Scientific Research Publishing

Geomaterials, 2019, 9, 40-53
http://www.scirp.org/journal/gm
ISSN Online: 2161-7546
ISSN Print: 2161-7538

Modeling the Drying Kinetics of Earth Bricks Stabilized with Cassava Flour Gel and Amylopectin

Mondésir Ngoulou[1], Raymond Gentil Elenga[1*], Louis Ahouet[1,2], Stevina Bouyila[1], Serge Konda[2]

[1]Laboratoire des Matériaux et Énergies (LME), Faculty of Sciences and Technics, Marien Ngouabi University, Brazzaville, Congo
[2]Bureau de Contrôle du Bâtiment et Travaux Publics (BCBTP), Brazzaville, Congo
Email: *rgelenga@gmail.com

How to cite this paper: Ngoulou, M., Elenga, R.G., Ahouet, L., Bouyila, S. and Konda, S. (2019) Modeling the Drying Kinetics of Earth Bricks Stabilized with Cassava Flour Gel and Amylopectin. *Geomaterials*, **9**, 40-53.
https://doi.org/10.4236/gm.2019.91004

Received: December 12, 2018
Accepted: January 18, 2019
Published: January 21, 2019

Abstract

Earth bricks could contribute to alleviate the housing shortage in the world, thanks to their low cost, easy production, and low environmental impact. However, to manufacture bricks with required properties, many raw soils must be ameliorated. In Central and Eastern Africa, the waste water of the cassava processing is used to improve earth brick mechanical properties. This technique is interesting, because it is sustainable, low-cost and easy to implement. But, studies on this stabilization method are scarce, in particular on the drying kinetics of these bricks. Now, it is important to know the drying duration, because the earth brick's strength is strongly correlated to its moisture content. Thus, this study aims to quantify and to model the effect of adding cassava flour gel and amylopectin on the drying kinetics of earth bricks. Depending on the soil nature, the drying duration decreases from 7% to 25% for a stabilizer content of 20%. For the five models used, the coefficient of determination is superior to 0.997 and the chi square is inferior to 3×10^{-4}. In average, the best model is Khazaei, followed in order by Avrami-Page, diffusion, Yong and Peleg. The effective coefficient of diffusion of water is about 4×10^{-5} m·s^{-2}. The parameter T of the Khazaei's model is strongly correlated to the drying duration and the stabilizer content, and their relationships have been deduced.

Keywords

Earth Brick, Stabilization, Drying Kinetics, Modeling, Cassava Starch

1. Introduction

Although the housing is one of the basic human needs [1], the access to a healthy housing remains a great challenge in many countries. Indeed, in 2008, UN-Habitat estimated that it is necessary to build 96,150 new housings per day during the next 25 years to overcome the housing shortage [2]. Sub-Saharan Africa has the greatest housing deficit in the world [2], due to its high population growth, high cost of construction materials, and great low-income households. Owing to their low cost, easy manufacturing and great availability of the raw material, earthen constructions could significantly contribute to alleviate this deficit. But they suffer to be less durable than modern constructions [3]. To be durable, the construction must be done according to basic architectural rules, in particular with a good foundation and a large veranda [4]. In addition, the soil properties have to be up to geotechnical standards. Unfortunately, only some raw soils are suitable for construction [5] [6]. In many cases, it is necessary to improve the soil properties by adding a stabilizer as cement [7], lime [8], plant fibers [9] and ash [10]. But, to remain affordable to low income households, the improvements must be low-cost. Among local, sustainable and low-cost stabilizers used traditionally, there is the waste water of the cassava processing. This waste water contains starch at low content and is used instead of the ordinary water for the manufacturing of earth bricks [11]. Although this empirical knowledge from Central and Eastern Africa is not well known, it is supported by recent studies on clay-starch interactions [12] [13] [14] [15]. Indeed, these studies have revealed that strength of starch polymer is increased by adding clay. After their molding, the stabilized earth bricks are usually dried during months in open air. Generally, the monitoring of the curing process consists on the measurement of the brick's strength at the 7^{th}, 14^{th}, 21^{st} and 28^{th} days, as for concrete. To optimize the production of bricks, it is essential to know exactly the effect of adding the stabilizer on the drying kinetics of bricks, because the presence of water affects strongly the bricks' mechanical properties. But little is known on the drying kinetics of earth stabilized bricks. This lack is particularly true for stabilized bricks with starch. In addition, cassava starch is a mixture of amylose and amylopectin. The effect of the components on the brick properties is not yet known.

The objective of this work is to assess the effect of adding the cassava flour gel or amylopectin on the drying kinetics of earth brick and to model the kinetics. For this purpose, a natural clayey soil, and *Cubitermes* sp. and *Macrotermes* sp. mound soils had been used as raw materials. Mound termite soils are often used by traditional brickmakers instead of natural clayey soils, because they are usually more clayey than surrounding soils. Besides, five empirical or semi-empirical drying models had been chosen among the most used for modeling the drying kinetics.

2. Materials and Methods

2.1. Soils, Cassava Gel and Brick Manufacture

The termite mound soils were obtained by crushing uninhabited termite mounds. After crushing, soil grains larger than 2 mm were eliminated by sieving. The *Cubitermes* sp. mounds were collected in the savanna around Ngo in the south of Congo, while the *Macrotermes* sp. mounds were collected at Kombé, in the south of Brazzaville. The natural clayey soil was collected in a brickwork quarry, at Dolisie.

The plasticity of the soils was estimated through the Atterberg's limits according to the NF 94,051 standard [16]. The grading analysis of the soils was performed by sieving and sedimentometry according to the NF 94,056 and NF 94,057 standards [17] [18], respectively. The soils' characteristics obtained are reported in **Table 1**.

The cassava flour gel was prepared by heating the cassava flour in water until the total disappearance of free water. The cassava flour has been obtained by finely molding about 50 kg of dried cassava tubers. These dried tubers were bought in a local market and are usually used for the human feeding.

To make the bricks, after mixing the gel, the soil and tap water in the good proportions, the mixture was molded and compressed with a mechanical press at 6 MPa. The tap water content used for the mixture is the optimum moisture content (OMC) of the soil determined by the Proctor test. The Proctor test was performed according to the NF 94,093 standard [19].

