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WASTE STABILIZATION POND EFFLUENT REUSE FOR IRRIGATION IN NIGERIA

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Abstract

Waste stabilization pond (WSP) effluent have been effectively utilized for irrigation schemes in most developed countries. Motivated by the benefits accruing from such schemes, some researchers have called for similar reuse in Nigeria. The paper discusses the problems of operation of waste stabilization ponds in Nigeria and stresses the vital importance of solving these problems before such schemes could be safely and optimally operated. In particular, properly designed, sited, constructed and maintained ponds, and adequate monitoring as well as recognition of the interaction among various management levels are important.

KEYWORDS: Waste stabilization pond (WSP), effluent reuse, irrigation

1. INTRODUCTION

A waste stabilization pond (SWP) is a basin, dug on the earth, used for wastewater treatment. Its lower capital cost demand, especially where land cost it small, and lower operational and maintenance cost makes it a better promising waste treatment option for most less developed countries (Mara et al., 1983; Mara and Pearson, 1986). WSP if properly designed and operated achieves virtually total removal pf helminth eggs (Feachem et al., 1983; intestinal nematode eggs (Lakshminarayama and Abdulappa, 1972); Ascaris Spp and hookworm (Mara and Silva, 1986); viruses (Oragui et al., 1987); and a greater than 99(Mara et al., 1983).

Its use extends to industrial waste treatment (Bartoszewski and Bilyk, 1987; Duarte et al., 1987); algal production which can be used to supplement animal feed and acquaculture (Mara and Pearson, 1986).

In addition, the high incidence of sunlight in Nigeria and lack of adequate facilities for maintenance of complex mechanical systems, make it very suitable for the Nigerian environment. WSP can produce odor-free effluent rich in nutrients and attractive for agricultural reuse (Bartone and Arlosoroff). Hence, some researchers (Tarafdar, 1989; Agunwamba, 1991) in Nigeria have called for SWP effluent reuse in irrigation. However, such reuse is fraught with many problems which will militate against its successful and safe use in Nigeria, unlike in the developed countries.

Although the problems of public acceptance of effluent irrigation, public health risks, and environmental polution have been discussed (Bartone and Arlosoroff, 1987; Agunwamba, 1992), little was said about the problems that stem from WSP systems. The paper discusses this aspect. Several other issues must be addressed and resolved before WSP can efficiently meet reuse standard in the less developed countries.

2. OPERATION AND UTILIZATION OF WSP IN IRRIGATION

2.1 Operation of WSP

Waste stabilization ponds are utilized in all climatic zones of the world to treat domestic and industrial wasterwater and their use seems to be increasing in all continents. For instance, in Europe ponds are found in 16 countries. They are used in Federal Republic of Germany for communities ranging from a few 100 to about 4000 inhabitants (vuillot and Boutin, 1987). Over 1400 pond systems are operated in France; 90% of them are used for the treatment of wastewater in small rural communities (< 2000 inhabitants) (Vuillot et al., 1987). In USA waste stabilization ponds are a common wastewater treatment systems (Banerji and Ruess, 1987). They are also used in less developed countries.

A preliminary survey has shown that, unlike in the developed countries where properly structured maintenance and monitoring programmesfor WSP system are practised, ponds in Nigeria are neither monitored nor properly maintained.

For instance, at Abakpa Nike (near Enugu) two WSP system; designed for treating domestic waste water efflent from a housing estate, are in a poor state. The second pond is virtually dried up and is almost covered by bush. The sides of the ponds are eroded in many places. Blockage of wastewater pipes, large fluctuations in the quantity and quality of the effluent and reduction in the strength of influent sewage - all due to inadequate and irregular water supply - are frequent. Decreased depth of pond due to deposition of sediments have encouraged the growth of nuisance vegatations. No facilities are provided for regular maintenance.

Operational and maintenance staff stregth is inadequate compared with what is standard. The pond system is currently serving more than 500 housing units with an estimated population of over 6000 people. It is attended to by only one labourer whereas the labour requirement is as shown in Table 1 (Mara, 1976);

Table 1: Labour Requirement for WSP.

Population served	Supervisors	Labourers
5,000	-	2
10,000	-	3
50,000	1	6
100,000	2	8

Table 1 do~s not iclude the staff require for regular pond monitoring and analysis.

Similarly, ponds in Obafemi Awolowo University, Ahmadu Bello University, University of Nigeria, Nsukka and so on are not properly maintained. Although the effluents from these ponds do not meet the WHO Technical Report Series 778, 1989), they are still used for uncontrolled irrigation. In Nsukka for instance, several peasant farmers including pond workers grow vegetables and maize with WSP wastewater during the dry periods. Planting is done right to the edges of the ponds which destabilizes the side sloped and exposes the soil surface to erosion (Agunwamba, 1993).

Since 1970, the two facultative ponds at Nsukka have not been desludged. Banks have caved in several places. Unremoved scum and grasses interccept wastewater particles. Dead zones are developed which reduce the ponds effective area, cause short-circuiting, and consequently result in poorer effluent quality

Such ponds cannot be used safely for irrigation. Inadequately operated and maintained ponds will reduce agricultural productivity, lead to below-capacity working and/or to erratic effluent supply which will in turn lower the area cultivated. Pond operation cost (e.g. in desludging) may appear lower initially but in time there will be an ienvitable increase in average cost of operation, reuse or even disposal.

2.2 Utilization of WSP in Irrigation

One of the reasons for the increase in the popularity of WSP is the usefulness of its effluent in irrigation. It has been shown that no adverse public health and environmental impact is associated in WSP effluent reuse if appropriate resue policies and control measures are adopted (Bartone and Arlosoroff, 1987).

In the south-western USA treated wastewater effluents are being increasingly used as irrigation water (Pescod and Elliot, 1985). It is the most immediately available additional water resource for irrigation in semi-arid areas of Israel where storage reservoirs are introduced to store effluent for use in dry periods (bartone and Arlosoroff, 1987). Efforts are being made to reuse up to 430 million m3 per year by the year 2010. It has also been used for irrigation in other countries as shwon in Table 2. The list is not exhaustive.

3. BENEFITS AND DISADVANTAGES OF WSP EFFLUENT REUSE

Polulation pressures, water shortage and agricultural demands have foreced many countries into using WSP effluent for irrigation schemes (Bartone and Arlosoroff, 1987). Communities in Nigeria that have WSP will benefit from such schemes in many ways.

Table 2: Data on significance of effluent irrigation in several countries (Bartone and Arlosoroff, 1987).

Country (City)	Volume reused $\times 10^6 m^3/yr$	% of total sewage	% of total irrigation
Australia	149	11	-
China	10,000	27	-
Chile(Santiago)	190	100	100**
Germany	100	3	10
India	730	55	-
Israel	152	85	18
Mexico(Mixico DF)	1,500	100	80
South Africa	70	16	-
Tunisia (Tunis)	68*	75*	-
USA (Arisona)	790*	-	27*

* Planned expansion of existing reuse.

** dry season condition.

3.1 Water Conservation.

Water supply may be conserved by reducing excessive water use by households and industry. Public education can help instil in Nigerians the need to conserve the limited water resouces. In addition, it is necessary to explore for more water sources (e.g. rain water) and plan for wastewater reuse. In the water-scarce northern fringe of Nigeria wastewater reuse is one of the attractive alternatives for water conservation.

3.2 Avoidance of Illegal Use

When reuse is not planned and reuse policies not defined, reuse still take place out of economic necessity - but without proper sanitary control (Bartone and Arlosoroff, 1987). This obviously jeopardises public health and leads to environmental hazards. For instance, some local farmers grow vegetables with poorly treated wastewater around the treatment works at Nsukka. The vegetables are usually sold in the gneral market where even those who oppose watewater reuse completely buy from. If proper scienctific safe reuse is planned and the local farmers adequately enlightened such dangerous misuse will be avoided.

3.3 Income Generation

Planting will no longer be limited to one planting season. With a reliable year round source of irrigation water farmers will enjoy higher yields of some crops like maize, wheat, beans, vegetables etc. Effluent reuse will help irrigate more land and increase agricultural productivity. For example, at Abuja with an estimated population of 1.64 million by 2000

AD 137.7 million m3 of effluent will be produced annually. This can irrigate an area of 176500 and produce 449,596 tonnes of wheat annually (Pescod and Elliot, 1985; Tarafdar, 1989). Besides, the rich nutrients in wastewater effluents will reduce farmers expenditure on fertilizers.

3.4 Dietary Improvement

Farmers will produce a variety of foods that will improve their standard of living.

3.5 Reduced Environmental Pollution

The problem of waste disposal is avoided. WSP effluent reuse is not without some negative impacts such as: risk of transmission of communicable diseases to both farmers and consumers; accumulation of toxic chemicals in foodstuffs and salts in soils; and pollution of surface and underground water sources. However, these negative impacts can be easily controlled by resolving a number of policy issues which have be summarized eleswhere (Bartone and Arlosoroff, 1987).

One of such issues is the technological problems which concerns the sewage treatment system selected. Although WSP has been suggested as the treatment options that could economically (and for some other reasons given above) satisfy reuse criteria for irrigation, its operation to achieve the standard experienced in the developed countries in Nigeria may prove elusive because of certain problems. The requirements for successful utilization of WSP effluent in irrigation are discussed below

4 REQUIREMENTS FOR A SUCCESSFUL AND SAFE WSP EFFLUENT REUSE

4.1 Maintenance

It is essential to develop a structured and well-organised maintenance approach and ensure that the required maintenance and service functions are performed on a regular schedule (Sims and Hamwey, 1981). The degree of general maintenance and house keeping needed at the site is minimal; yet, for maximum benefit to be reaped from WSP special attention has to be paid to them. Routine maintenance tasks include: general checking and pretreatment cleaning; control of vegetation around the ponds; control of vegetation inside the ponds; removal of floating materials; and cutting of macrophytes (in macrophyte ponds). It is also necessary to remove sludge deposits from inlet and outlet structures. Sounding the sludge thickness in the various parts of the pond will show when the pond needs desludgeing.

Maintenance programme may not necessarily follow those used in the developed countries but should be adapted to local conditions. For instance, control of vegetation depends mainly on climatic and soil conditions. Operational requirements must be met through appropriate supervision and maintenance. A good maintenance programme enusres efficient and smooth planning operation. Lack of proper maintenance may finally lead to high cost. For instance, when farming is allowed around the pond and scums are not removed, there is the tendency for the pond to get filled up before the design period and the frequency of desludging in bound to increase (Agunwamba, 1993).

4.2 Monitoring and Evaluation

The organisation that looks after the WSP system should provide the expertise and facilities for measuring and recording information on the ponds performance accurately and reliably. This is useful for several reasons.

(i) Pond process is so complex that it has not been fully understood. Existing equations describing the process have been found inaccurate (Marecos do Monte and Mara, 1987). Hence, pond design is approximate. There is the need to obtain the actual performance as opposed to the design value. For instance, of the 20 WSP systems investigated in Misccouri and kansas, USA many did not meet the expected performance (Banerji and Reuss, 1987).

(ii) Design equations are based on researches done in the developed countries. Since climatic and environmental factors (e.g. wind, rainfall, run off) affect pond performace, data are needed to adapt these models to local conditions. For instance, existing design procedures do not allow for the possibility of flooding. But this can be a problem in ponds sited in communities with poor drainage and land management. The people living near the ponds at Nsukka have frequently had their yard covered with sewage debris due to over-flooding. Construction and operation of ponds in erosion prone areas should be done with care; otherwise the pond will get filled up before the designed period (Agunwamba, 1992; 1993).

(iii) Monitoring is essential to know when the pond's effluent quality deviates from what is expected. This will hlep to prevent unacceptable levels of pollution in the environment. Presence of pathogenic organisms will endanger public helath. The level of nutrients should always be known to help assess whether crops requirements are met. Execessive suspended solids, dissolved solids may lead to the blockage of irrigation appurtenances like pumps, pipes and oriffices. Monitoring will help identify when any of these problems have occurred so that appropriate action may be taken to aviod serious consequences (Adin, 1986).

Water supply will afect the quantity and quality of wastewaters and hence the performance of treatment ponds. Since water supply in a typical Nigerian community is erratic, variations in effluent quality are expected. This provides a further reason for monitoring.

(iv) Expected variations of the effluent quality call for normal monitoring. Hydraulic overloading may appear in the rainy season leadng to reduced residence times, and consequn ently poorer effluent. This may be compounded by run-off pollutants especially if the catchment area is porrly managed. Algal population usually varies from one season to another and affects suspended solids (SS) and nitrogen (Pearson et al., 1987). Concentrations of BOD and SS generally increase as wastewater flows decreases. Increased influent BOD will increased availability of nutrients. Much SS tend to shade off light from lower depths and hence reduce the photosynthetic activity. If $BOD > 300mg/1$, light rather than the availability of mutrients becomes a limiting factor for algae growth. This results in oxygen deficiency. Reduction in wastewater flows results from reduced water use (Dezellar and Maier, 1978).

4.3 Staff Remuneration

Sewage workers should be paid higher than their counterparts in other sections of the organisation because of the health hazards and poor image associated with their work. An interview conducted among the workers at Nsukka waste water treatment plant revealed that they are disgruntled and frustrated. Most of their counterparts in other sections earn more than them because they could not obtain the necessary trade test certificates. Trade tests on sewage treatment do not exist in the country. It is necessary to extend such benefits to them.

4.4 Manpower

The quality and quantity of workers as well as their attitude towards work are very important. Their interest and morale could be boosted by incetive and remuberation. Employing well trained staff or training already employed ones will greatly improve their efficiency. Such staff will appreciate the importance of maintenance and/or monitoring programmes and the consequences of ignoring them. Workers should be knowledgeable about simple pond operations such as weed, vegetation and odour control, sucm removal and so on. Simple pond processes should be clearly understood by the supervisors so that they will not indulge in actions that will endanger the very system they are supposed to protect.

The should be knowledgeable about porblems likely to impair the pond such as (Vuillot et al., 1987).

(a) Water level going down

(b) formation of septic zones in aerobic ponds.

(c) numerous vegetation in ordinary pond

(d) destruction of embarkments by rats and other burrowing animals.

(e) mosquito breeding in ponds.

(f) algal blooms reducing the quality of the effluent.

Provision of maintenance mannuals will be helpful. In France, for instance, plant owners, operators and local services in charge of techinal assistance are provided with a manual on pond operations.

4.5 Organisational Set Up

Good supervision is very important even with all the other requirements met. Planners and managers in the whole set up must be enlightened enough to appreciate a little of the processes of waste water treatment in ponds; otherwise finance meant for pond maintenance would easily be diverted to other areas that seem to be more important. A good organizational structure is all the more important since pond maintenance requirements are minimal, and hence may easily be ignored.

4.6 Budget

Finance must be adequately provided for operation and maintenance of the pond system. Odour control, replacement of working tools, monitoring, desludging, and several other operations require finance.

4.7 Design and Reuse Criteria

Since pond performance depends greatly on climatic conditions, some design criteria proposed for a certain area may not apply to others (Finney and Middlebrooks, 1980). Design equations need to be verified with local data so that, if necessary, they could be modified to suit local conditions. Also, effluent reuse standard has to be developed based on local conditions (Crook, 1991).

5. INTERGRATED SYSTEM APPROACH

Successful reuse of WSP effluent in irrigation requires interaction at various levels: from the design, siting of pond system, effleunt quality to irrigation system selection, types of crops, final reuse to effect of reuse on public health and the environment. The best management approach should incorporate the main goals, the important factors affecting each management level and the constraints within which the goals should be achieved as shown in Table 3.

Among the three levels and within each level there are mutual and conflicting interactions.

Hence, maximising all the goals within any level or among all the levels may not be possible because of the conflicting goals. Within each level there are some conflicting requirements. Use of deep ponds in level 1, for example, will maximize nutrient conservation, minimize the discharge of haevy metals but reduce efficiency. In level 3, infiltration of toxic chemicals and salt into underground water reduces their accumulation on the soil.

The interaction between the three levels are very important. For example, maximum reuse at the 2nd level will be moderated by the negative effect on the soil in the 3rd level. Secondly, reuse cannot rise above the present scienctific knowledge about processes that take place in ponds and interaction between all chemicals, soil and crops. Also the feed back from the 3rd level will control not only reuse but also the operation of the pond. Many other relationships among and within the levels could be recognised. Since

Table 3: Systems and Goal Constrains Hierarchy.

A. Design, Construction and Monitoring level

Goals:
- Maximize efficiency (larger land area, more number of ponds, lower depth etc).
- Maximize nutrients conserved (higher depth)
- Minimize algal concentration
- Minimize discharge of heavy metals (deeper ponds).
- Meet other reuse standards.
- Avoid illegal reuse and hence spread of diseases.

Systems Constraints:
- Technology
- Land
- Budget
- Environmental Reuse Standard

↓

B. Reuse level

Goals:
- Maximize crop yield
- Maximize wastewater use (to avoid disposal problems, conserve water and minimize fertilizer use).

Systems Constraints:
- Socio-cultural factors
- Types of crop
- Aesthetics
- Land Availability
- Budget
- Environmental reuse standard

↓

C. Environmental Monitoring Level

Goals: Minimize negative environmental impact
- Salinity
- Communicable diseases
- Toxic compounds
- Underground water Pollution. Run off to streams.

