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Design, Fabrication and Evaluation of a Mini-Silo for Cowpea Storage in Mubi Area of Adamawa State, Nigeria

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Abstract: Mubi is one of the cowpea producing areas in Adamawa State, Nigeria. However, a considerable percentage of the harvested beans are lost at various levels of handling due to agents of deterioration as well as the rudimentary postharvest techniques and storage facilities. Farmers and grain handlers have employed various approaches for enhancing the storability of harvested grains; some of their methodologies are associated with limitations and challenges. In view of these, a deep-type, mini-silo was designed, fabricated and evaluated for the storage of Cowpea in Mubi area of Adamawa State. The silo was designed to withstand buckling and excessive heat transfer to the stored grains and it has a storage capacity of 1.517m^3 and a headspace volume of 0.198m^3. It was evaluated in terms of the relative humidity and temperatures of the headspace and the ambient environment. Results indicate that metal silo could be an alternative to the unethical use of hazardous chemicals for the preservation of beans.

Keywords: Metal silo, Cowpea, beans, Mubi, Relative humidity

I. Introduction

Mubi area is one of the beans producing areas in Adamawa state, Nigeria. Like other agricultural materials, beans is surplus at the harvest season around November and December, however between the month of February through October it becomes scarce in the market due to agents of deterioration such as termites, rodents, insects and meteorological factors (temperature and relative humidity) [1]. In Africa for example, an estimate of postharvest losses in maize alone accounts for over four billion United States dollars, an equivalent of what Africa received annually in food aid [2]. The main causes of postharvest deterioration in grains are pests (insects, rodents, birds and termites), moisture and temperature, fungi, inadequate handling and storage facility [3]. Scarcity of these commodities is apparently associated with hikes in prices, causing a reasonable number of grain handlers to resort to the application of unapproved harmful chemicals in order to preserve or enhance the storability of agricultural produce at the expense of humans' health ([1], [4]). Earlier, small-scale farmers used jute sacks, baskets, earthen pots and gourds to store materials, but their storage capacity was the major challenge in addition to their inability to prevent reasonable moisture migration across its walls of such storage structures [5]. Comparably later, it was suggested that storing grains in polyvinyl films enhances its storability based on atmospheric modification; however, such method does not adequately protect grains from insect, termites' or rodents damage.

The suitability or otherwise of any storage structure depends on the climatic/ meteorological parameters existing in the region of the intended storage, and on the nature of the materials to be stored. Reference [6] investigated the comparative performance of termites' mud clay, reinforced concrete and galvanized steel for a storage period of eight months, their study revealed that though metal silo is most suitable considering the airtight environment created by its walls. However, its grain headspace indicated an increase in relative humidity from 54.1 to 64.7% with a corresponding decline in temperature from 30.3 to 27.7^{o}C within eight months. In a related study on a wooden silo, References [4],[7] identified the following as necessary parameters to investigate in assessing the performance of a storage silo – colour, joints, overturning of structure, foundation settlement and deflection of the silo floor.

Considering the growth rate of population and the challenges of postharvest losses encountered in grains as well as other agricultural materials, there is the need to develop a storage structure that could be used to store grains and at the same time withstand the challenge posed by meteorological factors at least in Mubi area. Metal silo offers the following advantages- adequate maintenance of product quality during storage, it is airtight and allows for

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effective fumigation with non-residual fumigants, insecticides application is unnecessary, it requires little space and it offers perfect protection against rodents and moisture [8]. However, the cost of the European brands of silos are beyond the reach of small-scale farmers in this area of the country, thus, the need to construct one from locally available materials to cut down on the cost of the structure. Other reasons in favour of this project are cost-effectiveness, ease of operation and maintenance and availability of materials for construction.

1.1 Design Objectives

The metal silo was designed with the following objectives – to develop a silo that is suitable for storing a wide range of granular agricultural materials with maximum safety measures, airtight silo with ease of loading and offloading. The silo was designed to minimize the quantity of heat flow across the silo walls (from outside) even during the hottest months of the storage period.