2.2. Monitoring and Modeling of the Drying Kinetics

The brick's curing kinetics was monitored by following the evolution of the brick's mass. A brick was considered dried when the variation of their mass during three days was less than 2%.

Five empirical or semi-empirical drying kinetics models had been used: the diffusion model, the Weibull model, the Peleg model, the modified Kazaei model and the Unified expression of Yong et al. Besides, the concept of the characteristic drying curve has been applied on the drying kinetics.

Table 1. Characteristics of the natural clayey soil (N), the *Cubitermes* mound soil (C) and the *Macrotermes* mound soil (M) used to manufacture earth bricks. W_L = Liquid limit; W_p = Plastic limit; ω_{omc} = Optimum moisture content; γ = apparent density; OM = organic matter.

Soil characteristics	N	C	M
Clay (%)	18.7	25	20
Silt (%)	40.7	25	20
Sand (%)	40.6	50	60
W_L (%)	47.2	11.6	28
Wp (%)	25.4	2.1	11.6
PI (%)	21.8	9.5	16.4
ω_{omc} (%)	17.8	15.2	11
γ (t/m^3)	1.54	1.72	1.98
OM (%)	1.93	5.00	0.46

The Page model (Equation (1)) has the same form as Avrami's law (crystallization kinetics) or the Weibull model (ultimate strength for brittle materials) [20] [21].

$$M_r(t) = \exp(-kt^n); \ \ \alpha = k^{-1/n} \tag{1}$$

$M_r(t)$ is the removable water content; a is called the scale parameter or the time to remove 63.2% of the removable water, and thus it is related to the drying speed. n is the shape parameter, and it is superior to 1 for drying kinetics where the drying rate increases firstly until its maximum and then decreases continuously until 0 (equilibrium). On the contrary, if the drying process is governed by the moisture diffusion, the n value is less or equal to 1. This model has been used to simulate vegetables' drying kinetics, crystallization kinetics and the failure of brittle materials [21].

The diffusion model (Equation (2)) is the simplified solution of the Fick's law [21] [22].

$$M_r(t) = a\exp(-kt) + (1-a)\exp(-kbt) \tag{2}$$

a, b and k are adjusted parameters. For infinite plates, k is equal to $D\pi^2/4L^2$, with D the effective coefficient of diffusion, L the half-thickness of the plate. This model has been used for several products.

The Peleg model has been modified to express the moisture ratio instead the water mass in the product (Equation (3)) [23] [24]. It is often used to simulate the sorption-desorption curves.

$$M_r(t) = 1 - t/(a+bt) \tag{3}$$

a and b are adjusted parameters, but a is the inverse of the initial drying rate.

Equation (4) is the modified Khazaei model [25] [26] to take into the account the fact that the initial moisture ratio is equal to 1 [5].

$$M_r(t) = 1 - a(1-\exp(-t/T)) - bt \tag{4}$$

a, k and b are adjustable parameters. The inverse of T has the same meaning as k in the Page model, that is, it is equal to the duration to remove 63.2% of the removable moisture. The parameter b is equal to the drying rate near the end of the drying process. This model appears as a correction of the Page model.

The unified expression of Yong *et al.* (Equation (5)) [27] has been recently established to simulate grading distributions of soils. We extend its use to the drying kinetics because when this model is reliable, it leads to a single expression $U(t)$ (Equation (6)) of all curves as a well-known characteristic curve.

$$M_r(t) = ct^{-\mu}\exp(-t/T) \tag{5}$$

$$U(t) = (t^{\mu}M_r)/c = \exp(-t/T) \tag{6}$$

c, μ and T are adjusted parameters.

The concept of the characteristic drying curve assumes that the normalized drying rate f ($f = v(t)/v(0)$, $v(t)$ is the drying rate at the time t) depends only on the moisture content and the nature of the material [28] [29]. Thus, for the same material dried in different conditions (temperature, air velocity), the curve f versus M_r should be the same.

The determination of the models' parameters for each drying curve is performed with the Origin Pro 8 software. The fitting goodness of the models is estimated through the reduced chi-square (χ^2) and the coefficient of determination (R^2). The best model has the lowest χ^2 and the highest R^2. Besides, these models are compared through the Aike's Information criterium which takes into account the number of parameters in the model. According to the AIC, for the same precision, the best model is that has the lowest number of parameters.

3. Results and Discussion

3.1. Effect of Stabilizers on the Drying Kinetics

The drying kinetics curves of the compressed and stabilized clayey soil bricks as well as those of the *Cubitermes* mound soil and the *Macrotermes* mound soil are reported in **Figure 1**. It appears that adding the cassava flour gel or amylopectin increases the earth bricks' drying rate. This increasing is clearly reflected by the brick's drying durations deduced from these curves and reported in **Figure 2**.

For non-stabilized bricks, it seems that the variation of the clay percentage does not influence significantly the drying duration. Indeed, all non-stabilized bricks have the same drying duration of 28 days in average. But this duration should be considered as the minimum owing the fact that bricks used in this study are smaller than those used in construction. Besides, the incorporation of the cassava flour gel or amylopectin in the soil reduces the drying duration from 2 to 7 days depending on the soil, that is, a decrease of 7% - 25% in comparison with the non-stabilized brick. The greatest reduction is obtained with termite mound soils. In average, the reduction obtained by stabilizing with cassava flour gel is greater than that with amylopectin. This reduction of the drying duration could be explained by the higher drying rate of the cassava flour gel and amylopectin (about one week) in comparison with that of non-stabilized bricks (about one month).

3.2. Evaluation of the Drying Kinetics Models

The statistical parameters of this modeling are reported in **Table 2** and **Figure 3** illustrates the goodness of the models for these drying kinetics. All the models fit well the drying curves. Indeed, in average, the values of the coefficient of determination (R^2) and the Chi square (χ^2) are equal to 0.997 ± 0.002 and (3 ± 2) × 10^{-4} for the Yong model, 0.998 ± 0.002 and (2 ± 2) × 10^{-4} for the Avrami-Page model, 0.986 ± 0.009 and (14 ± 12) × 10^{-4} for the Peleg model, 0.999 ± 0.001 and (1 ± 1) × 10^{-4} for the Khazaei model, and 0.997 ± 0.003 and (2 ± 2) × 10^{-4} for the diffusion model.