Systems Contraints:
- Social factors
- Technology.

the whole system is affected by dynamic climatic, environmental, technological and social factors, it is only rational to assume that the relationships are dynamic and complex.

At the moment, the author is developing an optimal approach for wastewater reuse in irrigation. The approach would be illustrated with several field examples.

6. CONCLUSION

Effluent WSP reuse in irrigation in less developed countries cannot be safe and successful if adequate monitoring and maintenance programmes are not incorporated in the already existing systems. Special efforts, more than in the developed countries, are required in design and operation of waste stabilization ponds with respect to improvement in land management, development of right attitude towards work and pond design criteria that incorporates local variations. It is only when the interactions among the various levels of management are recognised and incorporated in the overall plan that effluent reuse in the less developed countries will be safe and efficient. Successful reuse is more than siting a pond and allowing wastewater flow inot it. There must be a well structured management set up, even within the management of the pond system itself.

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ESTIMATING WATER APPLICATION EFFICIENCY IN BORDER IRRIGATION SYSTEM

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Abstract

Fok and Bishop (1869) equation to predict the application efficiency in border irrigation assuming advance of water front of the form $L = at^b$ has been applied to a field study in South- Western Nigeria. Application efficiency from three different border sizes were evaluated from the field study. Results show that the observed field data were within 2.5values with small border sizes. Increased application efficiency, was observed as time ratio (G) increased. For maximum efficiency,an optimum value of G = 3 was evaluated at stream sizes less than 7l/s. The computed application efficiencies were found to be directly affected by the infiltration constants, B and N. The efficiencies computed from this model compared well with those of Bishop (1961) and Gupta et al (183).

KEYWORDS: Water application efficiency, irrigation

1. INTRODUCTION

The cost of the different forms of energy prevailing in most countries will continue to make favourable the use of surface irrigation methods in the future. Thus any effort to improved irrigated agriculture on a world wide scale will need to lay more emphasis on surface irrigation methods. The optimal design of surface methods can therefore be an important way to increase farm profits and to use water most efficiently. Well-designed method can increase efficiencies of water application levels to 60-80 percent, compared with typical efficiencies of 20-40 percent commonly reported by Bos and Nugteren (1978), Clyma, et al (1975) and Valenzuela and Pena (1980).

Commonly used deign criteria for border irrigation system are based on desired water application efficiencies. There are many mathematical models from which these parameters can be predicted as evident in literature basset et al., 1981, singh and Ram 1983, Strelkoff and Clemens, 1984). The complete model treating all phases of surface irrigation cycle usually are based on free- surface hydrodynamic equations of mass continuity and momentum conservation or their approximation (Sherman and Singh, 1978, 1982). Because these equations involve moving boundaries, rather complicated numerical methods are needed to obtain their solutions. These complex models have sufficient accuracy for field use.

The cost of computation using these models are however substantially greater than simplified models. Accuracy can be influence by the programmer in the selection of grid sizes and arrangement of node points. Besides, they require extensive programming and their use are limited by the availability of computers and supporting facilities. Sometimes solutions have to be found by using digital computer and both the initial and boundary conditions have to be specified. These limitations make this method unattractive in a developing country like Nigeria.

The problem of modelling border irrigation can be considerably simplified by employing the volume balance approach which is accurate enough for engineering application. This paper is therefore aimed at comparing a simple but reliable method for predicting application efficiency in a border irrigation system with actual field estimate of application efficiency.

1.1 Theoretical Analyses

1.1.1 Basic assumptions

The equation describing the fluid flow patterns in borders have been described on the basis of the following assumptions:

1. The border is homogenous i.e. its slope, width, composite roughness and intake do not change with location.

2. Inflow q is constant.

3. The border is wide enough so that the side effect can be neglected.

4. The field slope is assumed uniform with values which can be approximately described as "mild".

5. The advance water length, L, is related to the advance time t by a power function (Fok and Bishop, 1965) of the form

$$L = at^b \qquad (1)$$

Where a and b are empirical constant.

The application efficiency model derived in this paper assumes the approach of Fok and Bishop (1965) irrigation advance which is one of the most popularly used models. A short discussion of this model follows:

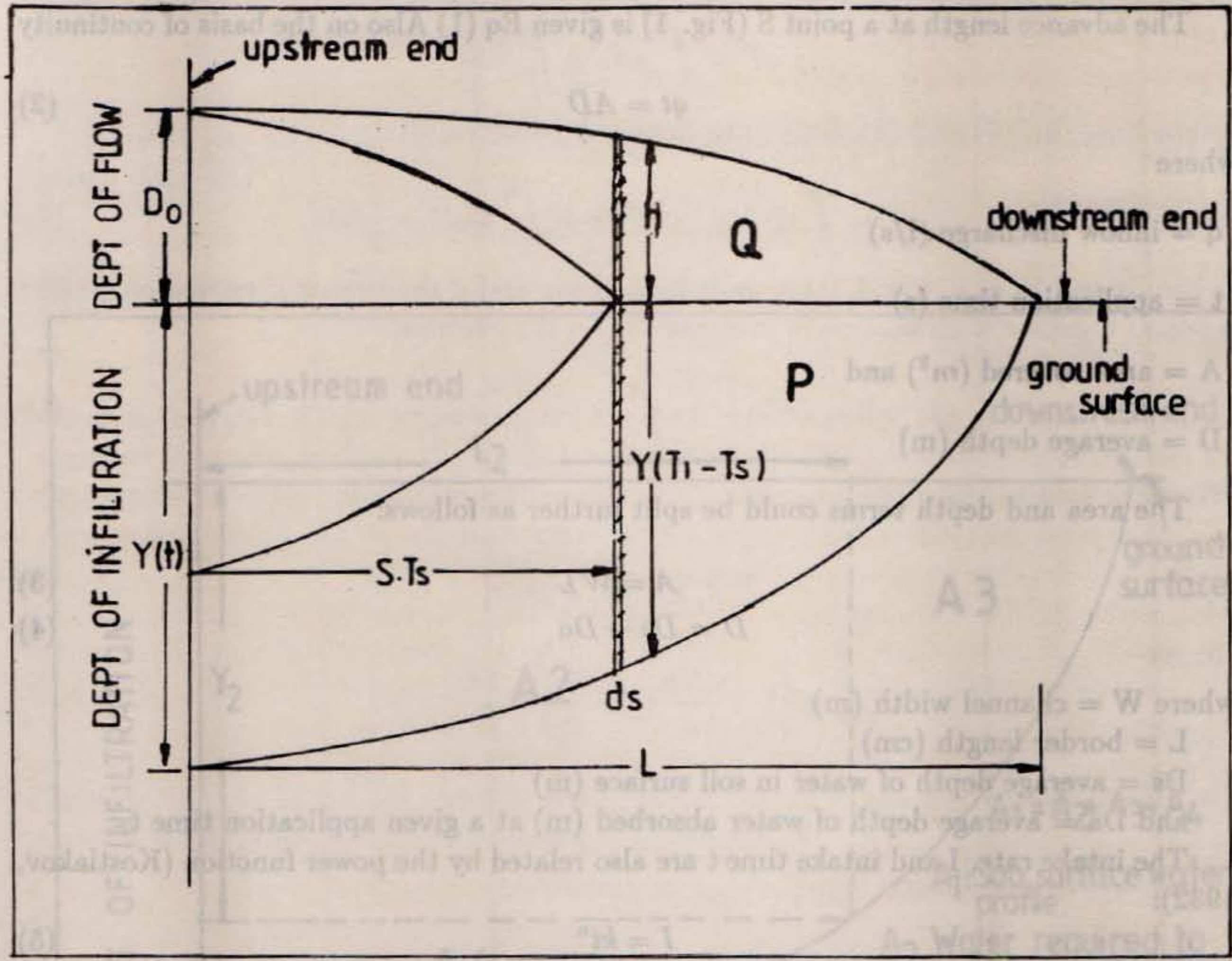

Figure 1: Accumulated infiltration and surface storage as a function of border distance and time

The advance length at a point S (Fig. 1) is given Eq (1) Also on the basis of continuity

$$qt = AD \quad (2)$$

where

q = inflow discharge (l/s)

t = application time (s)

A = area covered (m^2) and

D = average depth (m)

The area and depth terms could be split further as follows:

$$A = WL \quad (3)$$
$$D = Ds + Da \quad (4)$$

where W = channel width (m)
L = border length (cm)
Ds = average depth of water in soil surface (m)
and Da = average depth of water absorbed (m) at a given application time t.
The intake rate, I and intake time t are also related by the power function (Kostiakov, 1932):

$$I = kt^n \quad (5)$$

where k and n are empirical constant.

The accumulated intake depth y, can be obtained by integrating equation (5) with respect to time to give:

$$y = kt^{n+l}n + l = Bt^N \quad (6)$$

where B, an empirical constant $= \frac{k}{n+l}$ (6a)
and N, an empirical exponent $= n + l$ (6b)
The water level, h at successive points measured from the point of entry is related to the parameters Do, t and T as follows:

$$h = Do(l - \frac{t}{l}) \quad (7)$$

where Do is the normal depth of flow at point of entry, t is advance time at a certain distance S and T is the total advance time.

By volume balance (Fig. 2):

$$qT = P + Q \quad (8)$$

where P is the accumulated infiltration and Q is the surface storage.

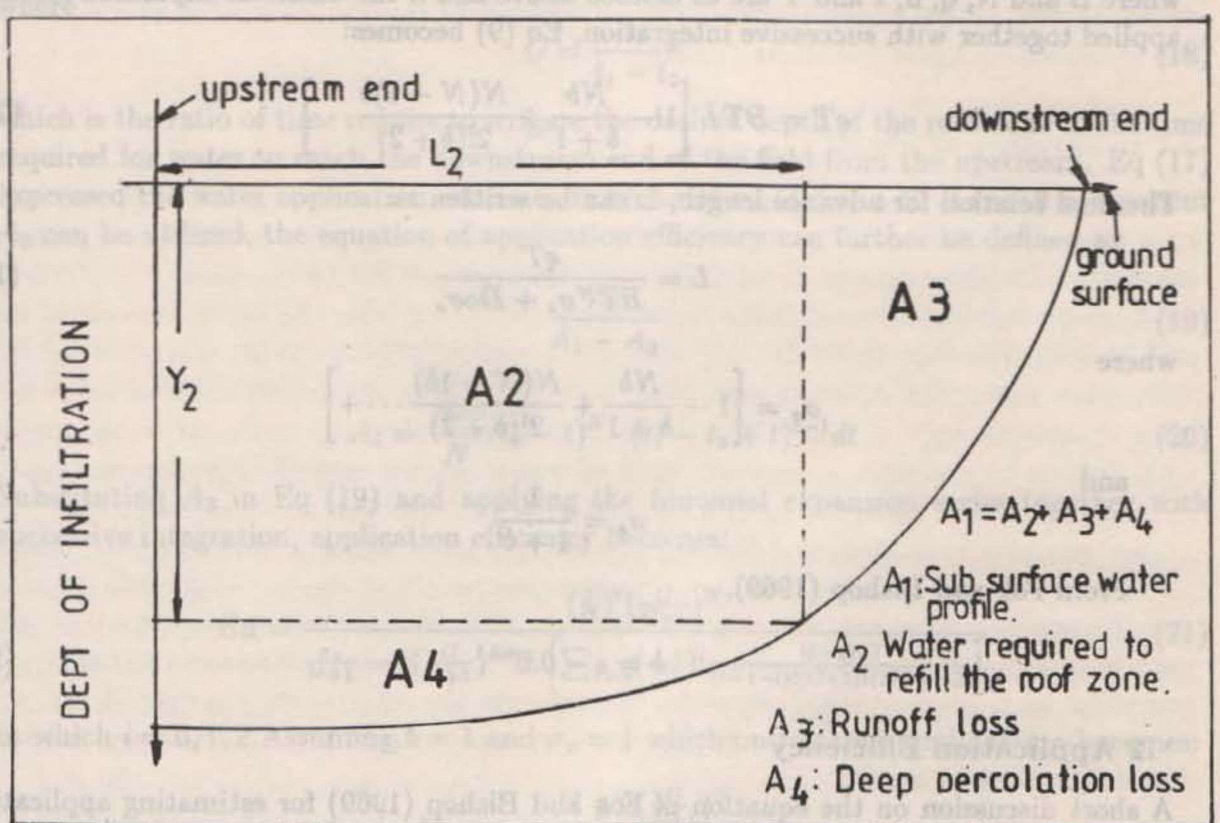

Figure 2: Definition Sketch of infiltration pattern when the root-zone is saturated

$$qT = \int_o^L yds + \int_o^L hds \tag{9}$$

From Eqs. (6), (7) and (8), Eq(9) can further be written as:

$$qT = \int_o^L BL(T-t)^N ds + \int_o^L Do(1-\frac{t}{T})ds \tag{9a}$$

where B and N, q, n, t and T are as defined above and if the binomial expansion series is applied together with successive integration, Eq (9) becomes:

$$qT = BTL\left[1 - \frac{Nb}{b+1} + \frac{N(N-1)b}{2!(b+2)}\cdots\right] \tag{10}$$

The final relation for advance length, L can be written as:

$$L = \frac{qT}{BT^N\sigma_z + Do\sigma_s} \tag{11}$$

where

$$\sigma_z = \left[1 - \frac{Nb}{b+1} + \frac{N(N-1b)}{2!(b+2)}\cdots+\right]$$

and

$$\sigma_s = \frac{1}{1+b'}$$

From Fok and Bishop (1969),

$$b = e - 0.6^{n+1} \tag{12}$$

.2 Application Efficiency

A short discussion on the equation of Fok and Bishop (1969) for estimating application efficiency is given as follows: With reference to Figure 2. A_1 is the water distribution profile in the soil over a time period t_1. Also Y_2 is the depth of water required to refill the root zone soil reservoir. The time taken to reach the end of the field, L_2, the is $t_1 - t_2$ where t_2 is the time taken to irrigate to the depth of Y_2. Thus, A_2, the area representing the fraction of applied water that is stored is given by:

$$A_2 = L_2Y_2 \tag{13}$$

Application efficiency, Ea can be expressed as

$$Ea = \frac{A_2}{A1} \tag{14}$$

The water fistribution profile in the soil at any given time is expressed by:

$$A_1 = Ba\sigma_z t_1^{b+N} \tag{15}$$

whilst the fraction of applied water stored A_2 can be described by the following relation:

$$A_2 = Y_2 L_2 = B t_2 N_a (t_1 - t_2) b \tag{16}$$

Substituting all these terms into various equations gives the final expression for application efficiency

$$Ea = \frac{G^N}{\sigma_z (G+1)} b + N \tag{17}$$

where

$$G = \frac{t_2}{t_1 - t_2} \tag{18}$$

which is the ratio of time require to irrigate the desired depth of the root zone to the time required for water to reach the downstream end of the field from the upstream. Eq (17) expressed the water application efficiency in terms of σ_z, G, b and N. If runoff component A_3 can be utilized, the equation of application efficiency can further be defined as:

$$\frac{A_2}{A_1 - A_3} \tag{19}$$

$$A_3 = \frac{Bab}{N}(t_2 - t)^N \cdot (t_1 - t_2 + t)^{b-1} dt \tag{20}$$

Substituting A_3 in Eq (19) and applying the binomial expansion series together with successive integration, application efficiency becomes:

$$Ea = \frac{(\frac{1}{G})^b (\frac{G}{G+1})^N}{\frac{\sigma_z}{N+1} - b(\frac{G}{G+1})^{N+1} \left[\sum_{1=o} (-1)^i \frac{(b-1)!G}{(b-1-i)!(G+1)^i(N+1+i)!}\right]} \tag{21}$$

in which $i = 0, 1, 2$ Assuming $b = 1$ and $\sigma_z = 1$ which on further simplification becomes:

$$Ea = \frac{N + 1(\frac{G}{G+1})^N}{(G+1)^N - (G)^N + 2} \tag{21a}$$

Eq (21a) was used by Fok and Bishop (1969) to estimate the water application efficiency. However, the equation did not take into account the amount of surface storage after the water is turned off from the upstream end. For borders with mild slope, the average surface storage can be assumed to flow down to the downstream end as runoff loss. Thus equation (21) can be modified by the average surface storage Ds. Thus Eq (21) becomes

$$Ea = \frac{(1/G)^b \left(\frac{G}{G+1}\right)^N}{\frac{\sigma_z}{N+1} - b(\frac{G}{G+1})^{N+1} \left[\sum_{i=0} (-1)^i \frac{(b-1)!G}{(b-1-i)!(G+1)^i(N+1+i)!}\right] + Ds} \tag{22}$$

where Ds is as defined above.

2. MATERIALS AND METHODS

To test validity of equations of application efficiency in this paper, experiments on border system were performed in Ogu Oshun River Basin Development Authority (OORBDA), Itoikin, South Western Nigeria. Itoikin is located on latitude 6°51'E and longitude 3°51E. The vegetation is tropical rain forest, but massive cultivation has transformed it into a derived savannah. The soil is imperfectly drained during the rainy season when the water table is only 90cm from the surface. The surface is dark in colour and sandy loam in texture while subsoil is sandy clay loam to sandy clay, blocky to blocky subangular in structure with yellow brown mottles. The soil belongs to the Yampere series Mohrs, 1963) and classified as Aquic Paledults (USDA, 1975).

