assumed to have been removed during the drying process.

5. Model Validation

The formulated model was validated by direct analysis and comparison of the model-predicted V_o values and those from the experiment for equality or near equality.

Analysis and comparison between these V_o values reveal deviations of model-predicted V_o from those of the experimental values. This is believed to be due to the fact that the surface properties of the clay and the physiochemical interactions between the clay and binder, which were expected to have played vital role during the evaporation of water were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted V_o value to that of the corresponding experimental value.

Deviation (Dn) (%) of model-predicted values from the experimental V_o values is given by

$$Dn = \left(\frac{P_D - E_D}{E_D}\right) \times 100 \qquad (13)$$

Where

P_D = Dry volume of clay (after drying) as predicted by model (mm^3)

E_D = Dry volume of clay (after drying) as obtained from experiment (mm^3)

Correction factor (Cf) is the negative of the deviation i.e

$$Cf = -Dn \qquad (14)$$

Therefore

$$Cf = -100\left(\frac{P_D - E_D}{E_D}\right) \qquad (15)$$

Introduction of the value of Cf from equation (15) into the model gives exactly the corresponding experimental value of V_o.

6. Results and discussions

Comparison of Tables 1-10 shows that the magnitude of the various essential volumes and other related parameters vary with the clay mineralogy, clay particle size, coefficient of expansion and the expansion factor. Figs. 1-9 show close alignment between curves (V_o(exp) and V_o(mod)) of the dry volume of clay as obtained from experiment and derived model respectively. The degree of this alignment is a clear indication of the validity and precision of the derived model. The model shows similarities with Cooper`s equation (Cooper,1978); $\ln(V/V_s) = SC$, where V= Total volume of clay the body before drying, V_s = dry volume of clay body after drying, C = volume fraction of water in the clay body at any point in time and S = slope. In the case of the past related work (Cooper,1978), a plot of $\ln(V/V_s)$ against C gives the slope S as the coefficient of expansion α_c. It was found from the present work that since all the water in the clay body was removed, a plot of $\ln(V/V_o)$ against x also gives the slope as the coefficient of expansion α_c. Based on the foregoing, $V_s = V_o$ and C = x.

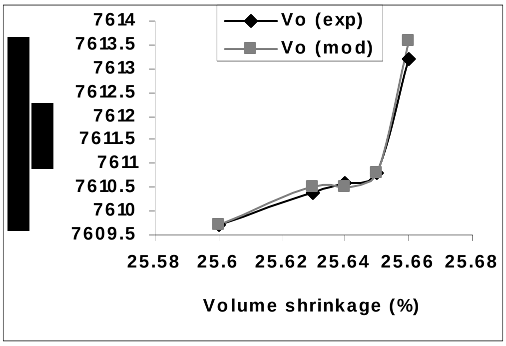

Fig.1 Comparison of the dry volumes of Olokoro clay as obtained from experiment and as predicted by model. (for particle size; <100µm)

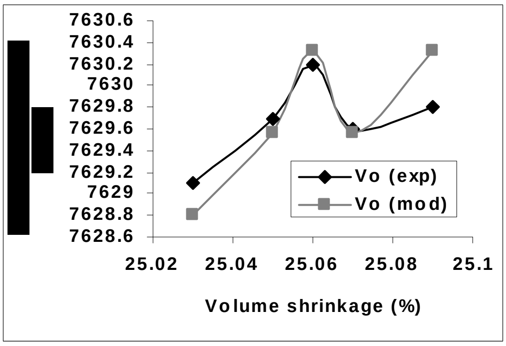

Fig.2 Comparison of the dry volumes of Olokoro clay as obtained from experiment and as predicted by model. (for particle size;100-300µm)

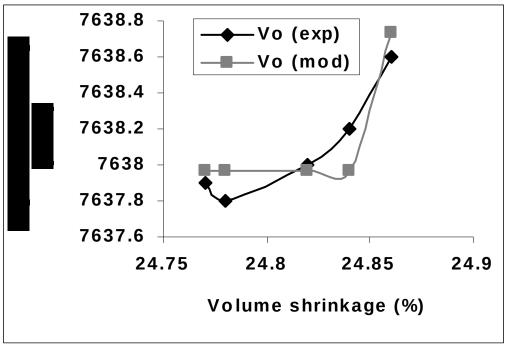

Fig.3 Comparison of the dry volumes of Olokoro clay as obtained from experiment and as predicted by model. (for particle size;300-1000μm)