The ranking of the models depends on the statistical parameter used as criteria (**Table 3**). In average, the best model is the Khazaei one ($0.997 \le R^2 \le 1$, and $R^2 = 1$ for one third of the curves), followed in order by Avrami-Page, Diffusion, Yong and Peleg. In particular, it could be noticed that even for the AIC criterion which favors model with fewer parameters, the Khazaei's model remains the best despite its four parameters, except for *Macrotermes* mound soil bricks.

The values of the models' parameters are listed in **Table 4**. The value of the time exponent, the parameter n, is in average 1.02 ± 0.16 for the Khazaei's model, and 0.99 ± 0.15 for the Avrami-Page model. These values around 1 indicate that the drying process is governed by the water diffusion, and are consistent with the goodness of the diffusion model for these drying kinetics. Indeed, when n = 1, these models could be considered as the approximations of the diffusion model.

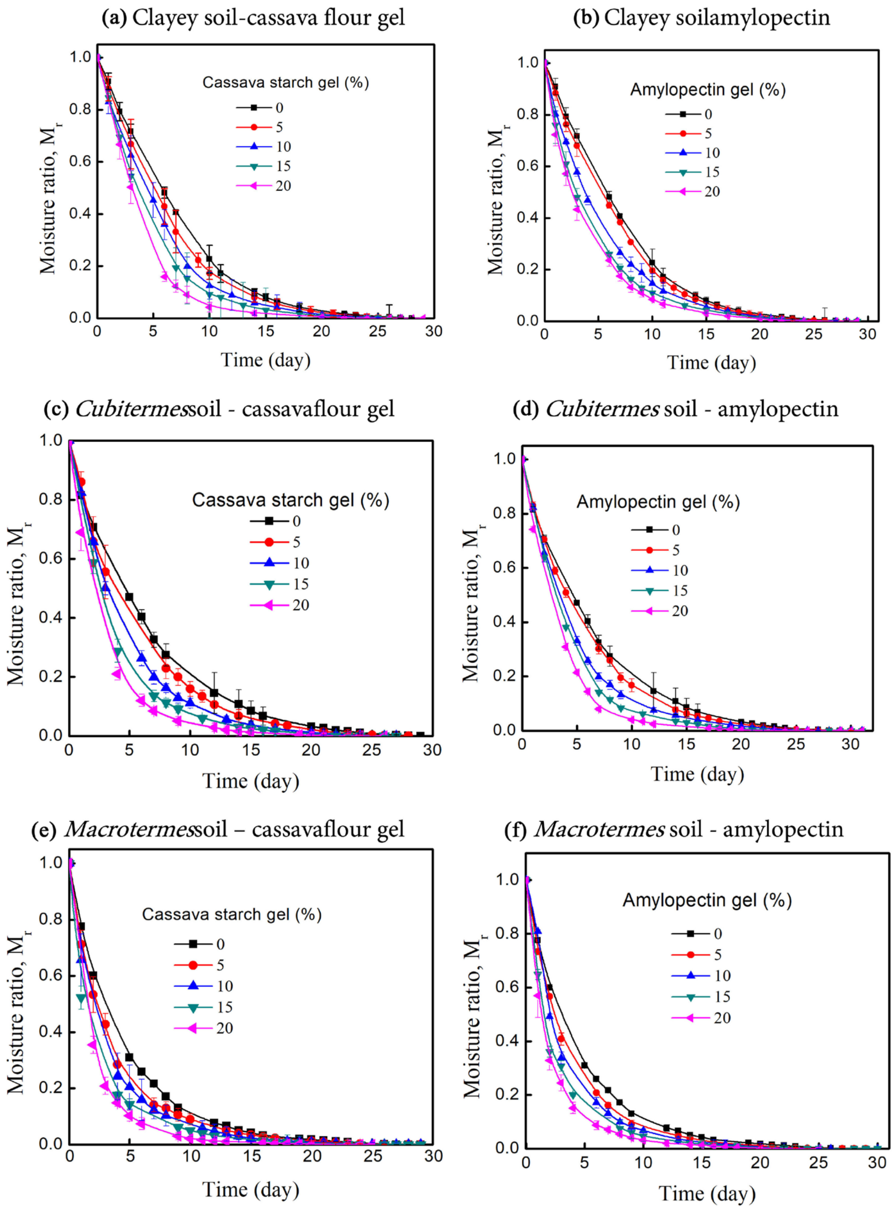

Figure 1. Drying kinetics of earth bricks made with: a clayey soil stabilized with cassava flour gel (a), and amylopectin (b); *Cubitermes* mound soil stabilized with cassava flour gel (c), and amylopectin (d); *Macrotermes* mound soil stabilized with cassava flour gel (f), and amylopectin gel (e).

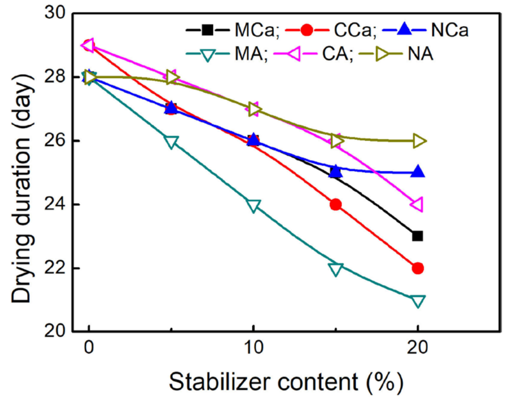

Figure 2. Variation of earth compressed bricks drying duration according to the stabilizer content. M = *Macrotermes* mound soil; C = *Cubitermes* mound soil; N = Natural clayey soil; Ca = Cassava flour gel; A = Amylopectin gel.