2.1 Infiltration of Water

Field investigations were conducted at different initial moisture contents of 8.9, 9.3, 11.7. 12.9, 16.8, 17.1, 20.9, and 22.6 percent. The values represent specific levels of soil moisture content on irrigated rice plots at Ikoikin at different periods of the year. Two sets of readings on infiltration were taken out at 5cm and 45cm from the upstream end of the plot at each moisture level. Double ring infiltrometer (Michael 1978) was used for the infiltration tests. The infiltrometers 25cm high and having 60cm and 30cm as outer and inner diameters were installed to a depth of 10cm. A specially designed water supply with devices to maintain a constant head of water (11cm) in both cylinders was used. Arrangements were made for measuring depth up to the second decimal place.

Soil samples from 15cm and 30cm depths using a jarret auger at different locations on the plot were taken prior to each run. Each experiment was conducted for 130 minutes and the readings were noted at regular intervals. The average values from the locations were recorded and plotted as a function of elapsed time. The results were then analyzed according to Kostiakov (1932) equation to compute the infiltration constant B and exponent, N. The method of averages for least square curve fitting program was used to determine these constants.

2.2 Application Efficiency

The application efficiency was determined by measuring the soil moisture content to a depth of 60cm at 15cm intervals before and after irrigation at three pre-determined distances, (5, 25 and 45 metres from the upstream end). The change in soil moisture content was determined from the profile.

The total quantity of water supplied at the upstream end was determined. Precalibrated 90 V-notch was use to measure the inflow rate. Constant discharge was maintained over the crest of weir by keeping the head of water flow constant. Water was allowed to fall in a distribution box of 5cm length provided with 8cm circular holes at one metre centre to centre distance.

The time taken for a specific discharge rate to advance from upstream to downstream end (t_1) was noted. The total time (t_2) to apply 8cm of water using this same discharge

Table 1. Infiltration constant and exponent and exponent at different initial moisture content.

Initial moisture content	Infiltration coefficient B(cm/mN)	Infiltration exponent N
8.9	0.740	0.437
9.3	0.564	0.470
11.7	0.512	0.500
16.8	0.417	0.636
17.1	0.389	0.650
20.9	0.338	0.663
22.6	0.272	0.665

rate was also noted. The time ratio (G) was then computed from Eq. (18). The efficiency was then determined from the ratio of water stored in the root zone to that supplied from the upstream end. The experiments were conducted on three border sizes 6m×50cm×50m and 45m × 50m each replicated three times.

3. RESULTS AND DISCUSSIONS

Table 1 details the infiltration constant and exponents analyzed according to Kostiakov equation. The constants B decreased with increasing moisture contents. The observations is in conformity with the theoretical model presented by Philip (1968) which assume that water transfer on the Darcy scale occurs only in the micropores. These microspores may be treated as a distributed sink in exchanging with microsporous, the rate of which depends upon the water potentials or water contents in the pore spaces.

The effect of initial moisture content on application efficiency (Ea) at different time ratios using q = 2 //s is shown in Fig 3. The efficiency decreases with increase in initial moisture content up to G = 3. Beyond this point the trend was reversed. This trend of the computed Ea from Eq (22) shows that the dominant parameter that influences the Ea is the exponent N.

The irregular pattern of the effect of moisture content on Ea may be due to the hysteresis mechanisms involved in soil water during and after water application to the soil (Poulovassilis, 1976, 1983). The mechanisms is attributed to the ever changing diameter of the capillary system in the soil mass. When the dry soil is wetting, the larger-diameter suctions will not be refilled until the suction force has taken to that corresponding to the larger-diameter suction. The converse is true as wet soil dries. Consequently, the infiltration exponent which is the dominant factor influencing Ea in the soil is affected by the capillary phenomenon.

The effect of G on application efficiency is also shown in Fig. 3. The computed Ea using Eq (22) was found to increase to a value of G 3 (average peak value) and thereafter decreased with increasing value of G. Application efficiencies at higher discharge rate

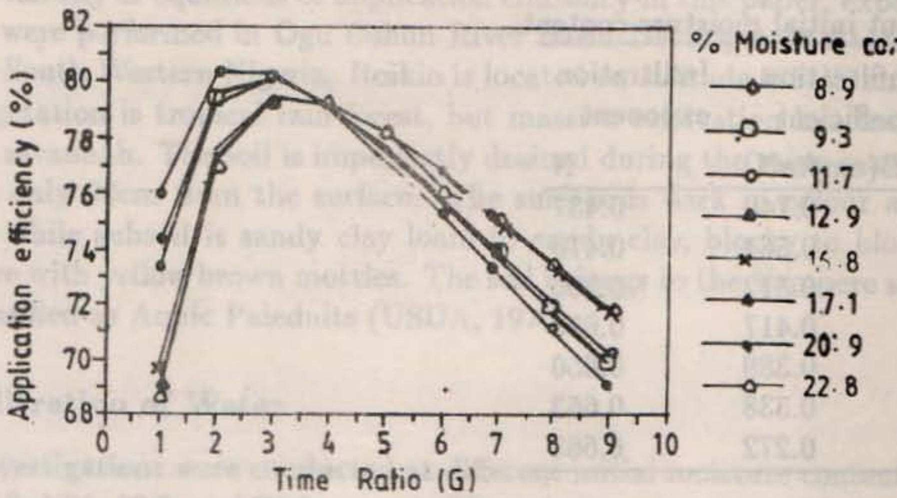

Figure 3: Effect of initial moisture content on application efficiency at discharge rate of 2 l/s

shows a similar trend (Fig. 4). Fok and Bishop (1969) also reported increases in Ea values up to $G = 4$.

Actual field practices of irrigation systems generally show difficulty in obtaining values of G greater than 4. This is because these high values of G can only be obtained by reducing the length of border or increasing the discharge rate. If in an attempt to obtain higher values of G, the length is reduced beyond 20 m, it might cause land preparation problem. On the other hand if the stream size is so large such as 30 1/s, it may lead to reduced efficiency. Therefore, for good border design, a proper combination of the length and stream sizes is very important. Generally, maximum efficiency was obtained with value of G between 3 and 4 for discharge rates less than 7 1/s.

The effect of the varying discharge rates on Ea at initial moisture content of 8.9% is shown in Fig. 4. The highest Ea was obtained with low values of q. Similar trend was observed with those computed at initial moisture content of 17.1% (Fig. 5). Data gathered by Bos and Nugteven (1978) suggested a quadratic dependence of Ea on q for field irrigation practices. Their analysis of average values of Ea and q for various types of irrigation indicated that Ea increased from 38% to 70% for a range of 0.025-0.040 m^3/s for q and decreased thereafter to 40% at $q = 0.33m^3/s$.

Mankarious et al (1991) however reported no clear functional relationship between the two variables from data on conventional farm irrigation practised in different parts of Egypt. The reason advanced to this observations is that seldom do farmers have facilities, understanding or time to carefully control their irrigations in accordance with the multivariate relationships between irrigation water requirements, soil conditions, field dimensions, application rates, application time and efficiencies. This is also true for most irrigation presently carried out in Nigeria.

For and Bishop (1969) evaluated Ea from an equation similar to that of Eq (21a) which

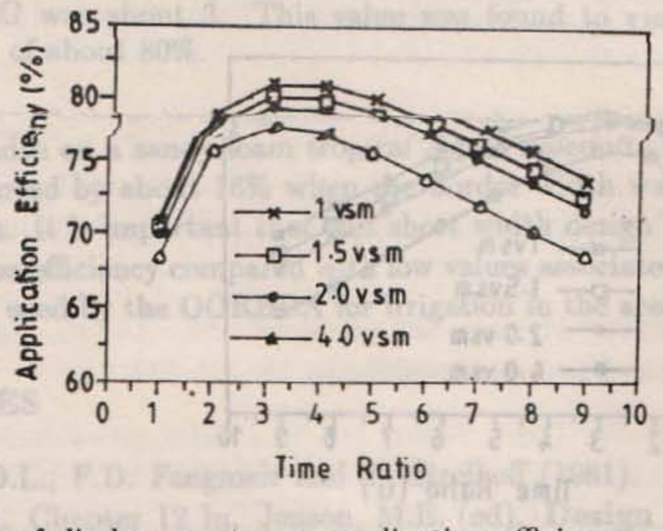

Figure 4: Effect of discharge rates on application efficiency using the analytical model equation at 8.9% initial M.C

Table 2. Observed and computed application efficiencies (Ea) in border irrigation at 4l/s.

Bordr dimension (mx)	Time ratio (G)	Application Efficiency (%) Observed	Eq(21)	Eq(22)	EaG*	EaB*
6 ×50	3.41	78.5	919	76.6	90.8	93.0
15 ×50	2.80	73.6	90.7	75.5	85.5	88.8
45 ×50	1.50	54.3	83.5	70.3	80.9	84.9

*EaG as computed from Gupta et al (1983). ** EaB as computed from Bishop (1961).

assumes b = 1. Also if the function b = 0 is substituted in Eq (21) an equation similar to that obtained by Murty and Agarwal (1970) will be obtained. The serious disadvantage of these equations is that they give application efficiencies at extreme conditions of linear and instantaneous advance which seldom occur under field conditions.

To test these equations (Eq 21 and 22) and other models with the observed values, application efficiency of the three border sizes were evaluated at discharge rate of 4-1/s and it is presented in Table. The computed Ea compares well with the observed Ea especially with the smallest border size (6m×50m). Higher Ea were observed with this border size than the other two. This may not be unconnected with a more uniform water advance associated with smaller border than larger ones.

The percentage deviation (PD) of the computed Ea from Eqs (21) and (22) and other existing equations are shown in Table 3. Eq (22) has the least PD with a minimum of 2.5% with the observed. The PD of Eq (21 and that of Bishop are very close to each other. The PD of Bishop and Gupta et al (1983) equations are 15.6 and 13.5% respectively. These are higher than that of Eq (22). The higher values of Ea obtained from Gupta et al (1983) equation may have been basically due to not taking into considerations the effect of

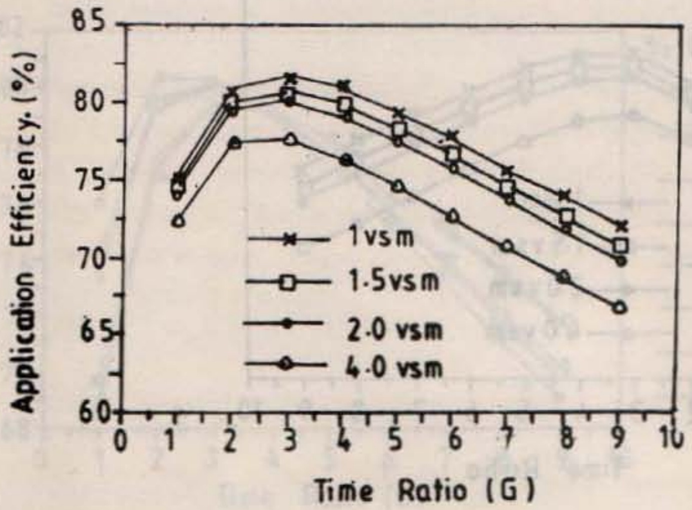

Figure 5: Effect of discharge rates on application efficiency using the analytical model equation at 17.1% initial M.C

Table 3. Percentage deviation of computed from observed Ea using Eqs (21) and (22).

Border dimension (mxm)	Time ratio (G)	Absolute Percentage Deviation Ea(21)	Eq(22)	EaG*	EaB*
6 ×50	3.41	14.1	2.5	13.5	15.6
15 ×50	2.80	18.8	2.5	13.9	17.9
45 ×50	2.50	34.9	22.8	32.8	36.0

infiltration coefficient B which is greatly influenced by physical factors and initial moisture content of the soil. It is deducible here that the use of Eq (22) should be preferred to the other two considered here, because it takes into consideration both the surface storage factor and B which vary under different field conditions.

4. CONCLUSIONS

Simple equations to predict application efficiencies have been applied to border irrigation system in South-Western Nigeria. Field investigations were conducted to test the validity and applicability of these predictive equations.

From the results of this study, the following conclusions were made:

1. Application efficiency in a border system was found to be greatly affected by the infiltration functions B and N. This observation was due to the fact that B and N are much influenced by initial moisture content during the infiltration process.

2. A proper combination of the infiltration exponent, and time ratio G were shown to yield higher efficiency. It appears however that of all the variables, only G, the time

ratios, can be manipulated easily. At discharge rates less than 7 l/s, the optimum value of G was about 3. This value was found to yield the highest application efficiency of about 80%.

3. The results of these investigations show higher application efficiency with narrow border width on a sandy loam tropical Aquic Paledults. The application efficiency was improved by about 16% when the border width was reduced from 45m×50m to 6×50m. It is important that this short width design be adapted to realize high application efficiency compared with low values associated with large-width borders presently used by the OORBDA for irrigation in the area.

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DEVELOPMENT AND PERFORMANCE EVALUATION OF A PEDAL-OPERATED MULTI-CROP CLEANER

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Abstract

Traditionally, the manual cleaning of crops has been a time- consuming and tedious operation. Although some of the existing machines for detaching crops from unwanted materials incorporate cleaning components, the power requirement of such machines is high and, hence, the prime mover is very expensive. Therefore, a pedal-operated multi-crop cleaner was designed, fabricated and tested. The machine has the dual functions of being utilized for a crop production operation while, at the same time, the operator is exercising himself for pleasure and physical fitness. The machine was tested for different crops at pedalling speed ranging between 30 rpm, and 60 rpm. The crop recovery efficiency varies between 79.3% and 99.5%, the heavy unwanted materials recovery efficiency varies between 82.9% and 95.4% and the light unwanted materials recovery efficiency varies between 44.0% and 91.5%. Therefore, at appropriate pedalling speed, the performance efficiency of the machine is very high.

KEYWORDS: Multi-crop cleaner, pedal-operated, development, performance.

1. INTRODUCTION

One of the major post-harvest operations for all crops is cleaning. Cleaning is used in this paper to embrace the removal of both the unwanted parts of a crop and the foreign materials in the crop such as damaged crop, inferior crop, vegetation, soil, sand and stones. These unwanted parts and foreign materials are collectively referred to as unwanted materials in the crop. Although, prior to cleaning, the crop would have been detached or loosened from the unwanted parts through the process of peeling, shelling, threshing, stripping, dehusking or dehulling, the crop and the unwanted materials still exist as a mixture.

Manual cleaning of crops is an arduous and time and labour consuming operation. On a 100-ha farm, Ademosun (1986) estimated that the man-hour requirements for the manual cleaning of groundnut, cassava and yam are 2500, 7000 and 6000 respectively. It is estimated by F.A.O. (1990) that 5 hours would be required to clean one tonne of rice manually. Chickpea is a popular source of protein in many Asian countries. According to Anwar et al (1991), chickpea is cultivated both in the tropical and temperate climates and its annual world production is about 7 million tonnes of dry grains from an area of about 10 million ha. The labour requirement for cleaning the crop is 9 man-hr per tonne. Also, the labour requirement for the manual cleaning of sugar cane was found by Shukla et al. (191) to be 395 man-hr per ha.

The methods adopted in the manual cleaning of crops from personal investigation of the author include the subjection of the crops to natural air current, hand picking. sieving, washing with water and immersion in water. In subjection to natural air current, grains are allowed to fall under gravity. During the process, the light chaff are drifted by the air so that the grains accumulate directly below the point of release. In hand picking, the crop is spread on a tray and unwanted materials are picked by hand from it while in sieving, wire mesh sieves containing the grains are moved back and forth in succession so that the small unwanted materials fall out of the sieve. Root crops are washed in water to remove the soil sticking to them, while grains are immersed in water and stirred so that the lighter unwanted materials floating on the water are dried or processed immediately so that they do not become rotten.

According to Culpin (1986), most of the existing mechanical cleaning devices are components of shellers, threshers, dehuskers, dehullers and combine harvesters at present. The sugar-cane cleaner developed by Shukla et al. (1991) was also required to crush the sugar-cane. Hence the machine consisted of a feeding chute, cushioned cylinder, lower and side rollers wrapped with kurnled rubber belt, blower, flap roller and an inclined platform fitted on a rigid frame. Each of these machines is designed for a specific crop. Besides, the power requirement of each machine is high because of the various operations that it has to perform. The power source is, therefore, an internal combustion engine or an electric motor. These power sources are expensive and, therefore, the local farmers cannot afford to purchase them.

The power requirement to perform the cleaning operation can be so minimized that human power will be sufficient if the cleaning operation is isolated. It is also necessary to apply the man power in such a way that drudgery is minimized. Ordinarily, pedalling a stationary cycle is a form of exercise performed for pleasure or to keep fit. It is gratifying, if during such exercise, the much needed power is also being supplied for cleaning crops and, thereby, contributing to food production.

2. MATERIALS AND METHODS

2.1 Theory of Pneumatic Cleaner

It has long been documented by researchers such as Mohsenin (1978) and Vaughan et al. (1980) that the separation of crop from unwanted materials is based on the differences in physical properties between the crop and the unwanted materials. Such physical properties include size, length, shape, weight or specific gravity, surface texture, colour, or reflectivity, affinity for liquid and conductivity of an electrical charge. Effective separation can be achieved by a machine that can differentiate between the crop and the unwanted materials in a consistent manner. Based on the physical properties, the researchers were able to identify the different types of cleaner: screen separator for size separation; indented cylinder and disc separator for length separation; spiral separator and screen with triangular hole separator for shape separation; pneumatic separator for weight or gravity separation; roll or dooder mill, draper belt, magnetic separator, buckhorn machine and vibrator separator for surface texture separation; electronic colour sorter for colour or reflectivity separation; magnetic separator and buckhorn machine for affinity for liquid separation; and electrostatic separator for conductivity separation. Since the cleaner discussed in this paper essentially makes use of a pneumatic cleaner, the principle of pneumatic separation will be discussed.