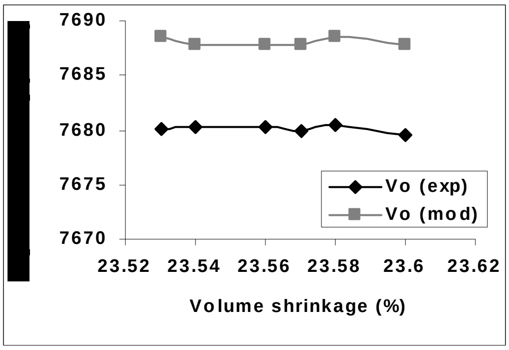

Fig.4 Comparison of the dry volumes of Ukpor clay as obtained from experiment and as predicted by model. (for particle size; <100μm)

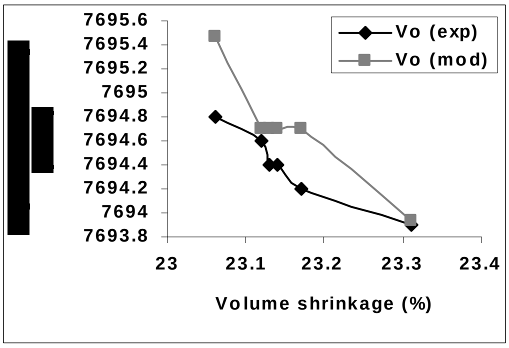

Fig.5 Comparison of the dry volumes of Ukpor clay as obtained from experiment and as predicted by model. (for particle size;100-300μm)

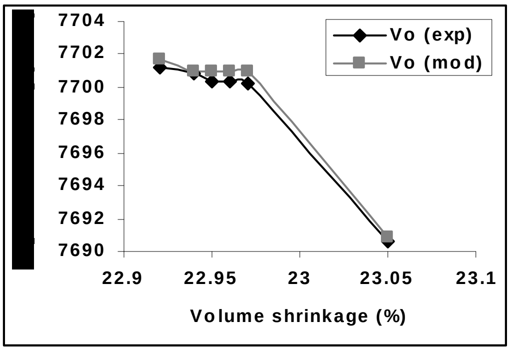

Fig.6 Comparison of the dry volumes of Ukpor clay as obtained from experiment and as predicted by model. (for particle size;300-1000μm)

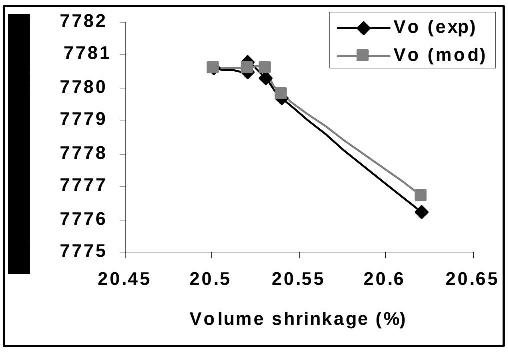

Fig.7 Comparison of the dry volumes of Otamiri clay as obtained from experiment and as predicted by model. (for particle size; <100μm)

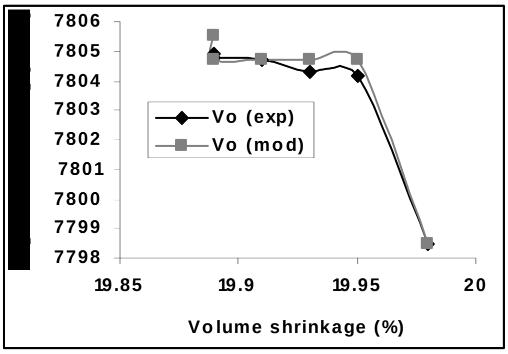

Fig.8 Comparison of the dry volumes of Otamirir clay as obtained from experiment and as predicted by model. (for particle size;100-300μm)