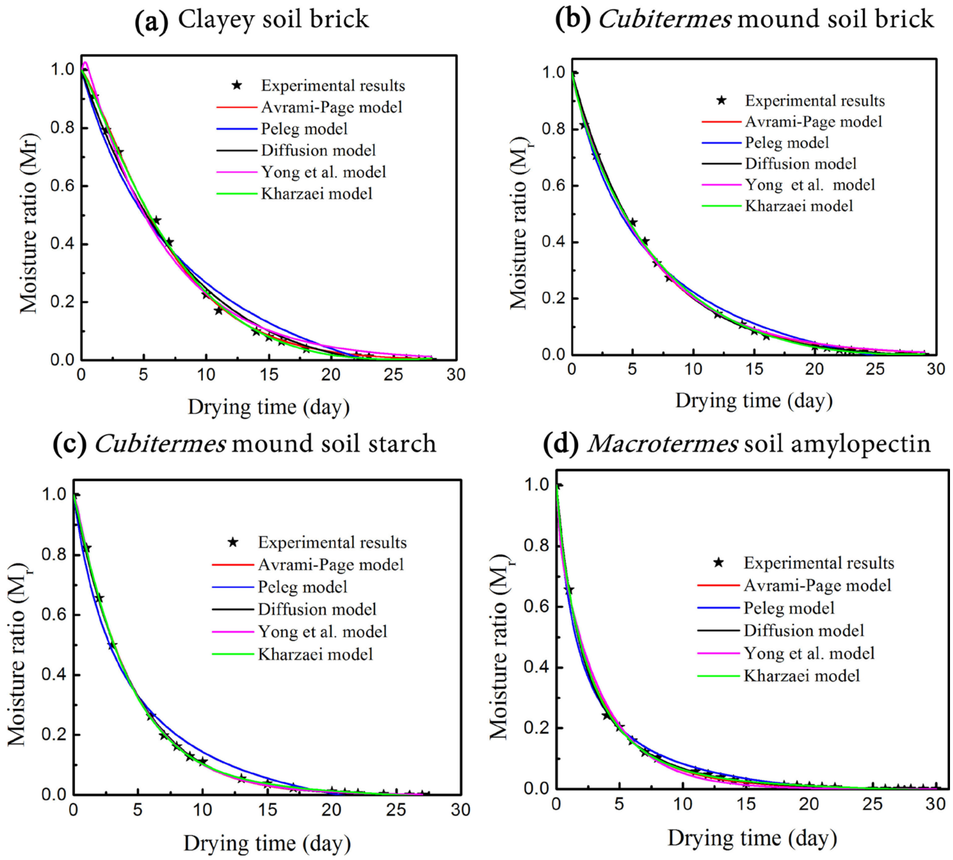

Figure 3. Drying kinetics of earth bricks modeled with the Avrami-Page's model, the diffusion, the Yong et al. and the Khazaei ones.

As already mentioned in the chapter Materials and methods, the values of the effective coefficient of diffusion of water (D_{ef}) had been deduced from the parameter k of the diffusion model. These values are listed in Table 5.

For all earth bricks, adding cassava flour gel or amylopectin increases the value of the effective coefficient of diffusion of the bricks. For the same percentage, in average, the increase in value due to cassava flour gel is higher than that due

Table 2. Values of the coefficient of determination (R^2), the Chi square (χ^2) and the Aike's Information criterium of the drying kinetics of earth bricks modeled with Avrami-Page, diffusion, Yong and Khazaei models. N = Natural clayey soil; C = *Cubitermes* mound soil; M = *Macrotermes* mound soil; 0, 5, 10, 15 and 20 are cassava flour gel (S) and amylopectin gel (A) contents used as a stabilizer.

CEB	Yong			Avrami-Page			Peleg			Khazaei			Diffusion		
	R^2	χ^2 (10^{-4})	AIC	R^2	χ^2 (10^{-4})	AIC	R^2	χ^2 (10^{-4})	AIC	R^2	χ^2 (10^{-4})	AIC	R^2	χ^2 (10^{-4})	AIC
N0	0.993	10.1	−102	0.998	2.6	−126	0.985	21.3	−93	0.999	1.1	−134	0.995	7.0	−108
NS5	0.996	4.5	−115	0.998	2.0	−131	0.986	16.3	−97	0.998	2.3	−123	0.996	4.9	−114
NS10	0.995	5.9	−111	0.997	3.5	−121	0.984	17.6	−96	0.997	4.0	−114	0.996	4.8	−114
NS15	0.997	4.2	−116	0.998	2.7	−126	0.966	41.7	−82	0.999	1.1	−135	0.992	0.0	−100
NS20	0.998	2.1	−118	0.999	1.3	−128	0.948	51.9	−73	1.000	0.0	−135	0.987	0.0	−90
NA5	0.996	4.6	−170	0.998	1.6	−196	0.986	14.0	−146	0.999	0.9	−205	0.998	2.4	−184
NA10	0.998	1.9	−155	0.999	1.2	−166	0.998	1.4	−163	0.999	0.9	−168	0.999	0.9	−170
NA15	0.999	0.8	−176	0.999	0.7	−181	0.998	2.0	−137	0.999	0.5	−174	1.000	0.4	−177
NA20	0.999	0.6	−172	0.999	0.5	−175	0.994	5.6	−157	0.999	0.6	−178	0.999	0.6	−183
C0	0.993	8.1	−128	0.994	6.6	−134	0.990	10.6	−125	0.998	2.0	−152	0.996	4.1	−141
CS5	0.999	1.8	−148	0.999	1.6	−151	0.974	29.1	−100	0.999	1.3	−150	0.996	5.2	−128
CS10	0.999	1.2	−154	0.999	1.3	−155	0.984	16.9	−109	0.999	1.1	−154	0.998	2.1	−145
CS15	0.996	3.1	−121	0.997	2.5	−127	0.989	8.5	−107	1.000	0.4	−151	0.999	1.2	−137
CS20	0.998	2.3	−117	0.998	2.1	−121	0.984	14.5	−92	1.000	0.3	−146	0.999	0.8	−132
CA5	0.999	1.5	−186	0.999	1.1	−195	0.989	11.2	−144	1.000	5.7	−206	0.999	0.7	−202
CA10	1.000	0.5	−211	0.999	0.6	−208	0.988	10.7	−145	1.000	0.2	−232	0.999	0.7	−204
CA15	0.997	2.1	−153	0.997	2.3	−153	0.977	16.9	−116	1.000	0.4	−185	0.996	2.8	−148
CA20	0.999	1.1	−175	0.999	1.0	−180	0.981	14.4	−125	0.999	1.0	−175	0.999	1.2	−173
M0	0.998	1.7	−183	0.998	1.3	−191	0.990	8.0	−152	0.999	0.5	−207	0.999	0.8	−201
MS5	0.997	2.3	−178	0.998	1.4	−191	0.993	5.5	−160	0.999	0.9	−195	0.999	1.0	−196
MS10	0.997	1.9	−190	0.999	0.7	−216	0.997	2.1	−190	0.999	0.6	−215	1.000	0.3	−235
MS15	0.997	1.8	−174	0.999	0.4	−187	0.999	0.5	−146	1.000	0.1	−201	1.000	0.2	−189
MS20	0.999	0.7	−156	0.999	0.4	−156	0.994	3.5	−181	1.000	0.3	−217	1.000	0.2	−203
MA5	0.999	0.6	−156	1.000	0.5	−164	0.991	9.0	−114	1.000	0.5	−159	1.000	0.4	−163
MA10	0.994	6.6	−117	0.993	7.3	−117	0.976	23.7	−97	0.995	0.5	−117	0.993	7.5	−114
MA15	0.992	5.7	−142	0.994	4.1	−150	0.990	6.9	−140	0.998	1.4	−167	0.998	1.4	−170
MA20	0.995	4.6	−115	0.998	1.9	−131	0.997	2.3	−128	0.999	1.3	−132	0.999	0.6	−147