In pneumatic separation, it has been established by many researchers such as Jodlowski (1976) and Standkovick and Woolever (1978) that air flow occurs around the dirty crop and there is, therefore, the action of the force exerted by the air on the crop, which is also subjected to the effect of its own weight. The resistance drag force, which is the force exerted by the air on the crop, is the resultant of the drag force, which acts horizontally, and the lift force, which acts vertically. The resistance drag force can be resolved into frictional drag, which is due to the tangential forces on the crop surface, and the profile or pressure drag, which is due to pressure distribution around the dirty crop. For a laminar or low velocity flow where variation in air density is small and vicous action governs the flow, the frictional drag is high and the profile or pressure drag is negligible. For a turbulent or high velocity flow where air compression instead of vicous action governs the flow, the profile or pressure drag is high and frictional drag is neglible.

The researchers reported further that when air stream is used for the separation of corp from unwanted materials, as the velocity of the air stream is increased, a terminal velocity of the crop is attained when the resisting drag force equals the gravitational force. Beyond this terminal velocity, the crop does not fall down. Therefore, it is possible to separate the crop from the unwanted materials if its terminal velocity is different from the terminal celcities of the unwanted materials. With known values of the weight, density, projected area and drag coefficient of any crop or unwanted materia, the terminal velocity of the crop or unwanted material can be calculated from an established mathematical expression.

Jodlowski (1976), Mohsenin (1978) and Ogunlowo and Ademosun (1991) have determined the drag coefficients of various crops. Also, the mathematic expressions and graphical relationship between the drag coefficient and Ronald's number for different shapes of materials are reported in Mohsenin (1978). With a knowledge of the effective dimension of a material such as the length of a rectangular material or the diameter of a spherical material and the velocity of flow of the material in a fluid of known density and absolute viscosity, the Ronald's number of the material can be calculated from established mathematical expressions reported in Mohsenin (1978). Many researchers who have worked on pneumatic separation such as Jodlowski (1976), Stankovick and Woolever (1978) and Shukla et al. (1991) have found that the efficiency of pneumatic separation is dependent on the aerodynamic properties of the crops, which are the terminal velocity, drag coefficient, Ronald's number, density and projected area.

Vaughan (1980) has classified pneumatic cleaners as pneumatic separators and aspirators with scalpers or graders. Although the three types of pneumatic cleaners are different in appearance, they utilize the same principle of separation as discussed above. In pneumatic separators, the fan is located near the air intake where is creates a pressure greater than atmospheric causing air to be force through the separating column under positive pressure. Aspirators differ from pneumatic separators in that the fan is positioned at the discharge end of the separator. The operation of the fan induces a vacuum in the separator causing the outside air under normal pressure to rush through the separator. With scalpers, the crop drops through the screen opening while the larger unwanted materials are carried over the screen while the smaller unwanted materials drop through the screen openings. The two types of screen design are perforated sheet metal and woven wire screen. Blencha (1983) has found that the optimum open area coefficient of a screen is 0.4.

2.2 Experimental Machine

The machine as designed is shown in Fig.1. The cleaning system of the machine was one meter high. The height of the operator's seat H, the length of the operator's handle E and the distance of the operator from the cleaning system were adjustable for the convenience of the operator. The reciprocating unit of the machine is shown in Fig. 2. After producing the machine frame and fabricating the various components, the machine was assembled by first installing the sieves B and C in the reciprocating from A to constitute the reciprocating unit. The reciprocating unit was mounted on four ball bearings. The holes of the top sieve B were larger than the size of the crop while the holes of the bottom sieve C were smaller than the size of the crop. Both sieves were installed in an oblique position. The top sieve was installed to tilt downward at the machine while the bottom sieve was installed to tilt downward at the back of the machine. The two collecting troughs were installed at the same level just below the bottom sieve C.

Watching from the operator's seat in Fig. 1, the front, collecting trough, which has the heavy unwanted materials outlet W, protruded to the right of the machine while the back collecting rough, which has the crop outlet X, protruded to the left of the machine. The crankshaft T, driven sprocket shaft O with its driven sprocket N, driving sprocket shaft L with its driving sprocket K and chain M were then installed. The connecting rod V was coupled to the reciprocating unit with a pin. The hopper D was installed on top of the machine frame A. The centrifugal fan, shown in Fig. 3, was assembled. The

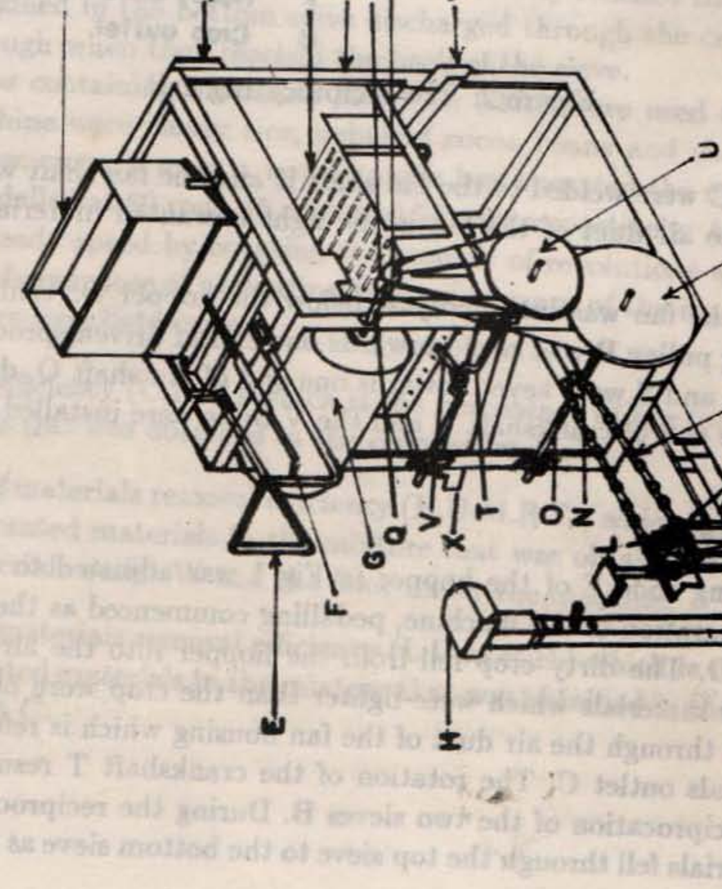

Figure 1: The pedal operated multi-crop cleaner

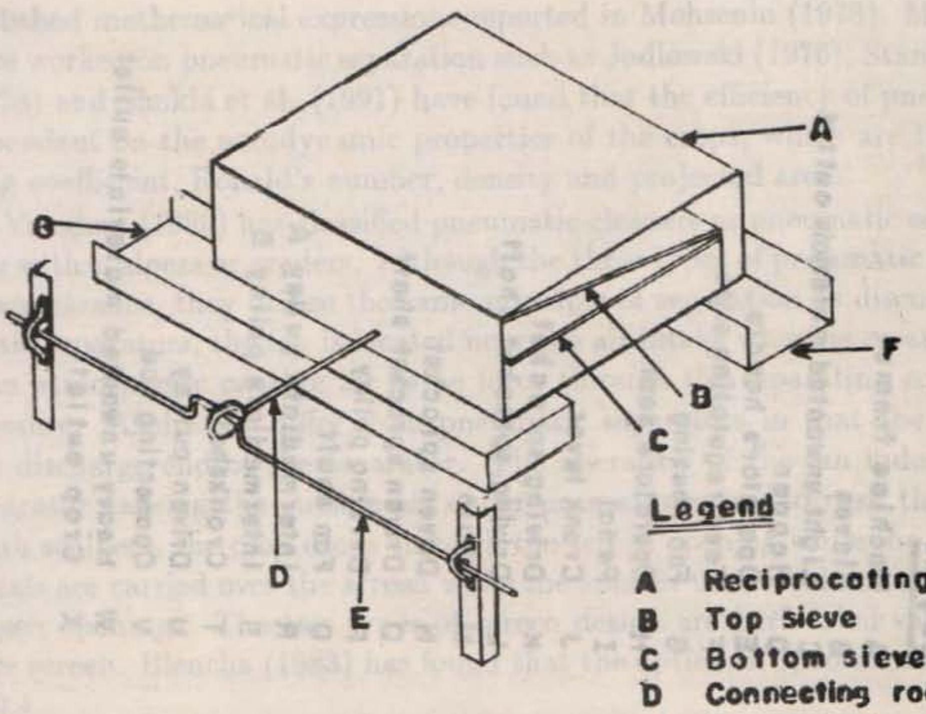

Figure 2: The reciprocating unit

curved fan blades C were welded to the fan shaft D and the fan shaft was installed in the fan housing B. The air duct of the fan is the light unwanted materials outlet A of the machine.

From Fig. 1, the fan was installed just below the hopper D. While ensuring proper alignment, driving pulley P was keyed towards one end of driven sprocket shaft O, intermediate pulleys R and S were keyed towards one end of fan shaft Q, driven pulley U was keyed towards one end of crankshaft T and the V-belts were installed.

2.3 Test Procedure

The feed regulating slide F of the hopper in Fig 1 was adjusted to the desired feeding rate before the operation of the machine, pedalling commenced as the dirty crop was fed into the hopper D. The dirty crop fell from the hopper into the air stream of the fan. All the unwanted materials which were lighter than the crop were blown out by the air stream of the fan through the air duct of the fan housing which is referred to as the light unwanted materials outlet C. The rotation of the crankshaft T resulted in the forward and backward reciprocation of the two sieves B. During the reciprocation, the crop and other small materials fell through the top sieve to the bottom sieve as they moved forward

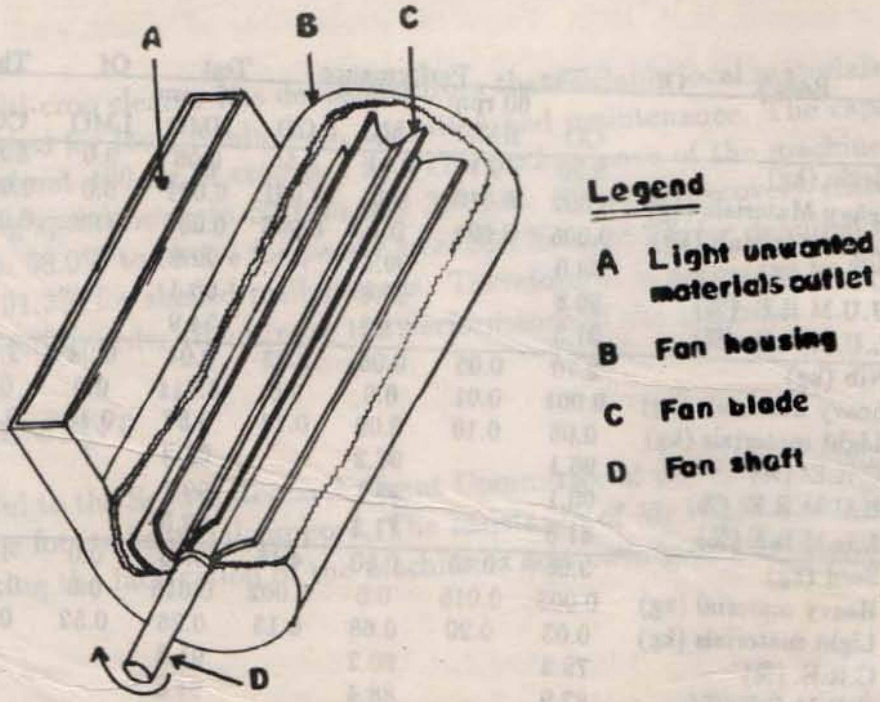

Figure 3: The centrifugal fan

from the back to the front of the sieve. The small materials fell through the bottom sieve to the floor as they moved backward from front to the back of the sieve. Meanwhile, the large unwanted materials retained in the top sieve discharged through the heavy unwanted materials outlet W of the front collecting trough when they reached the front of the sieve. Also, the crop retained in the bottom sieve discharged through the crop outlet X of the back collecting trough when they reached the back of the sieve.

The three crops containing unwanted materials which were used to test the performance of the machine were paddy rice, dehulled cocoa beans and shelled melon seeds. For each of the three crops, a man, a woman and a boy operated the machine. The man, women and boy pedalled at 60 rpm, 45 rpm, and 30 rpm respectively. An operator's mate served to ensure steady speed by counting the number of revolutions within a minute of a stop watch. For the purpose of evaluating the performance of the machine, three types of machine efficiency were determined:

1. Crop recovery efficiency (C.R.E.) which is the percentage of the total weight of crop in the mixture that was obtained in the crop outlet X.
2. Heavy unwanted materials removal efficiency (H.U.M.R.E.) which is the percentage of the heavy unwanted materials in the mixture that was obtained both in the heavy unwanted materials outlet W and the floor under the machine.

Light unwanted materials removal efficiency (L.U.M.R.E.) which is the percentage of the light unwanted materials in the mixture that was obtained in the light unwanted materials outlet C.

Table 1 Result Of The Performance Test Of The Machine

Crop		60 rpm CO	60 rpm HMO	60 rpm LMO	45 rpm CO	45 rpm HMO	45 rpm LMO	30 rpm CO	30 rpm HMO	30 rpm LMO
Paddy	Grain (kg)	5.50	0.1	0.01	5.56	0.05	0.0	5.58	0.08	0.0
rice	heavy Materials (kg)	0.002	0.019	0.0	0.001	0.021	0.0	0.001	0.021	0.0
	Light materials (kg)	0.005	0.004	0.1	0.006	0.005	0.08	0.006	0.007	0.6
	C.R.E. (%)	98.0		99.1		99.5				
	H.U.M.R.E. (%)	90.8		95.4		95.4				
	L.U.M.R.E¿ (%)	91.5		73.2		54.9				
Dehulled	Nib (kg)	2.70	0.05	0.06	2.73	0.04	0.04	2.76	0.02	0.03
Cocoa	heavy materials (kg)	0.001	0.01	0.0	0.0	0.011	0.0	0.0	0.011	0.0
Beans	Light materials (kg)	0.05	0.10	0.09	0.14	0.57	0.13	0.17	0.50	
	C.R.E. (%)	96.1		97.2		98.2	7			
	H.U.M.R.E. (%)	90.1		99.1		99.1				
	L.U.M.R.E (%)	81.3		71,3		62.5				
Shelled	Seed (kg)	3.65	0.45	0.50	4.15	0.45	0.0	4.20	0.4	0.0
Mellon	Heavy material (kg)	0.003	0.015	0.0	0.002	0.016	0.0	0.001	0.017	0.0
Seeds	Light materials (kg)	0.03	0.20	0.68	0.13	0.26	0.52	0.21	0.30	0.40
	C.R.E. (%)	79.3		90.2		91.3				
	H.U.M.R.E (%(	82.9		88.4		94.0				
	L.U.M.R.E. (%(	74.4		57.1		44.0				

C.R.E. Crop recovery efficiency

H.U.M.R.E. Heavy unwanted materials recovery efficiency

L.U.M.R.E. Light unwanted materials recovery efficiency

CO Crop outlet; HMO Heavy materials outlet; LMO Light materials outlet

3. RESULTS AND DISCUSSION

The result obtained during the performance test of the machine is given in Table 1. As the pedalling speed decreased, the crop recovery efficiency (C.R.E.) increased because the speed of the reciprocating unit reduced so that the crop had sufficient time to fall through the first sieve. The heavy unwanted materials removal efficiency (H.U.M.R.E.) also increased. This was so because, at the low speed of reciprocating unit, there was *sufficient time for the displacement of the heavy unwanted materials to the top and the* crop to the bottom, leaving the heavy unwanted materials alone in the sieve to discharge at the heavy unwanted materials outlet.

However, as the pedalling speed decreased, the light unwanted materials removal efficiency (L.U.M.R.E.) also decreased because the fan speed reduced. The result is in accordance with *the theory of pneumatic separation earlier discussed* which requires that the speed of the air stream is between the terminal velocities of the materials being separated in order to achieve effective separation.

The machine has, therefore, been able to effectively perform its function of separating crops from their unwanted materials. The normal running fit (H8-F7) selected for the mating machine members was appropriate as there was no relative motion between the mating members during operation. The existing local workshop tools were also suitable for the grade of machine work.

4. CONCLUSION

A pedal-operated multi-crop cleaner was developed from the available local materials and it was sufficiently rugged for local production, operation and maintenance. The capacity of the machine was about 400 kg of crop per hr. The performance of the machine was evaluated at pedalling speed between 60 rpm and 30 rpm. The crop recovery efficiency (C.R.E.) ranged from 98.0% to 99.5% for paddy rice, 96.1% to 98.2% for dehulled cocoa beans and 79.3% to 91.3% for shelled mellon seeds. Therefore, it is necessary to select a suitable pedalling speed in order to optimise the performance of the machine.