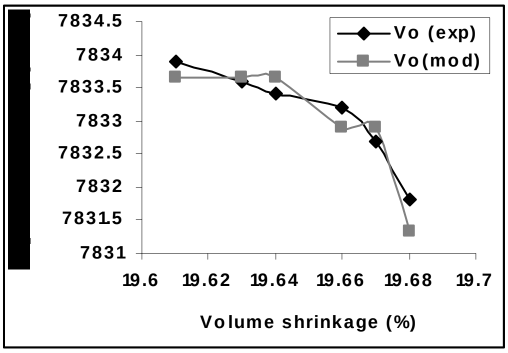

Fig.9 Comparison of the dry volumes of Otamiri clay as obtained from experiment and as predicted by model. (for particle size;300-1000μm)

Table 1: Chemical composition of clays used

Source	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	SiO_2	N_2O	K_2O	Loss of ignition
Otamiri	15.56	0.05	1.09	-	0.29	69.45	0.01	0.21	13.10
Olokoro	20.10	7.05	-	0.75	1.26	45.31	0.05	0.09	11.00
Ukpor	31.34	0.63	2.43	0.14	0.06	51.43	0.04	0.10	12.04

Table2: Relationship between volume shrinkage and essential volume parameters resulting from drying of Olokoro clay (for particle size; <100µm), $\alpha_c = 0.7$

Vs	V_o(exp)	V	V_R	x	V/V_o	$\ln (V/V_o)$	γ (10^{-3})
25.63	7610.4	8400	789.6	0.0940	1.1038	0.0987	4.7
25.66	7612.2	8400	787.8	0.0938	1.1035	0.0985	4.7
25.60	7609.7	8400	790.3	0.0941	1.1039	0.0988	4.7
25.64	7610.6	8400	789.4	0.0940	1.1037	0.0987	4.7
25.66	7613.2	8400	786.8	0.0937	1.1033	0.0983	4.7
25.65	7610.8	8400	789.2	0.0940	1.1037	0.0987	4.7

Table3: Relationship between volume shrinkage and essential volume parameters resulting from drying of Olokoro clay (for particle size; 100-300µm), $\alpha_c = 0.57$

Vs	V_o(exp)	V	V_R	x	V/V_o	$\ln (V/V_o)$	γ (10^{-3})
25.07	7629.6	8400	770.4	0.0917	1.1010	0.0962	4.5
25.09	7629.8	8400	770.2	0.0917	1.1009	0.0961	4.4
25.03	7629.1	8400	770.9	0.0918	1.1010	0.0963	4.5
25.03	7630.4	8400	770.6	0.0917	1.1009	0.0961	4.4
25.06	7630.2	8400	769.8	0.0916	1.1009	0.0961	4.5
25.05	7629.7	8400	770.3	0.0917	1.1010	0.0962	4.5

Table4: Relationship between volume shrinkage and essential volume parameters resulting from drying of Olokoro clay (for particle size; 300-1000µm), $\alpha_c = 0.43$

Vs	V_o(exp)	V	V_R	x	V/V_o	$\ln (V/V_o)$	γ (10^{-3})
24.82	7638.0	8400	762.0	0.0907	1.0907	0.0951	4.4
24.84	7638.2	8400	761.8	0.0907	1.0997	0.0951	4.4
24.86	7638.6	8400	761.4	0.0906	1.0997	0.0950	4.4
24.77	7637.9	8400	762.1	0.0907	1.0998	0.0951	4.4
24.78	7637.8	8400	762.2	0.0907	1.0998	0.0951	4.4
25.85	7634.4	8400	761.6	0.0907	1.0997	0.0950	4.3

Table5: Relationship between volume shrinkage and essential volume parameters resulting from drying of Ukpor clay (for particle size; <100µm), $\alpha_c = 0.45$

Vs	V_o(exp)	V	V_R	x	V/V_o	ln (V/V_o)	γ (10^{-3})
23.57	7680.0	8400	720.0	0.0857	1.0938	0.0897	2.9
23.56	7680.2	8400	719.8	0.0857	1.0937	0.0896	2.9
23.58	7680.4	8400	719.6	0.0857	1.0937	0.0896	2.8
23.54	7680.2	8400	719.8	0.0857	1.0937	0.0896	2.9
23.53	7680.1	8400	719.9	0.0857	1.0937	0.0896	2.8
23.60	7679.6	8400	720.4	0.0858	1.0938	0.0897	2.8