II. Design Variables

The following design variables were determined/estimated for the developed metal silo: hopper/wall thickness stresses, sheet thickness, thickness of lagging material, and silo capacity.

2.1 Description of the metal silo and agricultural material materials

The designed silo is deep/slender in nature (H_d > 4R; R = hydraulic radius, A/P, H_d = 3 m; 4R = 0.75 m) ([3], [5]). The cylindrical shape selected for the silo because of ease of construction and economy of installation space and its design capacity was 1.517 m^2. Considering the bulk densities of various granular agricultural materials - millet (720kg/m^3), rough rice (580 kg/m^3), wheat (770 kg/m^3), and beans/ cowpea (800 kg/m^3); the designed silo can store 1,092.24kg (millet), 879.86 (rough rice), 1,168.09kg (wheat), 1,213.6 kg (cowpea) at postharvest moisture content of 12% (w.b).

2.2 Stresses on Silo Wall and Hopper

Silo walls are subjected to both vertical and horizontal loads; vertical load due to friction between the stored grain and the silo wall, while the horizontal load is due to lateral thrust. The vertical and the horizontal pressures on the silo wall and bottom were estimated as 11.554kN/m^2 and 9.94 kN/m^2 respectively in accordance with Janssen, who developed equations based on the vertical equilibrium of a horizontal slice through stored material [9].

$$P_V = \left[\frac{\gamma A}{U\mu\, k_s}\right]\left[e^{k_s \mu z U/A}\right] \qquad (1)$$

Initially, lateral pressure on the silo wall was estimated only in terms of grain density and depth as $p_{ho} = Wh$; however, silos buckle under horizontal loads due to the friction of grains on the wall. Reference [10] noted that buckling failure in silos is caused more by eccentric loading than by any other cause; eccentric loading/discharge is common with shallow silos (H_d < 4R). A better formula for lateral pressure was developed by incorporating the Rankine coefficient, $K_s = \frac{1-Sin\theta}{1+Sin\theta}$

$$p_{ho} = K_s Wh \times r \qquad (2)$$

Where A = Cross-sectional area of silo (0.44m^2), μ = coefficient of friction between cowpea grain and silo wall (0.388), U = Internal perimeter of the silo (2.35m), P_{ho} = horizontal pressure on the silo wall (N/m^2), k_s = ratio of horizontal to vertical pressure (0.422), W = bulk density of cowpea (800kg/m^3), h = grain depth (3 m), r = silo radius (0.374 m), θ= angle of repose of cowpea (24^o) [11].

Silos of circular cross-section carry lateral forces by hoop tension and are more likely to fail by tension under excessive vertical load. The circumferential wall stress of silo with diameter less than five meters (D < 5 m) can be estimated using the membrane theory, which assumes that silo wall, is subjected to tensile force only [9].
Hoop tension was estimated using equation (3) and was found to be 3.72kN/m

$$T_h = rP_{ho} \qquad (3)$$

Where T_h = hoop tension (N/m), P_{ho} = horizontal pressure on the vertical wall section after filling the silo (9.94kN/m^2), r = silo radius (0.374 m)
None of the estimated stresses exceeded its permissible value; thus, the thickness of the sheet metal was estimated from equation (4)

$$t = \frac{D\{(g\rho_b * H) + P_H\} * 10}{\sigma_{permissible}} \quad (4)$$

Where t = sheet thickness (m), H = height of the material/grain above the bottom (3m), $\sigma_{permissible}$ = allowable/permissible design stress (415 MN/m^2), P = Horizontal pressure (4.8755kN/m^2), g = acceleration due to gravity (9.81 m/s^2).

2.2.1 Sheet Thickness

Reference [3] demonstrated that sheet thickness as low as 0.5mm (Gauge 25) can be used to construct a metal silo; due to its high resistance to corrosion. Consequently, in this study minimize the thickness of 2.059 *10^{-3}m was estimated {slightly beyond gauge 14 (1.897mm) but thinner than gauge 12 (2.656 mm)}; so gauge 12 (2.656 mm) sheet thickness was selected to enhance its strength against buckling.