ACKNOWLEDGEMENT

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A. APPENDIX

A.1 Design Considerations

The major factors taken into consideration in the design of the machine were power requirement, pedalling speed, air stream velocity, order of removal of unwanted materials, adaptability of the machine to different crops, materials selection, fit and tolerance, and machine operation and maintenance.

The power requirement of this machine must be too high for a man to provide since man is the power source. According to Crossley and Kolgour (1983), the power output of an average man on a continuous basis is 0.1 KW. It is necessary to ensure that the machine has only the essential components required for performing its function and the determination of the sizes of the components is based on the low power source. Pedalling a stationary cycle was also selected as of source of power in order to optimise the utilization of the low power supply by man. For the maximum utilization of the limited human power, the type of fan selected was the forward curved, centrifugal fan as recommended by Osborne (1979).

The machine was designed in such that, during operation, light unwanted materials were first removed with the application of fan so that they might not block the sieve which was applied to achieve further separation. The selection suitable size and shape of holes in the sieve was given due consideration for effective separation of heavy unwanted materials from the crop. The sieve and the pulleys could be changed easily and the orientation of the idler could be adjusted in order to be able to adapt the machine to suit various crops.

Materials for the fabrication of the machine were selected such that the stationary parts could be rigid and stable, the moving parts were light in order to minimize the power requirement and the parts that were in contact with the crops were non- corrosive in order to avoid contamination. The frame was made of 5mm×5mm angle iron to provide firm support. Although aluminium was more expensive than mild steel, the pulleys were made of aluminium in order to minimize weight. Since stainless steel was very expensive and the crops which were to be cleaned were dry, the sieves and hopper were made of galvanised sheet, SWG 16.

A.2 Components Design

All the major components of the machine were first designed. The major components included the centrifugal fan, two reciprocating sieves and connecting rod. The power transmission system was then designed. The shafts were designed last.

The width of the fan outlet was selected to be 35 cm which was the width of the sieve. The height of the fan outlet was 10cm. At a velocity of 4m sec^{-1} , the actual discharge was determined to be 0.14m 3^{o} The power requirement of the fan was calculated to be 35 W. All the sieves had round holes except the top sieve for rice which had oblong holes. In the design of the connecting rod, Euler's formula was used as recommended by Joshi (1981) and hall et al. (1988) instead of Tetmajor's formula because the slenderness ratio was found to be higher than 105. The power requirement of the reciprocating unit was found to be 50 W. The standard procedures stated in Hall et al (1988) were followed in the design of the transmission systems and the shafts.

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SOME ENGINEERING PROPERTIES OF THEVETIA NUT

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Abstract

Thevetia nuts have been discovered to be a rich source of oil that can be used for industrial purposes. As a first step in developing processing and handling equipment for the nuts, some engineering properties namely: size, sphericity, roundness, volume, surface area, density, static coefficient of friction against different materials, angle of repose and specific heat capacity were studied. Major diameter varied from 285 to 375mm while the thickness varied from 160 to 190mm. Values of 0.54 and 0.64 for roundness and sphericity respectively show the inability of the nut to roll. Densities of between 0.91 and $1.25g/cm^3$ show that it is not possible to use water as a medium of separation between the nuts and other crops. The nuts had highest coefficients of friction for plywood with grains perpendicular to direction of motion and lowest for galvanized steel.

KEYWORDS: Physical Property, Thevetia, nuts

1. INTRODUCTION

Thevetia plant (Thevetia Peruvians) is an erect perennial shrub that is mostly found in the tropics and sub tropical regions of the world (Ojo, 1987). The fruits are somewhat of the size and form of hickory nut.

Recently, scientists at the department of Chemistry, University of Ilorin have discovered that the seed contains a very high percentage of oil (Ojo, 1987). This has generated some level of interest in the crop and its fruit. Attempts at expressing the oil necessitated the development of processing systems for the fruit.

The fruit of thevetia vary widely in size. Harvesting is done manually by direct plucking or hand picking of mature fruits that drop from the tree. The fleshy part of the epicarp is then allowed to dry up revealing a brown or dark brown hard nut. Presently, the nut is manually cracked by using stones, mortar and pestle, or and other suitable device. Oil is obtained by pressing the seed obtained after cracking the dry epicarp.

As the initial stage in developing a machine for dehulling the nuts, the physical properties needed to be studied.

The objective of this study was therefore to determine some of the engineering properties of thevetia nut at safe storage moisture, namely: size, sphericity, roundness, volume, surface area, density, static coefficient of friction against different materials, angle of repose and specific heat capacity.

Sphericity is defined as the ratio of the surface area of a sphere, which has the same volume as that of the solid, to the surface area of the solid. Roundness of a solid is a measure of shape and is defined as the ratio of the largest projected area of an object in its natural rest position to the area of the smallest circumscribing circle.

Mohsenin (1970) listed many methods for finding sphericity and roundness and according to him, the method due to Curray (1951) is subject to least criticism. The method is given as follows:

$$Sphericity = \frac{d_1}{d_c} \tag{1}$$

$$Roundness = \frac{A_p}{A_c} \tag{2}$$

where d_c and A_c represent the diameter and area of the smallest circumscribing circle respectively, d_i denotes the diameter of the largest inscribing circle and A_p represents the projected area of the grain.

Some researchers (Fraser et al., 1978, Dutta et al., 1988, Oje and Ugbor, 1991) described the size of crops by measuring their three principal dimensions. Dutta et al., (1988) and Shepherd and Bhardwaj (1986) also described equations for measuring the surface area of grains. They also studied other properties including angle of repose, bulk density, true density, and porosity.

Oje and Ugbor (1991) determined static coefficient of friction for different surfaces such as galvanized steel, plywood and glass. They also described the determination of angle of repose by using a specially constructed box with a removable front panel. The box is filled with the crop, then the front panel is quickly removed. This allows the grain to flow to its natural slope. This slope is a measure of angle of repose. Ezeike (1988) used a parabolic profiles to estimate the error of measurement involved in a similar technique.

Fraser et al (1978) used the method of mixtures to determine the specific heat of fababeans.

2. MATERIALS AND METHODS

Several kilograms of thevetia nuts were obtained from several plants and mixed together. The batch was sun-dried until the pods were dry enough to be cracked since there is no approved method of determining moisture content of this material.

Since the seed is an oil seed, moisture content was determined by oven drying the nuts at as temperature of 130°C and a time of six hours (Ajibola et al., 1990). Moisture content was found to be 12.5%wb.

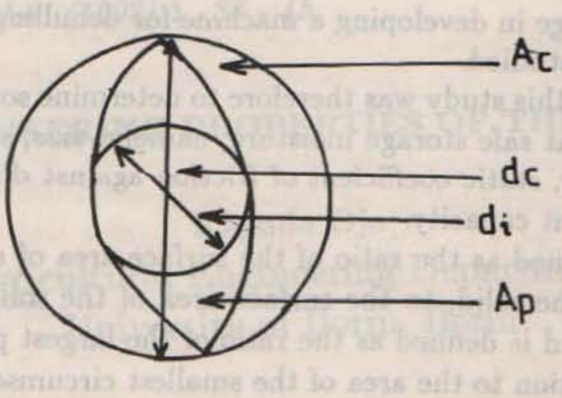

Figure 1: A traced theretia seed showing inscribed and circumscibed circles

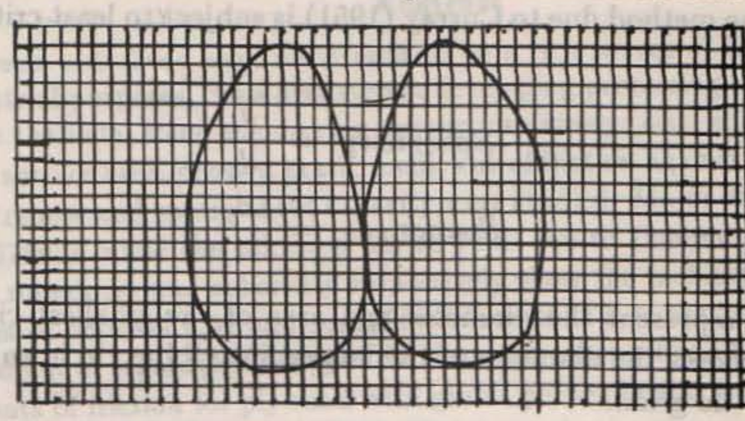

Figure 2: Pencil trace surface area of nut on graph paper

One hundred nuts were randomly selected from the sample. Measurements of dimensions on three mutually perpendicular axes were made; namely: major, intermediate and minor diameters. These dimensions were measured with a vernier callipers.

Sphericity and roundness were determined for the nuts. *Each nut was place in its natural resting position* on a sheet of graph paper. A sharp thin pencil was used to carefully trace the edges of the seed. The projected area and the diameters of circles inscribing and circumscribing the projected áreas (Fig.1) were measured (Oje and Ugbor, 1991).

The surface area was determined by first coating the surface with paint and contact printing on a light sensitive flexible paper (Oje and Ugbor, 1991). The surface edges traces on the paper were then pencil-traced on graph paper. The surface area was measured by counting the squares within the traced marks. A representative trace is shown in Fig. 2.

The volume, and hence density of each seed, was determined by the water displacement method as described by Oje and Ugbor (119). Individual nuts were immersed in water inside a measuring cylinder showing a notable rise in water level. The difference in the final and initial reading was recorded as the volume of nut. Density was obtained by dividing weight by volume.

The static coefficient of friction for the seeds was determined with respect to three structural materials, namely: plywood with its grain parallel and perpendicular to the direction of motion, and galvanized steel. A topless and bottomless box of dimensions 150 x 100 x 40mm was filled with the seeds and placed on an adjustable tilting surface. One end of this surface with the box resting on it was raised gradually with a crew device until the box just started to slide down. The angle of the incline was read from a graduated scale.

The angle of repose was determined by using a specially constructed box of 450 × 450 × 450mm having a removable front panel (Oje and Ugbor, 1991). The box was filled with the nuts, then the front panel was quickly removed. This allowed the nuts to flow to their natural slope.

An adiabatic drop calorimeter was used to determine the specific heat capacity by the method of mixtures (Oje and Ugbor, 1991). Water of known weight and temperature was poured into a calorimeter containing the nuts. At equilibrium, the final temperature was noted. Specific heat, C_s, was calculated by the expression

$$C_s = \frac{C_w M_w (T_{wi} - T_t)}{M_s (T_{si} - T_t)} \tag{3}$$

where,

C_s = the specific heat capacity of the nut, KJ/kg°C

C_w = specific heat of water, KJ/kg°C

M_w = mass of water, kg

T_{wi} = initial water temperature, °C

T_t = final temperature of mixture, °C

T_{si} = initial seed temperature, °C

3. RESULTS AND DISCUSSION

A summary of the results for all the parameters measured is shown in Table 1. The frequency distributions of some of the physical properties are also shown in Fig. 3.

Major diameter varied from 285 to 375mm (Table 1), although more than 50 percent were between 330 and 360mm. About 70% of the nuts had an intermediate diameter between 285 and 200mm and minor diameters between 160 and 190mm. The frequency distribution of the three dimensions are shown in Fig. 3. All the distributions are quite close to the normal distribution.

The highest roundness value obtained was 0.58 while the highest sphericity value obtained was 0.64. This shows that the nuts would rather slide than roll. This property should help in the design of hoppers and dehulling equipment for the seed.

Weight, volume and density have distributions that are close to that of normal distribution (Fig. 3). Weight distribution is even although about 50% of the nuts fall between 4.5 and 5.5 gm. Volume did not behave like weight. A large percentage (about 75%) fell within the range 3.5 and 5.5cm^3. This made the density distribution to be skewed to the

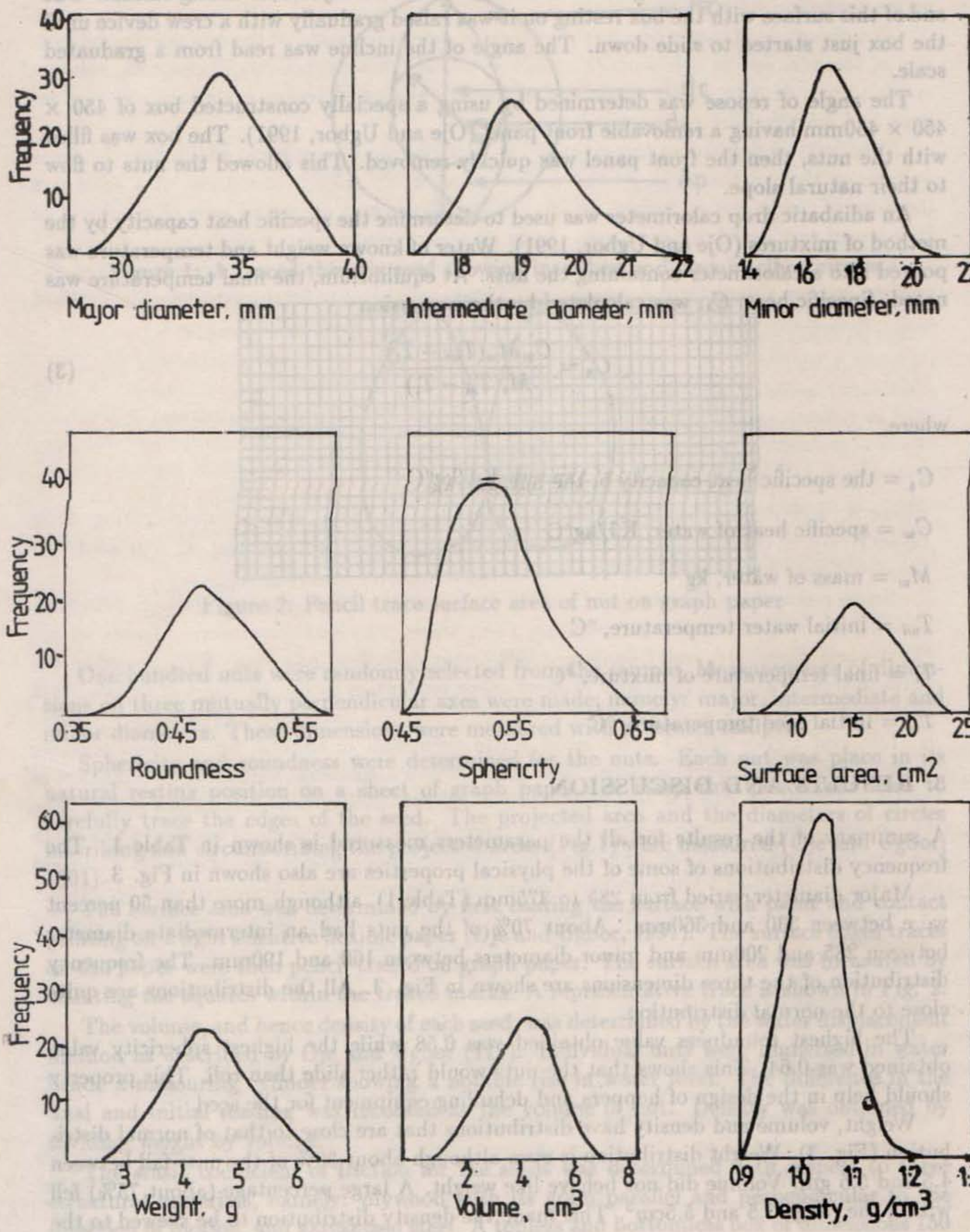

Figure 3: Frequency distributions of *some properties of Thevetia* seeds

Table 1. Some Properties of Thevetia Seed

Property	Number of observations	Mean value	Minimum value	Maximum value
Major diameter (cm)	100	3.45±0.453	2.87	3.92
Intermediate diameter (cm)	100	1.93±0.208	1.74	2.20
Minor diameter (cm)	100	1.70±0.272	1.50	2.00
Surface area (cm^2)	100	15.6±3.04	10.64	23.76
Weight (g)	100	4.63±1.045	3.35	6.21
Volume (cm^3)	100	4.24±0.911 2.30	6.10	
Density (g/mc^3)	100	1.02±0.166	0.91	1.26
Roundness	100	0.47±0.088	0.40	0.58
Sphericity	100	0.52±0.115	0.45	0.64
Static coefficient of friction on				
(a) plywood parallel to grain	6	0.56±0.038	0.52	0.60
(b) plywood perpendicular to grain	6	0.52±0.023	0.49	0.54
(c) galvanized steel	6	0.41±0.032	0.38	0.45
Angle of repose(degrees)	6	21±1.204	19 22.5	
Specific heat capacity(KJ/kg°C)	20	3.38±0.57	1.98	4.32

left. Most of the nuts have densities between 0.9 and 1.2 g/cm^3. It may therefore be difficult to separate the nuts from other crops by floatation in water.

The surface area appears to have a normal distribution with about 50% falling between 13 and $17cm^2$. The surface area ranged from 10.6 to $23.0cm^2$. Any machine to be designed for processing the nuts must take this wide range of surface area into consideration.

The static coefficient of friction for seeds was determined for three structural surfaces. The values were highest for plywood with the grain perpendicular to the direction of motion and lowest for galvanized steel. The coefficient was higher than values for oilbean seeds (Oje and Ugbor, 1991). This property is needed in the design of hoppers and other unloading devices.

The angle of repose of the nuts was found to be between 19 and 22 degrees at a moisture content of 12% wet basis. Specific heat varied from a minimum of 1.98 to a maximum of 4.32KJ/kg°C. It was not possible to develop any kind of relationship between specific heat and mass of nut as the figures appear to be independent of the mass.