Table6: Relationship between volume shrinkage and essential volume parameters resulting from drying of Ukpor clay (for particle size; 100-300µm), $\alpha_c = 0.33$

Vs	V_o(exp)	V	V_R	x	V/V_o	ln (V/V_o)	γ (10^{-3})
23.14	7694.4	8400	705.6	0.0840	1.0917	0.0877	3.7
23.12	7694.6	8400	705.4	0.0840	1.0917	0.0877	3.7
23.17	7694.2	8400	705.8	0.0840	1.0917	0.0877	3.7
23.13	7694.4	8400	705.6	0.0840	1.0917	0.0877	3.7
23.06	7694.8	8400	705.2	0.0840	1.0916	0.0876	3.6
23.31	7693.9	8400	706.1	0.0841	1.0918	0.0878	3.7

Table7: Relationship between volume shrinkage and essential volume parameters resulting from drying of Ukpor clay (for particle size;300-1000µm), $\alpha_c = 0.3$

Vs	V_o(exp)	V	V_R	x	V/V_o	ln (V/V_o)	γ (10^{-3})
22.96	7700.4	8400	699.6	0.0833	1.0909	0.0870	3.7
22.94	7700.8	8400	699.2	0.0832	1.0909	0.0870	3.8
23.05	7690.6	8400	709.4	0.0845	1.0922	0.0882	3.7
22.97	7700.2	8400	699.8	0.0833	1.0909	0.0870	3.7
22.95	7700.3	8400	699.7	0.0833	1.0909	0.0870	3.7
22.92	7701.2	8400	698.8	0.0832	1.0907	0.0868	3.6

Table8: Relationship between volume shrinkage and essential volume parameters resulting from drying of Otamiri clay (for particle size; <100µm), $\alpha_c = 0.17$

Vs	V_o(exp)	V	V_R	x	V/V_o	ln (V/V_o)	γ (10^{-3})
20.52	7780.8	8400	619.2	0.0737	1.0796	0.0766	2.9
20.50	7780.6	8400	619.4	0.0737	1.0796	0.0766	2.9
20.52	7780.5	8400	619.5	0.0738	1.0796	0.0766	2.8
20.54	7779.7	8400	620.3	0.0738	1.0797	0.0767	2.9
20.62	7776.2	8400	623.8	0.0743	1.0802	0.0771	2.8
20.53	7780.3	8400	619.7	0.0738	1.0796	0.0766	2.8

Table9: Relationship between volume shrinkage and essential volume parameters resulting from drying of Otamiri clay (for particle size; 100-300µm), $\alpha_c = 0.25$

Vs	V_o(exp)	V	V_R	x	V/V_o	ln (V/V_o)	γ (10^{-3})
19.93	7804.3	8400	595.7	0.0709	1.0763	0.0735	2.6
19.91	7804.7	8400	595.3	0.0709	1.0763	0.0735	2.6
19.89	7804.9	8400	595.1	0.0708	1.0762	0.0734	2.6
19.89	7804.8	8400	595.2	0.0709	1.0763	0.0735	2.6
19.95	7804.2	8400	595.8	0.0709	1.0763	0.0735	2.6
19.98	7798.5	8400	601.5	0.0716	1.0771	0.0743	2.7

Table10: Relationship between volume shrinkage and essential volume parameters resulting from drying of Otamiri clay (for particle size;300-1000µm), $\alpha_c = 0.26$

Vs	V_o(exp)	V	V_R	x	V/V_o	ln (V/V_o)	γ (10^{-3})
19.63	7833.6	8400	566.4	0.0674	1.0723	0.0698	2.4
19.61	7833.9	8400	566.1	0.0674	1.0723	0.0698	2.4
19.64	7833.4	8400	566.6	0.0675	1.0723	0.0698	2.3
19.66	7833.2	8400	566.8	0.0675	1.0724	0.0699	2.4
19.68	7831.8	8400	568.2	0.0676	1.0726	0.0701	2.5
19.67	7832.7	8400	567.3	0.0675	1.0724	0.0699	2.4

Conclusion

The model evaluates essential volume parameters during drying of wet clay. The model is dependent on the total volume of clay body before drying, the expansion factor and the volume fraction of water removed following the drying process. The expansion factor which forms part the model was found to depend significantly on the grain size of clay materials, clay mineralogy and the water expansion coefficient.

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