2.2.3 Silo Capacity Estimation

The capacity of the silo was estimated from the volume of the cylindrical portion and that of the hopper/frustum (equation 5)

$$V_s = V_c + V_f \quad (5)$$

Where V_s= Volume of the metal silo (m^3), V_c =Volume of the cylindrical portion of the silo (m^3), V_f = Volume of the conical frustum portion (m^3)

But, $V_c = \pi r^2 h$ (6)

Where r = radius of the cylindrical portion (m), h = height of the cylindrical portion (m)

For a silo radius of 0.374 m and height of 3m, the volume of the cylindrical portion was V_{c1}= 1.319m^3. During silo evaluation, the temperature of the inside environment was determined by inserting thermometers into the silo's headspace; so a depth of 45 cm was allowed and the volume of the allowed depth, $V_{c2(r = 0.375m,\ h = 0.45\ m)}$ = 0.198 m^3 (equivalent to 15% of the cylindrical portion). Thus, the total volume of the cylindrical portion $V_{cy} = V_{c1} + V_{c2}$ = 1.517 m^3.

The volume of the hopper (conical frustum) was estimated from equation (7).

$$V_f = \frac{\pi h}{3}(R^2 + Rr + r^2) \quad (7)$$

Where R = base (larger) radius of the frustum (m), r = radius of the smaller circle of the frustum (m), h = height of the frustum (m)

The silo was designed for full flow pattern; in consequence, the base slope was selected to be 50^o and the chute angle was set at 40^o so that even materials of low flow-ability could be emptied easily ([12], [11]). For the base slope of 50^o, R = 0.374m, and r = 0.0.294m the height of the frustum based on the similarity of triangles was h = 0.35 m. Applying equation (7), the volume was calculated as V_f = 0.125 m^3; thus, the total volume of the silo, Vs = 1.517 m^3.

2.2.4 Thickness of Lagging Material

For safe storage of grains, the temperature of the storage environment should not exceed room temperature (25 – 28^{o}C) [7]. Considering the mean maximum daily temperature of the hottest month in Mubi (39^{o}C) during from a five years data, the thickness of lagging material (sawdust) was calculated based on Fourier's law of heat transfer by conduction thick cylindrical wall using equation (8) in accordance with Reference [12].

$$q = -kA\frac{dT}{dr} \quad (8)$$

Where,

A = surface area of the cylindrical silo (= $2\pi rL$) at distance, and thickness, dr; r = radius of the inner wall of the silo (m), L = length of the silo (m), K = thermal conductivity of sawdust (W/m K)

By integration,

$$q \int_{r_1}^{r_2} \frac{dr}{r} = -2\pi rL \int_{T_1}^{T_2} dT$$

(9)

Nevertheless, for adequately dried grains, $T_2 > T_1$ (ambient air temperature is greater than grain temperature); thus, the negative sign above can be omitted. As assumed, earlier that only adequately dried grain is stored, and that the grain was adequately fumigated, provided there is sufficient lagging, the difference in temperature between the stored grain and the inner wall of the silo would be negligible. Therefore, T1 will be the temperature of the entire environment enclosed by the lagging material.

Where r_2 = outer radius of the lagging material (m), T_2 = maximum ambient air temperature of the hottest month in Mubi (^oC)

Therefore, $$q = \frac{2\pi rLk\ (T_2 - T_1)}{ln\left(\frac{r_2}{r_1}\right)} \quad (10)$$

$$ln\left(\frac{r_2}{r_1}\right) = \frac{2\pi rL\ k(T_2 - T_1)}{q}$$

Assuming a unit heat flow rate (q = 1J/s),

$$ln\left(\frac{r_2}{r_1}\right) = \pi rLk\ (T_2 - T_1) \quad (11)$$

Therefore $\frac{r_2}{r_1} = e^{\pi rLk\ (T_2 - T_1)}$

And $r_2 = r_1 e^{\pi rLk\ (T_2 - T_1)}$

As $r \rightarrow 0$ (as r becomes smaller), it could be assumed to be a smaller percentage of r_1; for example r = 0.1 % of r_1 = 0.001 r