CONCLUSION

Investigation of various properties of thevetia nuts revealed the following.

1. The frequency distributions of most of the properties approach the normal distribution.
2. The principal dimensions and surface area vary widely.
3. Thevetia nuts have values of sphericity and roundness that make it impossible for them to roll.
4. Hoppers and other unloading devices need not be built steeply because of the relatively low coefficient of friction.

Notation

A_p = projected area of nut

A_c = area of smallest circumscribing circle

C_s = the specific heat capacity of the nut

C_w = specific heat of water

d_i = diameter of largest inscribed circle

d_c = diameter of smallest circumscribing circle

M_s = mass of nut

M_w = mass of water

T_t = final temperature of mixture

T_{wi} = initial water temperature

T_{si} = initial seed temperature

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CORROSION RESISTANCE OF SOME STEELS IN COCOA MUCILAGE

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Abstract

The corrosion behaviour of 0.36% carbon, 0.18% carbon and galvanized steel, considered for possible application in the components of cocoa processing machinery, was evaluated in cocoa mucilage. The results show that the 0.36% carbon steel was least corroded, followed by the 0.18% carbon steel, while the galvanized steel was heavily corroded, with corrosion intensity increasing with duration of immersion. But generally all the materials show high rates of corrosion suggesting their unsuitability for use in cocoa mucilage environment without some forms of surface treatment.

Corrosion fatigue strength of 0.36% carbon steel, evaluated at 10^6 cycles in this environment, ranged between 50-55 MN/m^2. The corresponding fatigue limit in dry air was found to be 75 MN/m^2. The effect of corrosion products on the quality of fermented cocoa beans was found to be unacceptable as such exposed beans blackened and worthless.

KEYWORDS: Corrosion fatigue, fatigue strength, processing machinery, surface treatment, cocoa fermentation.

1. INTRODUCTION

Metallic corrosion, especially that of iron and steel, is a major problem in the food and agricultural processing industry. Attempts to provide some mechanical assistance in the on-farm (wet) processing of cocoa beans must therefore recognize and address this problem in relation to materials selection for machine component parts. The different primary processing operations of wet cocoa include pod breaking and bean extraction, bean fermentation, drying, packaging and storage. Corrosion problems are likely to be uncounted in bean extraction and fermentation and to a lesser extent drying, during which materials exposed to the cocoa mucilage are attacked (Faborode and Oladosu, 1991).

The problem of corrosion in cocoa mucilage becomes more pronounced as the mucilage is naturally degraded (fermented) by yeasts and other micro-organisms in which the sugars in the pulp are hydrolysed first into ethanol and subsequently into acetic acid. That is the pulp-seed medium becomes more acidic with time as fermentation progresses (Wood and Lass, 1985). Being an exothermic reaction, the temperature of the fermenting mass also rises. Fermentation normally takes about 5 days, after which the beans become pale brown in colour and exude some chocolate odour. The biochemistry of cocoa fermentation has been well studies (Beieh, 1991) and this would provide good basis for understanding the corrosion behaviour of the mucilage on materials of construction.

Cocoa mucilage is a pectin gel surrounding the seed in the pod. The gel contains essentially water with sugars, citric acid and small amounts of protein and mineral matter. The average analysis of mucilage composition is as given in Table 1 (Opeke, 1982). On breaking the pod the beans and the adhering mucilage undergo fermentation process. The sugars are converted first into alcohol(alcoholic fermentation), and subsequently, acetic acid is synthesized. The temperature of the system rises and the mucilage runs or drains away in the form of sweating. The sweating contains about 2-3% alcohol and 2.5% acetic acid. Temperature, pulp pH, ethanol and acetic acid contents increase gradually as fermentation progresses (Bernard, 1982). Temperatures have been observed to rise up to 53° C after 48 h of fermentation, before falling (Wood and Lass, 1985). There are two implications for corrosion reactions in the cocoa juice environment, as the temperature rise not only affects the rate of chemical or electrochemical reactions, but also the type and proportions of the products of the process (Biehl, 1991). Fermentation lasts for 5-6 days. The composition of the fermenting medium is thus in dynamic change in the first five days.

As local sourcing of industrial and construction materials is a desirable goal in developing countries, it is of interest to investigate the suitability of some locally produced steels in cocoa processing machinery. Some of such materials include a 0.36% carbon steel (ST-60-Mn), a 0.18% carbon steel (RST-37-2) and galvanized steel. ST-60-Mn structural steel is said to have the highest tensile strength (570-710 MN/m^2) of all carbon steels produced locally in Nigeria.

The specific objectives of the work therefore include:

1. determination of the corrosion rates of some steels in cocoa mucilage.

2. determination of the corrosion fatigue strength of 0.36% carbon steel, as well as the effect of corrosion on the number of stress cycles to failure, in cocoa mucilage.

3. evaluation of the effect of a corroded material on the quality of fermented cocoa beans.

Table 1. Chemical Composition of Cocoa Nucilage (pH 3.20-3.50)

Composition	Percent
Water	79.20 - 84.20
Dry substances	15.80 - 20.80
Non-volatile acids (citric)	0.77 - 1.52
Volatile acids	0.02 - 0.04
Glucose ($C_6H_{12}O_6$)	11.60 - 15.32
Sucrose ($C_{12}H_{22}O_{11}$)	0.11 - 0.90
Pectin	5.00 - 6.90
Starch	- - -
Protein	0.42 - 0.50
Ash	0.40 - 0.50

Source: Opeke (1982)

2. EXPERIMENTAL METHOD

2.1 Materials

2.1.1 Weight Loss Specimens

Three materials, ST-60-Mn, RST-37-2 and galvanized steels, of the chemical compositions shown in Table 2 were used in this study.

The materials were used in as-received condition. Experimental specimens were cut from the galvanized steel into rectangular pieces of 24mm by 16mm, while those of two other materials were cylindrical in shape. Surface preparation of the specimens, with the exception of the galvanized steel specimens, consisted of abrading through successive grades of SiC paper down to 600 grit, and finally polishing on a rotary polishing wheel using a slurry of 0.5 u alumina. This was followed immediately with rinsing of the specimens in distilled water and then in acetone before drying. The surface of galvanized specimens were not abraded but the specimens were washed in a solution of detergent and then rinsed in water and then acetone. The edges and one side of all the specimens were stopped off with nail polish (non-conducting paint) leaving an area of $25mm^2$ on each specimen surface to the exposed to the cocoa mucilage. The prepared samples were stored in a desiccator until they were needed for the experiment.

2.1.2 *Corrosion Fatigue Specimens*

The corrosion fatigue specimens were machined from ST 60 Mn material only. The specimen dimensions are as shown in Fig.. 1. To remove machine marks, the surface of the specimens were smoothened at the gauge section, by slowly rotating the specimens on a lathe machine while holding firmly against emerge paper. The final surface finish in all cases was 600 grit. The sample were then washed in a solution of detergent, rinsed in

Table 2. Properties and Chemical Analysis of Specimens

	Material		
	Mild steel (RST-37-2)	Medium steel (ST-60-Mn)	Galvanized steel
Mechanical Properties			
yield point (N/mm^2)	235 min	369 min	not determined
UTS (N/mm^2)	340 -470		
elongation %	26 min	10 min	
Laddle Chemical Analysis (%)			
carbon	0.12-0.17	0.35-0.42	not determined
silicon	0.18-0.28	0.20-0.30	
manganese	0.40-0.60	0.90-1.20	
phosphorus	0.040	0.040	
sulphur	0.040	0.040	
cupper	0.20-0.25		
chromium	0.10	0.10	
nitrogen	0.009-0.011	0.009-0.911	
tin	0.05	0.05	

Source: Osogbo Steel Rolling Mill, Osogbo, Nigeria

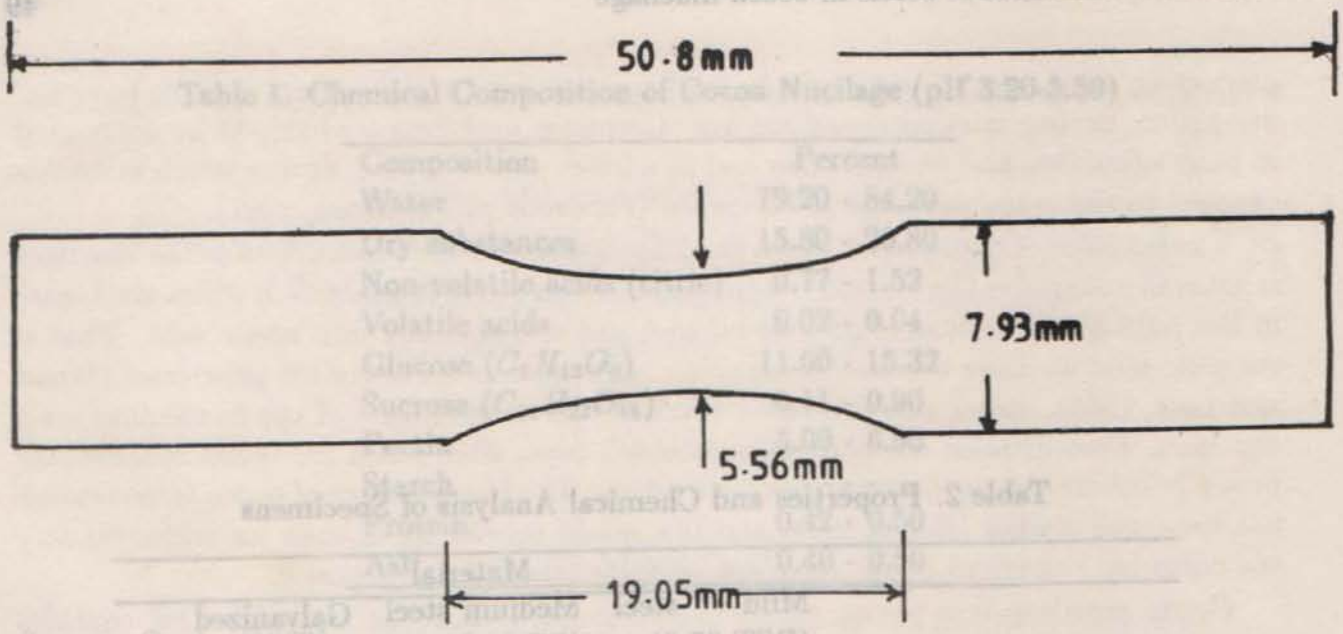

Figure 1: Standard Fatigue Test Specimen

distilled water and then in acetone before drying. They were then stored in a desiccator until needed for the experiments.

2.2 The Electrolyte

Fresh cocoa sweating was collected for the corrosion studies. One set of experiments was run in this environment with the samples exposed to the environment on the first day of collection of the mucilage. Another set was run in cocoa juice in which 10% distilled water has been added. This is in attempt to simulate situations where users of cocoa processing machinery wash or rinse their machines after use, with the possibility of incomplete removal of mucilage. It is expected that the corrosion reaction in this environment will be different from that of pure cocoa mucilage.

2.3 Methods

2.3.1 Weight Loss Experiments

The samples prepared for immersion were carefully weighed before exposure. Two exposure methods were used. In one (set A) the samples were withdrawn from their respective solutions after a certain interval of time ranging from four to thirty two days (continuous exposure). They were weighed and stored away. The practical equivalent of this corresponds to the non-cleaning of a cocoa processing machinery after use. In the second method (set B) the samples were returned to their respective solutions after weighing them (intermittent exposure). The intermittent exposure case simulates situations where the processing machinery is dry- cleaned daily after use by means of brushes and wipers. Using it the following day introduces a fresh environment. The procedure for determining weight loss in either case was to remove corrosion products on the samples using a soft brush, clean the samples properly before drying them in an oven. The dried samples were weighed carefully. The drying and weighing were alternated until constant weights were attained. The pH of the test and control solutions were monitored each time samples were withdrawn from solutions for weighing.

2.3.2 Corrosion Fatigue Experiments

Fatigue testing was done in pure bending using Avery 7305 Fatigue Testing Machine. The bending moments imposed on the specimens were calculated using the procedure in the Appendix I. The samples were tested in three different conditions. One test was run dry (dry fatigue test), while another was run on samples pre-corroded for different duration of time. The third category of test was done in-situ, that is, with the samples immersed in cocoa mucilage.

3. RESULTS AND DISCUSSION

3.1 Weight Loss

The weight loss measured in the undiluted cocoa sweating for the three materials are plotted in Figs. 2 and 3 as a function of time of exposure. The data for the test procedure in which the specimens were exposed to the solution and withdrawn after prescribed duration of time (see A samples) are presented in Fig. 2, while Fig.3 shows the data for the test procedure in which the samples were used over and over again (set B samples). The two sets of data show similar trends in corrosion behaviour with respect to time. The weight loss data in Fig. 3 are larger than those in Fig. 2 for any given time period after day two because the test procedure for the data in Fig. 3 was such that fresh metal surfaces were exposed to the corrosion medium.

For both procedures RST-37-2 steel exhibits the lowest resistance to the cocoa environment as shown by the weight loss data. This was followed by galvanized steel, with ST-60-Mn steel showing the highest resistance.

The weight loss data for tests done in cocoa juice diluted with 10% distilled water are presented in Figs. 4 and 5 respectively for the data for sets A and B samples. The corrosion rate in this environment is generally lower than in the undiluted cocoa juice.. This is to be expected because addition of water dilutes the mucilage solution and thus increases the pH of the electrolyte. The higher the pH the more stable the oxide film on steel tends to be up to a pH of about 12. The presence of a more protective insoluble corrosion product probably resulting from the presence of additional water may thus account for this behaviour.

The complexity of the biochemical processes and the dynamic changes occurring in the cocoa mucilage environment is however recognised as this makes it difficult to make a definitive inference about corrosion mechanism in the environment. This also relates to the reproducibility of corrosion results in the environment which is rendered difficult. From the starting nucilage which is predominantly a sugar solution, the electrolyte transforms into alcohol, then acids with, possibly, other by- products and end-products, each

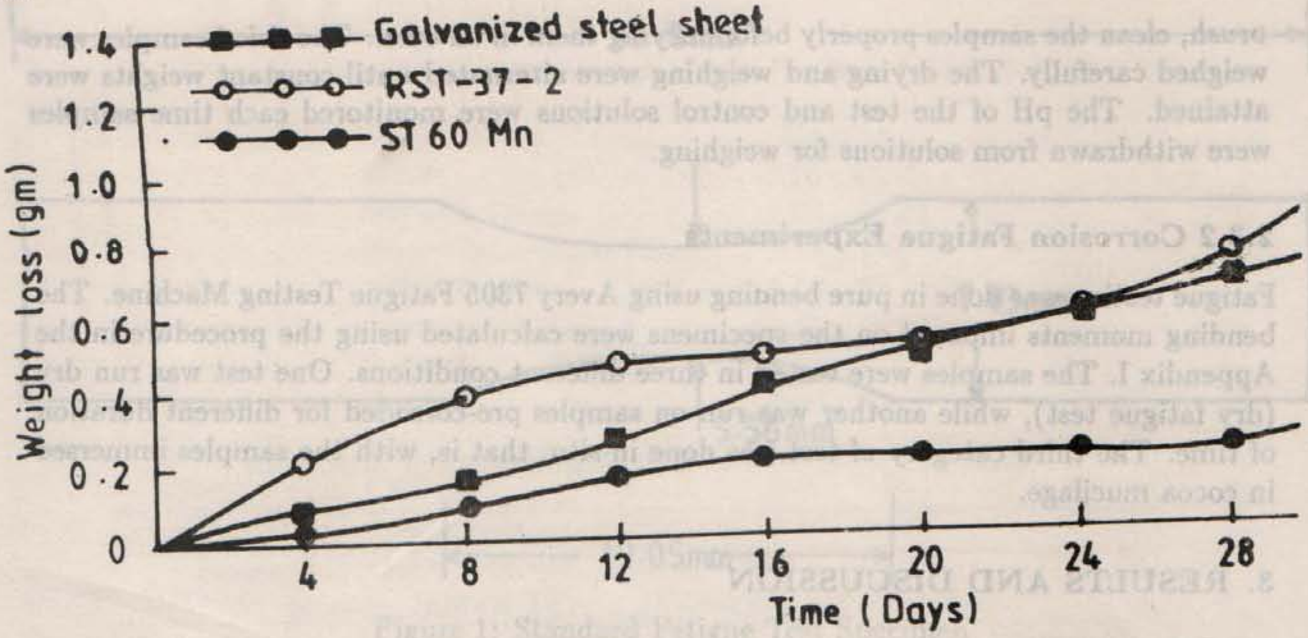

Figure 2: Weight Loss-Time Relationship for Specimens Continously Exposed to Undiluted Cocoa Mucilage

exhibiting different aggressiveness towards the exposed metal samples. The complex dynamics of the system and the on-going biochemical degradation processes make it difficult to quantify the effects of the various components of the electrolyte which also vary for different fermentation situations, impairing absolute reproducibility of results. The implication of this to the application of the results and future work is that the data reported are good in selecting materials for further investigation in actual environments simulating the service environment, as the case may be, more closely. That is, if for example, a different variety or a different batch of cocoa is used, even under the same technique of fermentation, the corrosion rate figures would be different.