Table 3. The models' ranking for bricks stabilized with cassava flour gel. N = Natural clayey soil; C = *Cubitermes* mound soil; M = *Macrotermes* mound soil; Kh = Khazaei model; Av = Avrami-Page model; Di = Diffusion model; Pe = Peleg model.

Rank	N			C			M		
	R^2	χ^2	AIC	R^2	χ^2	AIC	R^2	χ^2	AIC
1	Kh	Kh	Kh	Kh	Kh	Kh	Di	Kh	Di
2	Av	Av	Av	Di	Di	Di	Kh	Av	Av
3	Yo	Yo	Yo	Av	Av	Av	Av	Di	Kh
4	Di	Di	Di	Yo	Yo	Yo	Yo	Yo	Yo
5	Pe	Pe	Pe	Pe	Pe	Pe	Pe	Pe	Pe

Table 4. The values of the models' parameters.

CEB	Khazaei				Avrami-Page		Diffusion			Yong		
	a	T	n	b (10^{-4})	k	n	a	k	b	C	μ	dc
N0	1.16	8.44	1.16	−54	0.08	1.25	−36.14	0.08	1.01	1.10	−0.01	6.25
NS5	1.04	6.77	1.16	−14	0.11	1.20	−29.74	0.10	1.01	1.08	−0.01	5.74
NS10	1.07	6.12	1.10	−26	0.14	1.15	−32.62	0.12	1.01	1.05	−0.01	5.21
NS15	0.95	4.33	1.21	21	0.17	1.15	−16.13	0.15	1.02	1.10	−0.01	4.08
NS20	0.96	3.68	1.41	17	0.17	1.31	−41.65	0.18	1.01	1.33	−0.04	2.82
NA5	1.16	7.94	1.10	−51	0.10	1.19	−14.44	0.09	1.03	1.08	−0.01	5.93
NA10	1.05	5.69	0.97	−15	0.19	1.01	−0.01	0.03	7.21	0.99	0.00	5.29
NA15	1.01	4.27	0.91	−0.3	0.27	0.92	0.92	0.21	6.49	0.94	0.01	4.65
NA20	1.03	3.92	0.87	−9	0.31	0.89	0.89	0.23	7.83	0.91	0.01	4.29
C0	1.32	9.17	0.87	−81	0.16	0.99	−0.01	0.01	23.53	0.97	0.00	6.41
CS5	0.97	5.14	0.99	14	0.19	0.99	0.00	0.01	30.10	1.00	0.00	5.33
CS10	0.95	4.18	1.08	20	0.21	1.04	−11.38	0.19	1.01	1.03	0.00	4.30
CS15	0.93	3.14	1.13	30	0.29	0.97	0.10	0.13	2.42	1.00	0.00	3.55
CS20	0.96	2.48	1.03	18	0.39	0.96	0.11	0.15	2.73	0.98	0.00	2.80
CA5	1.06	6.25	0.97	−18	0.17	1.02	−0.06	0.07	2.49	1.00	0.00	5.65
CA10	0.95	4.22	1.09	18	0.21	1.03	0.00	0.06	4.01	1.03	0.00	4.38
CA15	0.96	3.84	1.20	14	0.21	1.11	−20.51	0.20	1.01	1.12	−0.02	3.54
CA20	1.00	3.17	1.02	0.8	0.29	1.05	−5.13	0.26	1.03	1.02	0.00	3.12
M0	0.99	4.18	0.92	6	0.26	0.92	0.82	0.20	3.10	0.18	0.61	0.32
MS5	0.95	3.10	0.92	19	0.35	0.86	0.46	0.18	2.70	0.89	0.02	4.09
MS10	0.97	2.63	0.84	12	0.44	0.80	0.49	0.20	3.54	0.85	0.02	3.66
MS15	0.98	1.78	0.70	7	0.66	0.68	0.39	0.21	5.24	0.68	0.06	3.48
MS20	0.98	1.81	0.89	9	0.61	0.82	0.25	0.24	2.78	0.77	0.04	2.56
MA5	0.97	3.42	0.93	10	0.31	0.91	0.63	0.21	2.38	0.93	0.01	3.98
MA10	0.88	2.52	1.28	48	0.32	0.97	0.16	0.14	2.63	1.04	0.00	3.08
MA15	0.96	2.13	0.91	17	0.50	0.82	0.36	0.20	3.26	0.87	0.02	2.86
MA20	0.96	1.75	0.87	20	0.60	0.79	0.33	0.23	3.44	0.79	0.03	2.65

to amylopectin. Besides, the effective coefficient of diffusion is highest for *Macrotermes* mound soil bricks, followed in order by *Cubitermes* mound soil ones, and natural clayey soil ones. The increase of the effective coefficient of diffusion with the addition of the cassava flour gel or amylopectin is the consequence of the fast-drying kinetics of these products in comparison to that of non-stabilized soils. Care must be taken for comparing values of the coefficient of diffusion because they depend on the material moisture content, the temperature and the method used to measure them. Data on drying of earth bricks are scarce. Our

Table 5. The values of the effective coefficient of diffusion of water in earth bricks stabilized with cassava flour gel ($D_{ef\ flour}$) and those stabilized with amylopectin ($D_{ef\ amylo}$).