Therefore, $$r_2 = r_1 e^{0.1\,\pi r_1 Lk\ (T_2 - T_1)} \quad (12)$$

The thickness of the lagging material was estimated in terms of the thermal conductivity of the lagging material (sawdust) (k), length of the silo that would be lagged (L), the temperature difference between the ambient environment (T_2). Other parameters included, the desired temperature of the inside environment of the designed silo (T_1), and in terms of the radius of the inner wall of the silo.

$T_2 = 39^oC$ (highest temperature of Mubi in warmest/hottest month, April), $T_1 = 28^o C$ (safe temperature for safe storage of dried beans) [1], L = 3m, and K= 0.6 W/mK [13].

Using equation (12), $r_2 = 0.695$ m

Therefore, the thickness of the lagging material ($r_2 - r_1$) = 0.37 m = 3.74 cm

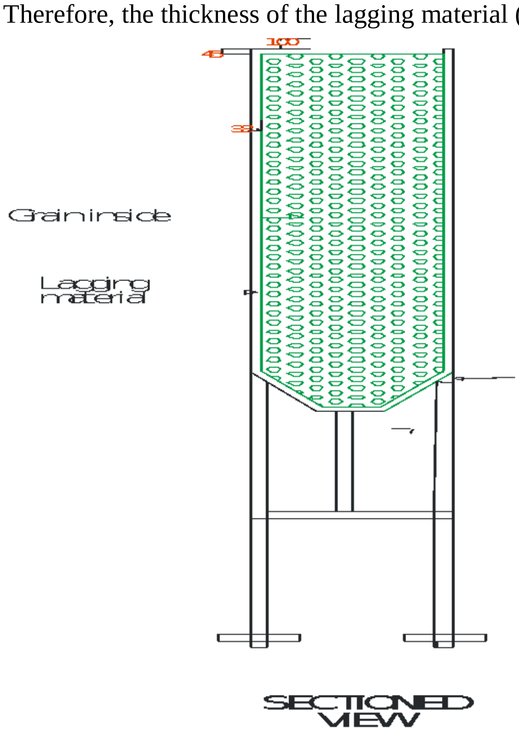

Figure 1, Sketch of the designed silo

2.3 Construction of Metal Silo

The first step was using the square to check the corners of the sheet metals; where the corner was not 90^o, the small amount necessary to make the end of the sheet square was cut off. Using the tape, the pattern was measured and all the silo parts were marked off and labelled appropriately before cutting. For the cutting, hammer, chisel and shear were used.

The seam/ folding method was used for joining the silo body which involves marking off a gauge of 8 mm mark along the edge to be folded (i.e. parallel to the axis of the cylindrical portion of the silo). The base was constructed by first marking out and off a sector of radius 0.812 m and a perimeter of 2.35m. To ensure full flow pattern of grain under its own weight, the hopper was folded to form a base angle of 50^o and welded to the cylindrical portion of the silo. In addition to selecting a sheet thickness that can withstand buckling, adequate structural strength was ensured by welding three-angle irons at the circumference of the silo (cylindrical portion) at an angle of 120^o apart and was extended to form its base support and the whole silo was painted using Aluminum – coloured antirust.

Hopper, Discharge chute, support and ladder

Cylindrical portion, silo cover and inlet port

Plate I, Constructed Silo

2.2 Quantity of consumables in silo construction

The details of the consumables used in the construction of the mini- silo including the component, type of construction material, dimension and the quantity are presented in table (1).