It is noteworthy that the positions of RsT-37-2 steel and that of galvanized steel are reversed in Figs. 4 & 5. As noted earlier, RST-37-2 steel, shows the least resistance in the undiluted cocoa mucilage (Figs. 2 & 3) while galvanized steel exhibits the least corrosion resistance in the diluted mucilage. The presence of additional water makes the diluted solution more aggressive to zinc and zinc-iron alloy layers on the galvanized steels. This is to be expected. It is because of the electronegativity of zinc with respect to iron or steel in the presence of water that it is widely used as a sacrificial anode coating on steels.

The plots of pH variation for both types of tests (Figs. 6 and 7) show that the pH rises for the first 4 days, drops over the next four days before picking up again for the remaining duration of the tests. It is to be noted that the tests were carried out mostly in the absence of cocoa beans, hence the trend in pH variation between day 4 and day 8 is not anomalous The pH declined during this period to emphasize the increasing acidity of the fermenting pulp, because there were no beans to absorb the acids produced as in normal fermentation. Generally, the almost continuous rise in the pH reflect the production of acetic acid and some lactic acid which are weaker acids than the citric acid present in the

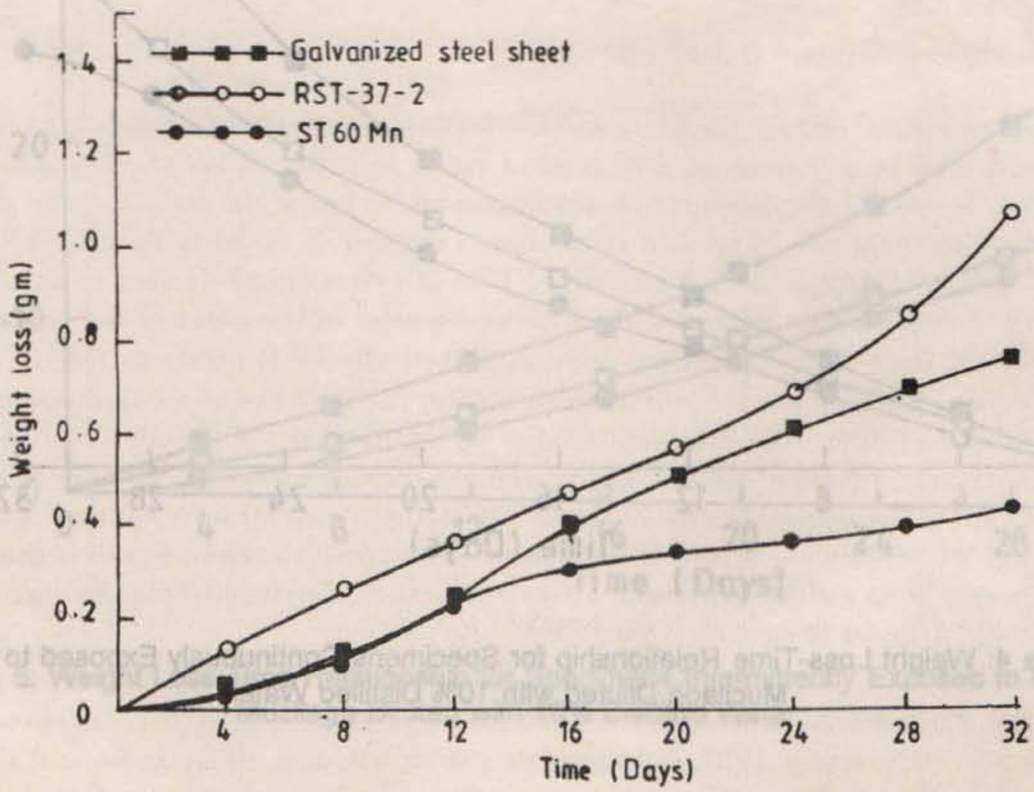

Figure 3: Weight Loss-Time Relationship for Specimens Intermittently Exposed to Undiluted Cocoa Mucilage

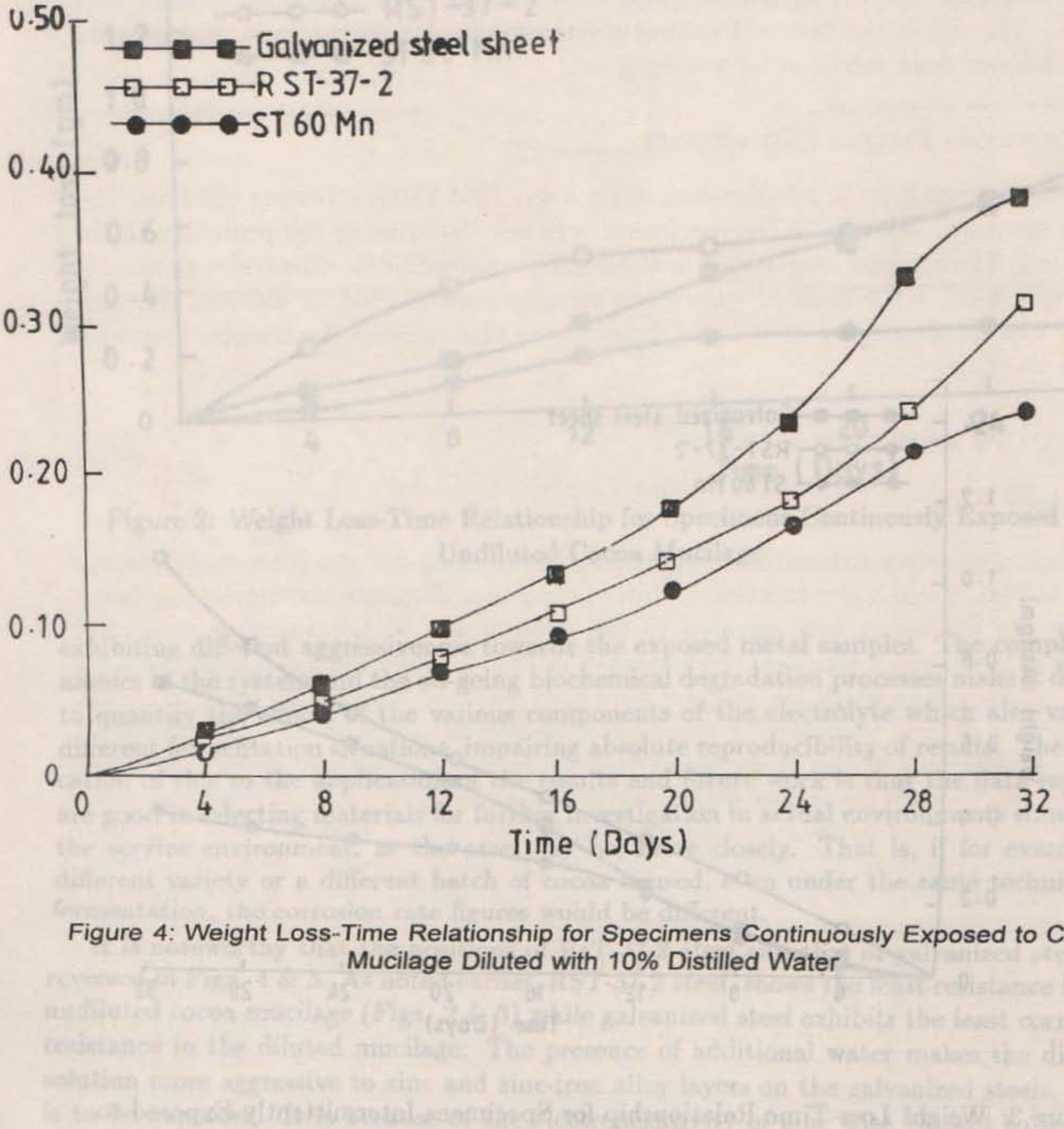

Figure 4: Weight Loss-Time Relationship for Specimens Continuously Exposed to Cocoa Mucilage Diluted with 10% Distilled Water

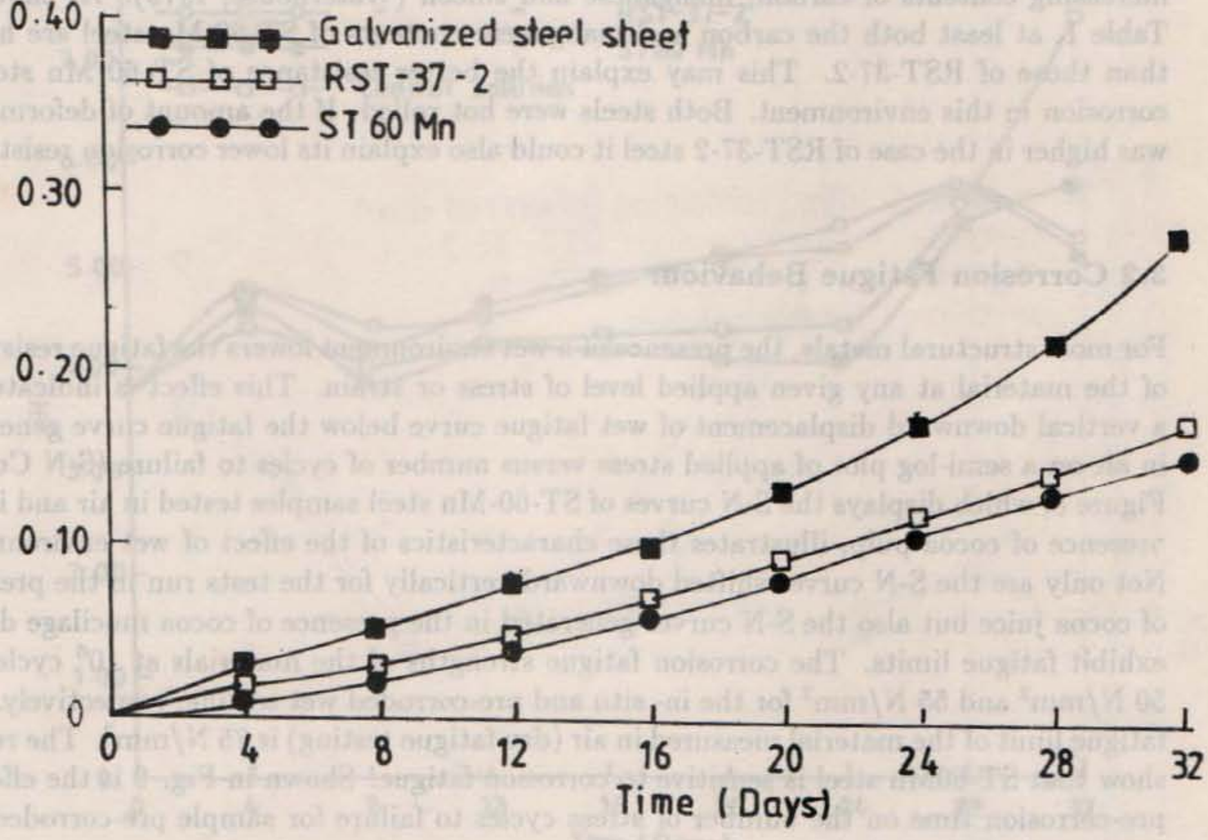

Figure 5: Weight Loss-Time Relationship for Specimens Intermittently Exposed to Cocoa Mucilage Diluted with 10% Distilled Water

fresh pulp.

The difference between the corrosion resistance of RST-37-2 and that of ST-60-Mn steels may be related to their composition. The variation in the content of elements such as carbon, manganese, silicon, copper, etc., in ordinary steels affect the corrosion behaviour of that steel to some degree, with the corrosion rate tending to decrease with increasing contents of carbon, manganese and silicon (Waterhouse, 1979). As shown in Table 1, at least both the carbon and manganese contents of ST-60-Mn steel are higher than those of RST-37-2. This may explain the better resistance of ST 60 Mn steel to corrosion in this environment. Both steels were hot rolled. If the amount of deformation was higher in the case of RST-37-2 steel it could also explain its lower corrosion resistance.

3.2 Corrosion Fatigue Behaviour

For most structural metals, the presence of a wet environment lowers the fatigue resistance of the material at any given applied level of stress or strain. This effect is indicated by a vertical downward displacement of wet fatigue curve below the fatigue curve generated in air on a semi-log plot of applied stress versus number of cycles to failure (S-N Curve). Figure 8, which displays the S-N curves of ST-60-Mn steel samples tested in air and in the presence of cocoa pulp, illustrates these characteristics of the effect of wet environment. Not only are the S-N curves shifted downward vertically for the tests run in the presence of cocoa juice but also the S-N curves generated in the presence of cocoa mucilage do not exhibit fatigue limits. The corrosion fatigue strengths of the materials at 10^6 cycles are 50 N/mm^2 and 55 N/mm^2 for the in- situ and pre-corroded wet testing, respectively. The fatigue limit of the material measured in air (dry fatigue testing) is 75 N/mm^2. The results show that ST-60Mn steel is sensitive to corrosion fatigue. Shown in Fig. 9 is the effect of pre-corrosion time on the number of stress cycles to failure for sample pre-corroded and wet tested. A linear behaviour is observed.

A number of theories on the mechanism of corrosion fatigue are available, but the operating mechanisms depend on the nature of the environment and the alloy system (Duquette, 1979; Scully, 1979; Johnson et al, 1958; Troiano, 1959; Jacko and Duquette, 1981). According to Duquette (1979) some of these mechanisms are: (i) stress intensification at the base of hemispherical pits formed by corrosion medium; (ii) chemical attack at plastically deformed areas with non-deformed areas acting as cathodes; (iii) film- breakdown or rupture exposing fresh metal to electrochemical attack; and (iv) adsorption of environmental species leading to lowering of surface energy and accelerated crack propagation. In addition, fracture due to hydrogen embrittlement mechanisms can occur as a result of hydrogen ingress and migration to the crack tip region (Imasioge et al., 1991).

Any of the above mechanisms could operated during the fatigue test reported herein except for mechanism (i). Mechanism (ii) is eliminated because of the absence of visible pits (up to 100 x) on the corroded samples. Even when pits are present, as observed by Duquette (1979), their mere presence on a metal that has suffered fatigue corrosion does not necessarily mean that the cracking had been caused by the pits.