CEB	$D_{ef\ flour}$ (10^{-5} m^2/s)	$D_{ef\ amylo}$ (10^{-5} m^2/s)
M0	3.88	3.88
M5	5.24	4.75
M10	6.18	6.44
M15	9.10	7.60
M20	8.96	9.26
C0	1.77	1.77
C5	3.16	2.60
C10	3.88	3.84
C15	5.16	4.23
C20	6.56	5.11
N0	1.92	1.92
N5	2.40	2.04
N10	2.65	2.85
N15	3.75	3.80
N20	4.41	4.14

values are higher than those of tropical woods, vegetables, and plant fibers [21] [24] [26] [30].

Figure 4 shows four examples of characteristic curves of these earth bricks. All relationships are nearly linear and f = M_r, with a coefficient of determination R^2 = 0.99 and a standard deviation SD = 0.02. These curves look like those predicted for thick samples and slow drying by Keey and Suzuki [24]. The linear relationship between f and M_r, instead of the concave shape, could be explained by the absence of the constant drying rate phase in these drying kinetics curves. Thus, the ratio v(t)/v(0) decreases continuously. On other words, earth bricks are not saturated with water. This result is consistent with the fact that these drying kinetics are driven by water diffusion.

Besides, the unified expression of Yong et al. fits well all drying kinetics curves of these drying curves. Figure 5 shows some of these curves.

3.3. Relationships between the Models' Parameters and the Drying Duration and the Stabilizer Content

The Khazaei's model, the Avrami-Page, and the diffusional models are all exponential. When the time exponent n = 1 as for these drying kinetics, the coefficients K of the diffusional model, and that of the Avrami-Page model, and the coefficient 1/T of the Kharzaei one have the same function. Thus, in the sequel, only the correlations between T and the stabilizer content, and the drying duration are reported because this model is the best for these drying kinetics. Figure 6 illustrates the evolution of T according to the stabilizer content and the drying duration.

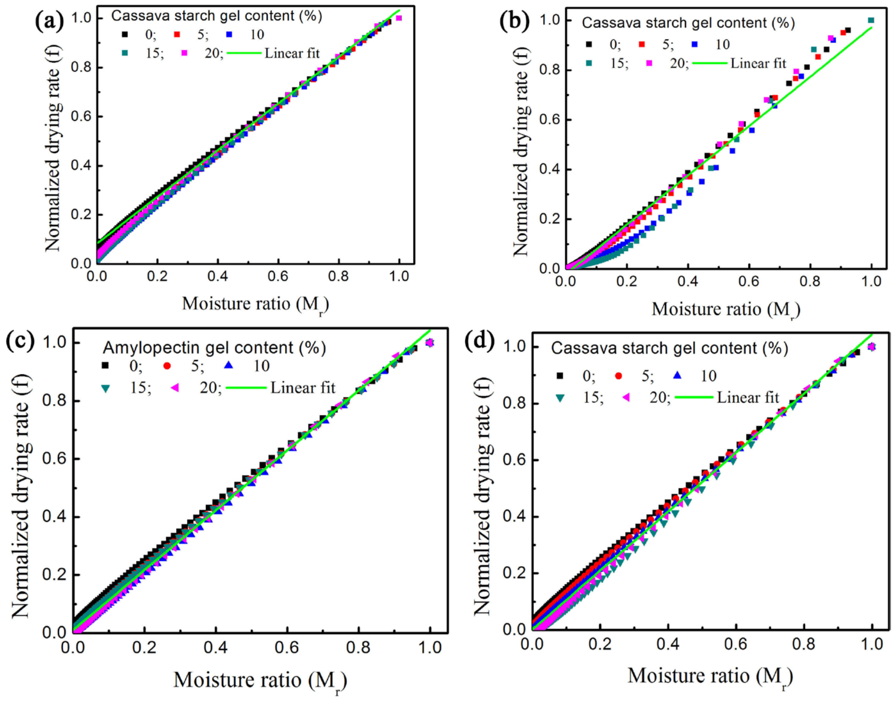

Figure 4. Characteristic drying curves of earth bricks manufactured with: (a) the natural clayey soil stabilized with cassava flour gel; (b) *Macrotermes* mound soil stabilized with cassava flour gel; (c) *Cubitermes* mound soil stabilized with amylopectin; (d) *Cubitermes* mound soil stabilized with cassava flour gel.