Table 1, Quantity of Construction Materials Used for various Components

S/No	Silo component	Construction material	Dimensions	Total quantity
1	Silo top (including the inlet and its cover)	Galvanized iron sheet (GI Sheet)	0.60 m^2 x 1	0.60 m^2
2	Inner cylindrical portion	GI sheet	2.35 m x 3.45 m	8.11 m^2
3	Outer cylindrical portion	GI sheet	2.59 m x 3.45 m	8.94 m^2
4	Silo base/frustum	GI sheet	0.754 m^2 x 1	0.75 m^2
5	Outlet chute	GI sheet	0.35 m x 0.4 m	0.14 m^2
		Total Area of sheet metal		**18.5 m^2**
6	Reinforcement bars	Flat bars	1$^{1/2}$ inch	2 bars
7	External reinforcement (anti-buckling bars)	Angle iron	2 inch	3 bars
8	Ladder + support	Angle iron	1$^{1/2}$ inch	4 bars

III Evaluation of the Constructed Silo

Prior evaluation, the silo was inspected for the presence of a hole or improperly welded jointly by checking around the inlet and outlet openings, point of intersection between the cylindrical portion and the hopper and at the points where the ladder was fixed to the silo in accordance with FAO (2015). The silo was evaluated in terms of the differences in temperature and relative humidity between the ambient air and the inside of the silo. Dry bulb and wet bulb mercury thermometers, and psychometric chart were used to estimate relative humidity and temperature depression of the two environments (silo headspace and ambient). Although the inlet and the outlet lids remained closed during the experiment, the inlet cover was removed intermittently to insert the thermometers for determination of both the wet and dry bulb temperatures of the storage headspace.

Readings were taken every three hours between 6: 00 am to 6:00 pm for one day (31st August 2016). Then, the effectiveness of the lagging material was evaluated by determining the dry bulb temperature of both the headspace and the ambient environments once daily (at noon) for a period of thirty days in April 2017 (the hottest month in Mubi based on a five-year data) in accordance with Reference [7].

Findings revealed that the relative humidity of both the ambient environment and the silo's headspace indicated increasing trend with an increase in temperature, yet, the relative humidity of the storage environment was comparably much lower than that of the ambient environment in the month of August in Mubi (Tables, 2 & 3).

Table 2, Temperature and Relative humidity of Ambient Environment in Mubi on 31 August 2015

Time	TDB(^{O}C)	TWB(^{O}C)	Td(DB-WB) (^{O}C)	Relative humidity (%)
6:00 am	25.04	22.14	2.9	77.0
9:00 am	28.21	26.09	2.12	86.3
12:00 noon	31.0	28.02	2.98	80.3
3:00 pm	32.43	29.16	3.27	81.0
6: 00 pm	33.22	31.07	2.15	87.6

TDB = Dry bulb temperature, TWB = Wet bulb temperature, Td = Dew point temperature

Table 3, Temperature and Relative humidity of Silo's Headspace on August 31st 2015

Time	TDB(^{O}C)	TWB(^{O}C)	Td(DB-WB)(^{O}C)	Relative humidity (%)
6:00 am	17.12	11.21	5.91	47.3
9:00 am	20.01	15.03	4.98	54.0
12:00 noon	28.10	15.41	12.69	54.7
3:00 pm	32.0	24.70	7.3	62.66
6: 00 pm	36.23	28.04	8.19	67.0

TDB = Dry bulb temperature, TWB = Wet bulb temperature, Td = Dew point temperature

The dry bulb temperature of the ambient environment was higher than that of the silo's headspace except for the days between 15th and the 19th in April 2016, where the two environments almost indicated similar temperatures (figure, 1). However, with respect to the safe storage temperature of 28^{o}C, storing beans in the designed silo was more promising than storing it in un-lagged metal drums as practiced by farmers and grain handlers in this area. Using un- lagged metal drums for storing grains such as meant may be damaged by excessive heat conducting through the walls of the metal drum; thereby reducing its viability for use sowing seeds in subsequent farming season [5].

The silo was able to perform its intended function of minimizing the temperature and relative humidity of the storage environment to a safe level; however, it can still be improved further such that that the temperature of the storage space falls below the safe limit. In the meantime, such performance can be achieved by erecting a shade above the silo.