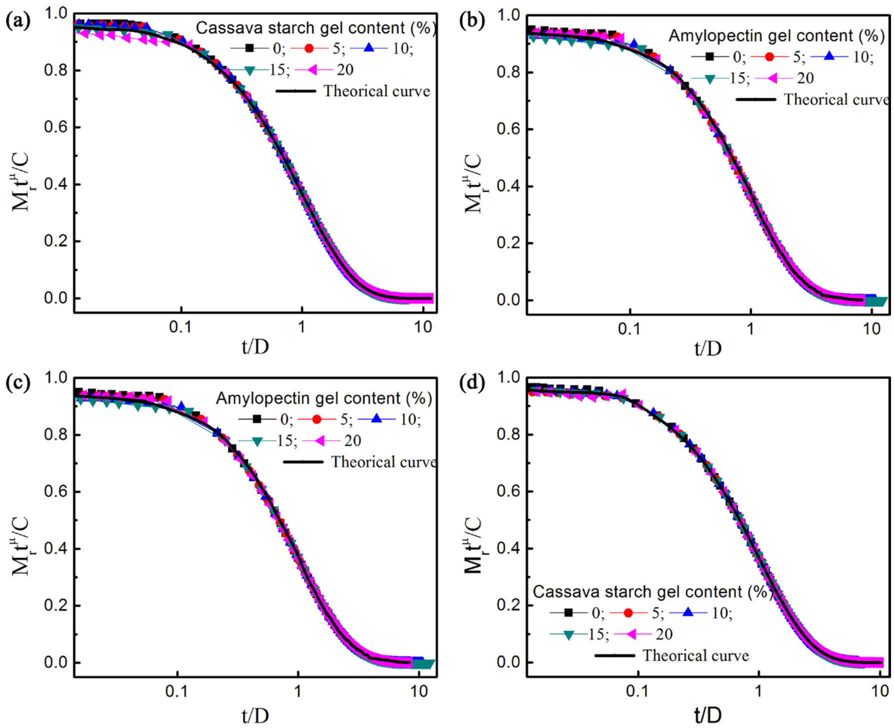

Figure 5. Unified expression of Yong's model applied to drying curves of earth bricks manufactured with: (a) the natural clayey soil stabilized with cassava flour gel; (b) *Macrotermes* mound soil stabilized with cassava flour gel; (c) *Cubitermes* mound soil stabilized with amylopectin; (d) *Cutitermes* mound soil stabilized with cassava flour gel.

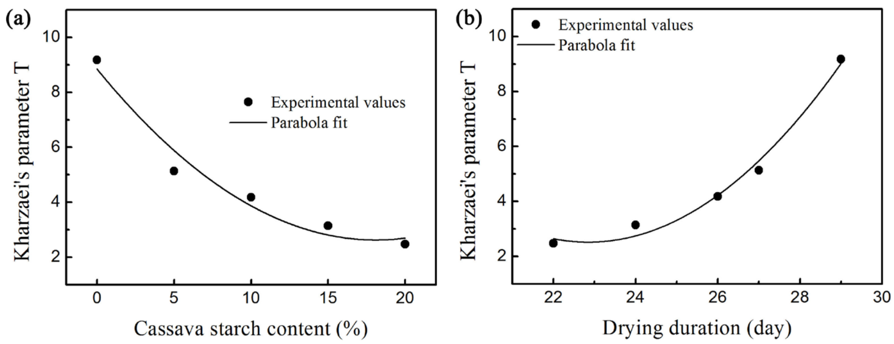

Figure 6. Evolution of the parameter T of Khazaei's model according to: (a) cassava flour gel content; (b) the drying duration.

Table 6. Relationships between the parameter T of the Khazaei's model and the drying duration (t) and the stabilizer content (x). N = Natural clayey soil; C = *Cubitermes* mound soil; *Macrotermes* mound soil; A = amylopectin; S = Cassava flour gel.

CEB	T vs duration	R^2	T vs stabilizer content	R^2
NA	$0.46t^2 - 23t + 283$	0.98	$0.002x^3 - 0.05x^2 + 0.09x + 8.5$	0.99
CA	$0.36t^2 - 18t + 227$	0.98	$0.02x^2 - 0.64x + 9.1$	0.98
MA	$0.34t - 6$	0.98	$-0.12x + 4$	0.97
NS	$1.4t - 32$	0.97	$-0.24x + 8.26$	0.97
CS	$0.17t^2 - 7.8 + 92$	0.98	$0.02x^2 - 0.69 + 8.8$	0.97
MS	$0.13t^2 - 6t + 77$	0.98	$0.01x^2 - 0.23x + 4.2$	0.98

Relationships between T and the stabilizer content and the drying duration are reported in Table 6. For all drying kinetics, T decreases when the cassava flour gel content or the amylopectin content increases. In addition, slower is the drying kinetics, higher is T. This result could be explained by: 1) T is inversely proportional to the initial drying rate ($V(0) = a/T - b$); 2) adding cassava flour gel or amylopectin increases the drying rate. Thus, adding cassava flour or amylopectin decreases the T value and the drying duration.

4. Conclusion

The aim of this work was to assess the effect of adding the cassava flour gel and the amylopectin in earth bricks on their drying kinetics and to model the drying kinetics. The results show that: 1) the drying duration decreases with the increasing of the stabilizer content. For the content of 20% and in comparison to non-stabilized bricks, this decrease varies from 2 to 7 days depending on the soil and the stabilizer. Termite mound soils have the greatest decrease, and the cassava flour gel is more effective than amylopectin; 2) all the five models used fit well the earth brick drying kinetics, with the coefficient of determination higher than 0.997 and the chi square inferior to 3×10^{-4}. The Khazaei's model is the best, followed in order by the diffusion, the Avrami-Page, the Yong and the Peleg ones. The characteristic drying curve of these earth bricks is nearly linear ($f = M_r$). The average value of the coefficient of diffusion deduced is 4×10^{-5} $m \cdot s^{-2}$.

The parameter T of the Khazaei's model is strongly correlated to the drying duration and the stabilizer content.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] UN-Habitat. (2009) The Right to Adequate Housing. Fac Sheet No. 21/Rev. 1. http://www.ohchr.org

[2] UN-Habitat. (2008) The State of African Cities: A Framework for Addressing Urban Challenges in Africa. United Nations Human Settlements Programme (UN-HABITAT).

[3] Hadjri, K., Osmani, M., Baiche, B. and Chifunda, C. (2007) Attitude towards Earth Building for Zambian Housing Provision. *Proceeding of the Institutions of Civil Engineers*: *Engineering Sustainability*, **160**, 141-149. https://doi.org/10.1680/ensu.2007.160.3.141

[4] Van Damme, H. and Houben, H. (2017) Earth Concrete. Stabilization Revisited, Cement and Concrete Research.