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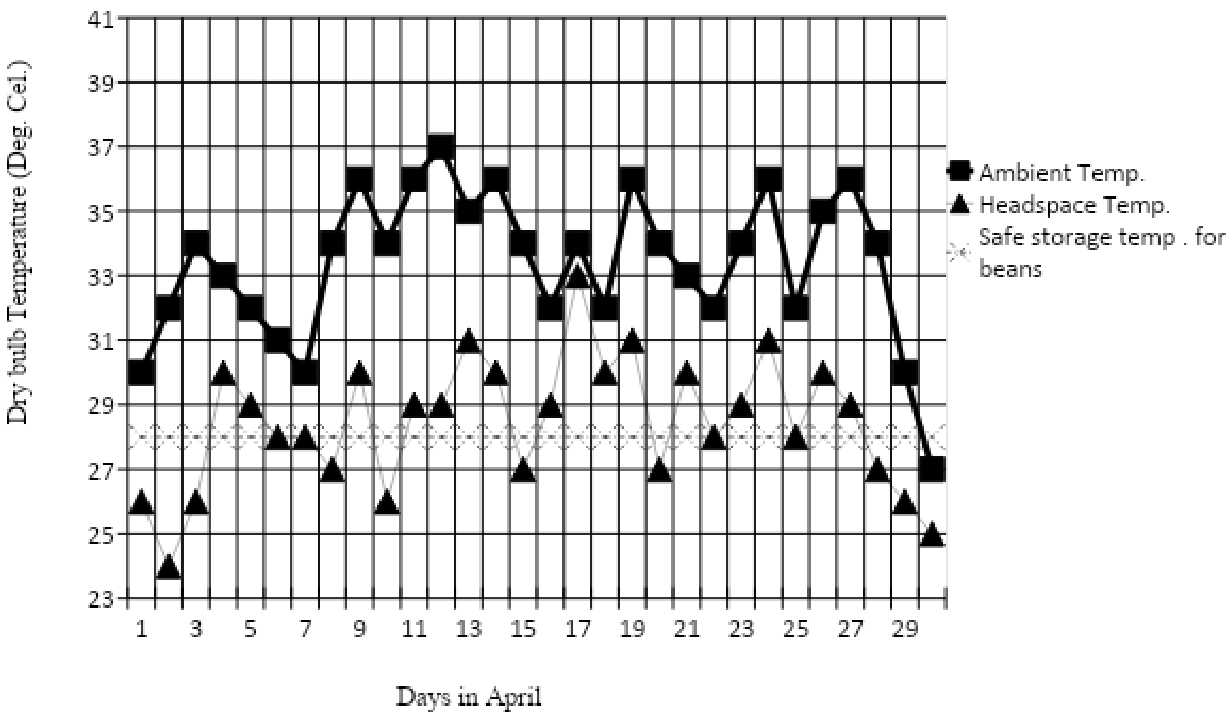

Figure 2, Temperatures of Silo Headspace, Ambient Environment and the Required Safe Storage Tmeperature for Beans

IV Conclusion and Recommendation

The following conclusions and recommendation were drawn -

4.1 Conclusion

A mini- metal silo (deep silo, $H_d > 4R$) of storage capacity 1.517 m^3 and headspace volume of 0.198 m^3 was designed to withstand buckling and excessive heat transfer. The structure was constructed Galvanized iron sheet (gauge 12) and evaluated in terms of the relative humidity and temperature of the headspace and the ambient environment in the month of August 2015, and dry bulb temperature only in April (the hottest month in Mubi) of 2016.

Findings revealed that the structure has performed its desired functions of protecting the grain against moisture (relative humidity) and heat for most of the days during which the silo was evaluated (figure, 1).

4.2 Recommendation

There is the need for future researches in the field of silo evaluation to investigate the comparative performance of silos constructed from mud, concrete and metal silo in terms of the rate of settlement of installed silos, headspace temperature and the effect of the volume of headspace in relation to the volume of stored materials.

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