[5] Bc Delgado, M.C.J. and Guerrero, I.C. (2007) The Selection of Soils for Unstabilised Earth Building: A Normative Review. *Construction and Building Materials*, **21**, 237-251. https://doi.org/10.1016/j.conbuildmat.2005.08.006

[6] Houben, H. and Guillaud, H. (1994) Earth Construction: A Comprehensive Guide. Intermediate Technology Publications, London.

[7] Bryan, A.J. (1988) Criteria for the Suitability of Soil for Cement Stabilization. *Building and Environment*, **23**, 309-319. https://doi.org/10.1016/0360-1323(88)90037-6

[8] Bell, F.G. (1996) Lime Stabilization of Clay Minerals and Soils. *Engineering Geology*, **42**, 223-237. https://doi.org/10.1016/0013-7952(96)00028-2

[9] Laborel-Préneron, A., Aubert, J.E., Magniont, C., Tribout, C. and Bertron, A. (2016) Plant Aggregates and Fibers in Earth Construction Materials: A Review. *Construction and Building Materials*, **111**, 719-734.

[10] Riza, F.V., Rahman, I.A., Zaidi, A.M.A. and Loo, L.Y. (2013) Effect of Soil Type in Compressed Earth Brick (CEB) with Uncontrolled Burnt Rice Husk Ash (RHA). *Advanced Materials Research*, **626**, 971-975. https://doi.org/10.4028/www.scientific.net/AMR.626.971

[11] Namango, S.S. (2006) Development of Cost-Effective Earthen Building Material for Housing Wall Construction: Investigations into the Properties of Compressed Earth Blocks Stabilized with Sisal Vegetable Fibres, Cassava Powder and Cement Compositions. Thesis, Doctor-Ingenieur. Brandenburg Technical University Cottbus.

[12] de Carvalhoa, A.J.F., Curveloa, A.A.S. and Agnell, J.A.M. (2001) A First Insight on Composites of Thermoplastic Starch and Kaolin. *Carbohydrate Polymers*, **45**, 189-194. https://doi.org/10.1016/S0144-8617(00)00315-5

[13] Husband, J.C. (1998) The Adsorption of Starch Derivatives onto Kaolin. *Colloids and Surfaces A*: *Physicochemical and Engineering Aspects*, **131**, 145-159. https://doi.org/10.1016/S0927-7757(96)03881-2

[14] Wilhelma, H.-M., Sierakowskia, M.-R., Souzab, G.P. and Wypych, F. (2003) Starch

Films Reinforced with Mineral Clay. *Carbohydrate Polymers*, **52**, 101-110. https://doi.org/10.1016/S0144-8617(02)00239-4

[15] Mbey, J.A., Hoppe, S. and Thomas, F. (2012) Cassava Starch-Kaolinite Composite Film. Effect of Clay Content and Clay Modification on Film Properties. *Carbohydrates Polymer*, **88**, 213-222. https://doi.org/10.1016/j.carbpol.2011.11.091

[16] NF P94-051 (1993) Soils: Investigation and Testing—Determination of Atterberg Limits—Liquid Limit Test Using Casagrande Apparatus—Plastic Limit Test on Rolled Thread. Association Française de Normalisation (AFNOR). http://www.afnor.fr

[17] NF P94-056 (1996) Soil: Investigation and Testing—Granulometric Analysis—Dry Sieving Method Washing. Association Française de Normalisation (AFNOR). http://www.afnor.fr

[18] NF P94-057 (1992) Analyse granulométrique des sols. Méthode par sédimentation. Association Française de Normalisation (AFNOR). http://www.afnor.fr

[19] NF P94-093 (1999) Soils: Investigations and Testing—Determination of Compaction Characteristics of Soil—Standard Proctor Test—Modified Proctor Test. Association Française de Normalisation (AFNOR). http://www.afnor.fr

[20] Avrami, M. (1940) Kinetics of Phase Change. II Transformation-Time Relations for Random Distribution of Nuclei. *The Journal of Chemical Physics*, **8**, 212-224. https://doi.org/10.1063/1.1750631

[21] Erbay, Z. and Icier, F. (2009) A Review of Thin Layer Drying of Foods: Theory, Modeling and Experimental Results. *Critical Reviews in Food Science and Nutrition*, **505**, 441-464.

[22] Crank, J. (1975) The Mathematics of Diffusion. Oxford University Press, Oxford.

[23] Peleg, M. (1988) An Empirical Model for Description of Moisture Sorption Curves. *Journal of Food Science*, **53**, 1216-1217. https://doi.org/10.1111/j.1365-2621.1988.tb13565.x

[24] Elenga, R.G., Dirras, G.F., Goma Maniongui, J. and Mabiala, B. (2011) Drying of Raffia Fiber. *BioRessources*, **6**, 4135-4144.

[25] Khazaei, J. and Daneshmandi, S. (2007) Modeling of Thin-Layer Drying Kinetics of Sesame Seeds: Mathematical and Neural Networks Modeling. *International Agrophysics*, **21**, 335-348.

[26] Elenga, R.G., Massamba, D., Niéré, R.R., Goma Maniongui, J. and Dirras, G.F. (2013) Convective and Microwave Dryings of Raffia Fruit: Modeling and Effects on Color and Hardness. *Research Journal of Applied Sciences, Engineering and Technology*, **6**, 2715-2723. https://doi.org/10.19026/rjaset.6.3776

[27] Li, Y., *et al.* (2017) A Unified Expression for Grain Size Distribution of Soils. *Geoderma*, **288**, 105-119. https://doi.org/10.1016/j.geoderma.2016.11.011

[28] Keey, R.B. and Suzuki, M. (1974) On the Drying Characteristic Curve. *International Journal of Heat and Mass Transfer*, **17**, 1455-1464. https://doi.org/10.1016/0017-9310(74)90055-6

[29] Langrish, T.A.G. (2008). Characteristic Drying Curves for Cellulosic Fibres. *Chemical Engineering Journal*, **137**, 677-680. https://doi.org/10.1016/j.cej.2007.07.001

[30] Nsouandélé, J.L., Bonoma, B., Simo Tagne, M. and Njomo, D. (2010) Determination of Diffusion Coefficient of Water in Tropical Woods. *Physical and Chemical News*, **54**, 61-67.