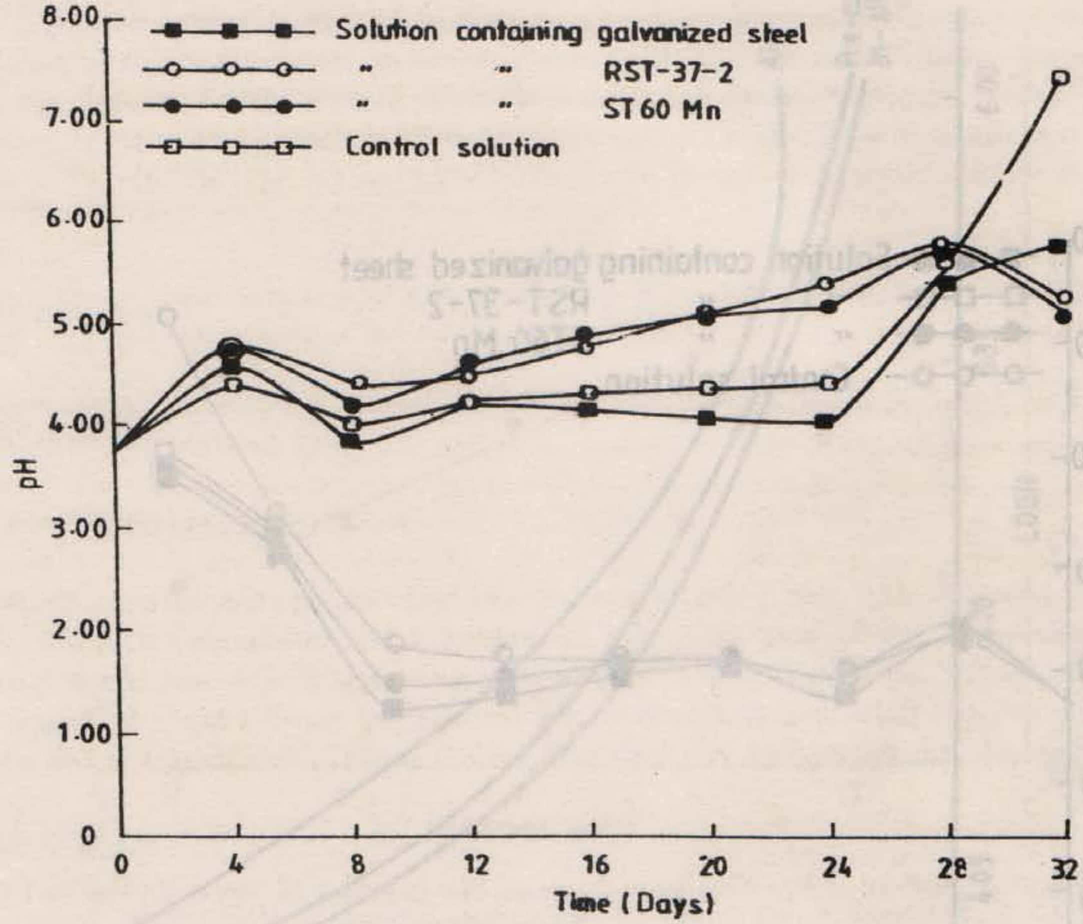

Figure 6: Variation of Pulp pH with Time in the Continuous Exposure Test

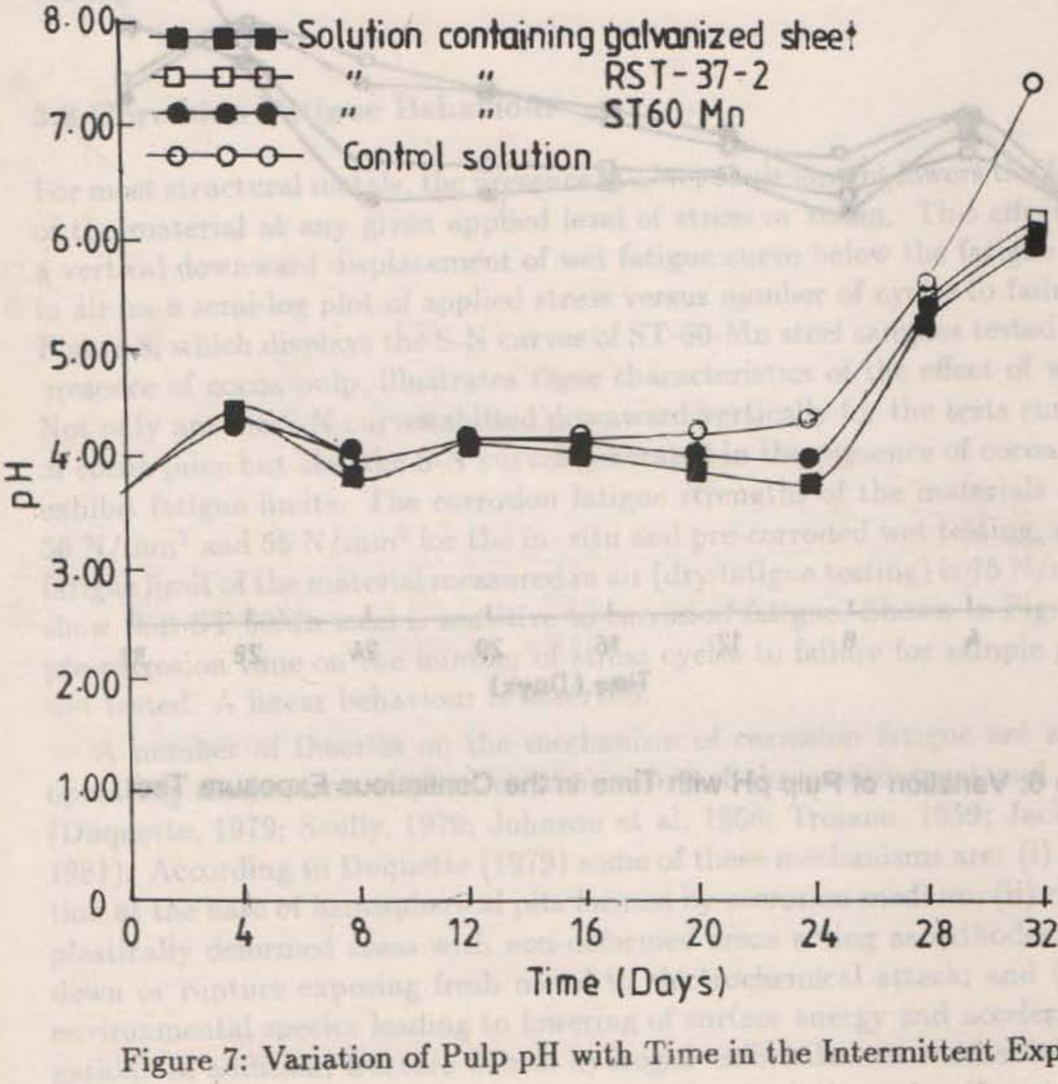

Figure 7: Variation of Pulp pH with Time in the Intermittent Exposure Test

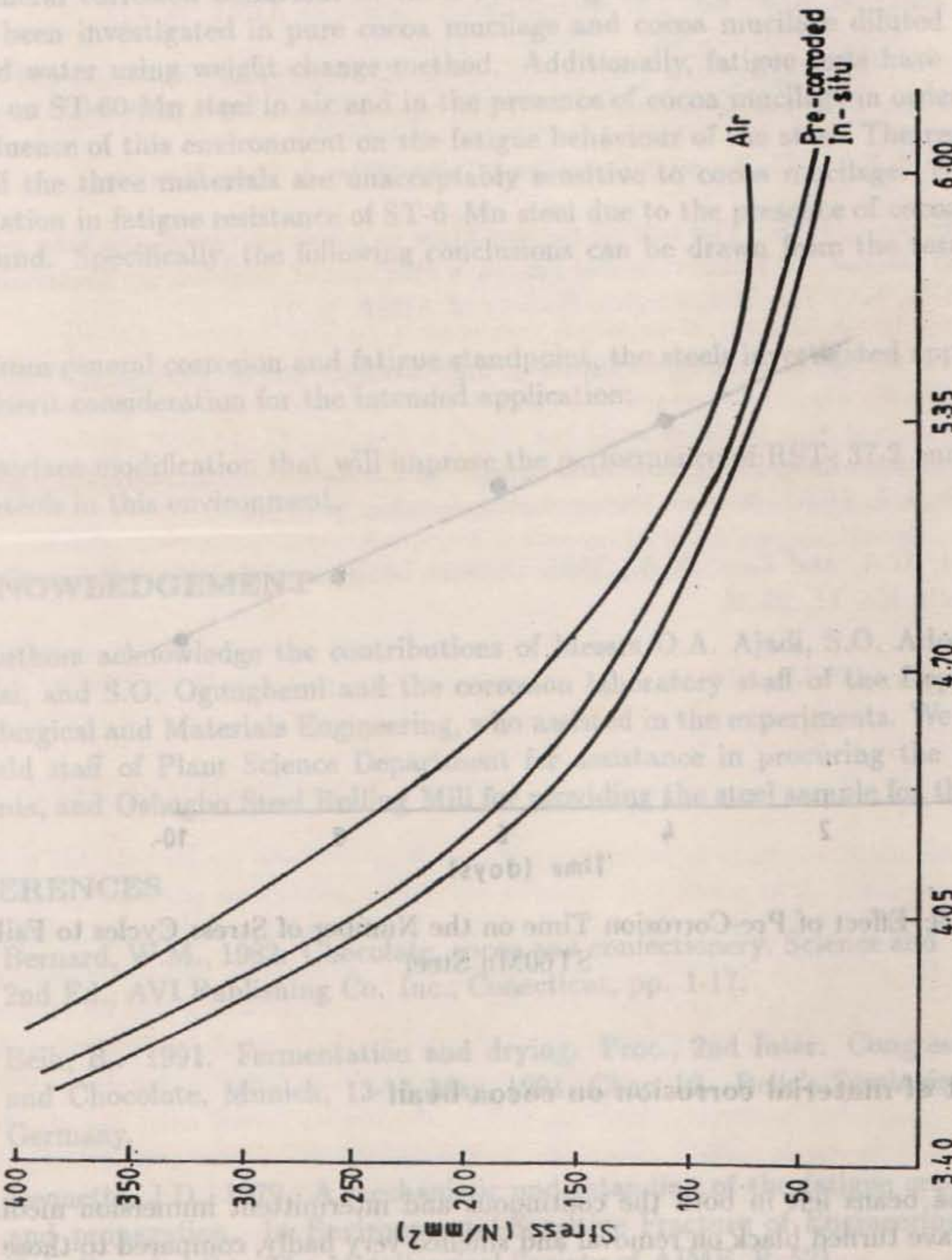

Figure 8: S-log(N) Curves for Specimens of ST-60-Mn Steel Tested dry and wet (Pre-Corroded and In-situ)

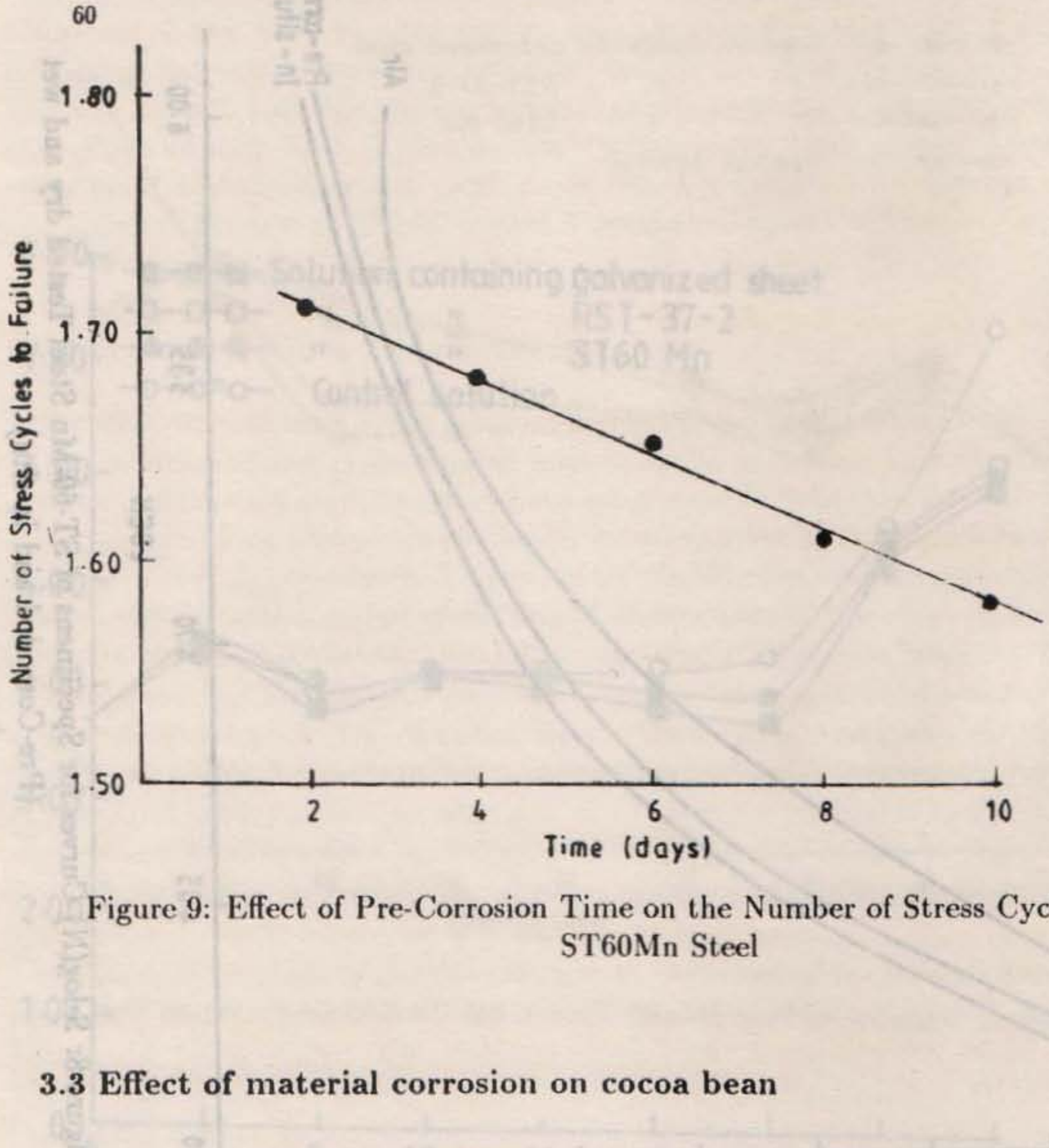

Figure 9: Effect of Pre-Corrosion Time on the Number of Stress Cycles to Failure ST60Mn Steel

3.3 Effect of material corrosion on cocoa bean

Some cocoa beans left in both the continuous and intermittent immersion media were found to have turned black on removal and smelled very badly, compared to those in the control sample which only slightly affected. The effect was generally more pronounced in the samples in the continuous immersion medium. Considering the steel materials, the beans in the ST-60-Mn were the least affected, followed by beans in RST-37-2 and the galvanized steel. These observations confirm the hypothesis that not only does the cocoa juice corrode materials of construction, the corrosion products as well have detrimental effects on the fermenting beans, with the obvious implication on the quality of the resulting raw cocoa.

4. CONCLUSION

The general corrosion behaviour of three steels - galvanized, RST-37-2 and ST-60-Mn - have been investigated in pure cocoa mucilage and cocoa mucilage diluted with 10% distilled water using weight change method. Additionally, fatigue tests have been conducted on ST-60-Mn steel in air and in the presence of cocoa mucilage in order to assess the influence of this environment on the fatigue behaviour of the steel. The results show that all the three materials are unacceptably sensitive to cocoa mucilage. Evidence of degradation in fatigue resistance of ST-6–Mn steel due to the presence of cocoa mucilage was found. Specifically, the following conclusions can be drawn from the results of the study:

1. from general corrosion and fatigue standpoint, the steels investigated appear not to merit consideration for the intended application;

2. surface modification that will improve the performance of RST- 37-2 and ST-6-Mn steels in this environment.

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APPLICATION OF HERTZ'S THEORY OF CONTACT STRESSES TO COCOA POD DEFORMATION

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Abstract

Hertz's theory of contact stresses was employed in the analysis of cocoa pod deformation when subjected to a uni-axial compressive stress, in its lateral axis, between rigid parallel plates. A two- sample t-test comparison of the experimentally measured values of the stiffness modulus and those obtained from the initial Hertz theory equations indicated a very significant difference, which was observed to be due to the irregular shape of the pod, its furrowed circumference and internal hollowness. Correcting factors developed to account for these irregularities significantly improved the predictions of the modified Hertz relation.

KEYWORDS: Hertz theory, cocoa pod, agric product deformation, contact stress.

1. INTRODUCTION

One of the operations involved in the on-farm processing of cocoa is the breaking of the pods to extract the wet beans, which are subsequently fermented. Until now this is done manually, but efforts are being made by researchers (Jimenez, 1967; Ofi, 1980; Faborode and Oladosu, 1990) to develop a mechanical device for pod breaking. It is considered necessary to first characterize the pod's breaking behaviour, by carrying out compressive loading tests (ASAE, 1990), to obtain its force-deformation characteristics.

Although agricultural materials are generally non homogeneous, non-isotropic or non-elastic it has been found possible to define an elastic range of behaviour within which their elastic parameters can be quantified. Moshern (1986) observed that under small strains most agricultural materials exhibit extensive elasticity, to which the Hertz theory of contact stresses is applicable.

An earlier work (Maduako, 1989) on the mechanical properties of cocoa pods has shown that its breaking under parallel plate loading is a complex process, in which the stress and strain cannot be accurately measured because of the variation in the area under load with increased loading. Hence adopting the methods employed by Rehkugler (1964) and Reece and Lot (1975) in their studies on the breaking of eggs, the breaking force and the absolute deformation were measured to define a stiffness modulus, which is the ratio of the maximum failure load to the deformation at failure. The force-deformation curve was observed to be mostly linear.

The objective in this work is to adapt the Hertz theory of contact stresses to predicting the stiffness modulus of a cocoa pod, from its independent physical properties and hence provide a better theoretical basis for understanding its breaking behaviour.

2. THEORETICAL DEVELOPMENT

2.1 The Fundamental Hertz Relations

In deriving Hertz relationships for contact stresses, certain fundamental assumptions are imperative. These are; that the material is homogeneous, the load is static, the surfaces are smooth, and that the radii of curvature of the contacting bodies, by far, exceed the radius of the contact surface (Mohsenin, 1986). This latter assumption implies that only a normal (compressive) stress arises over the contact surface, the effect of tangential stress being negligible.

Timoshenko and Goodier (1951) derived an expression relating the applied force to the radius of the contact surface as:

$$a = \left[\frac{3}{4}\pi F(\Lambda_1 + \Lambda_2)\left(\frac{R_1 R_2}{R_1 + R_2}\right)\right]^{\frac{1}{3}} \tag{1}$$

where a = radius of the contact surface

F = applied force between contacting bodies

Λ_1= material/property constant of first body (body 1)

Λ_2= materials/property constant of the second body (body 2)

R_1= radius of curvature of body 1, and;

R_2 = radius of curvature of body 2

The total deformation of both bodies in contact was then given as:

$$D = \left[\frac{9}{16}\pi^2 F^2(\partial_1 + \partial_2)\left(\frac{R_1 R_2}{R_1 + R_2}\right)\right]^{\frac{1}{3}} . \tag{2}$$

Most fruits are convex, ellipsoidal or spheroidal in shape (Mohsenin, 1986; Peleg, 1984). Mohsenin (1986), considered the case of contact between two fruits, one having minimum and maximum radii of curvature R_1 and R'_1, and the other, R_2 and R'_2. Their combined deformation was expressed as:

$$D = \frac{3K}{2}\left[\frac{F^2A^2}{2}\left(\frac{1}{R_1}+\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_2}\right)\right]^{\frac{1}{3}} \quad (3)$$

and A, which relates the poison ratio of the bodies to their elastic moduli, is given by the following expression, i.e:

$$A = \frac{1-V_1^2}{\pi E_1} + \frac{1-\nu_2^2}{\pi E_2} \quad (4)$$

where K = shape constant

V_1, V_2 = poison ratios of the bodies

E_1, E_2 = Young moduli of elasticity of the bodies.

In Eqn. 3, the contact area between the two bodies was considered elliptic rather than circular as indicated in the case of spherical fruits (Holt and Schoorl, 1977; Schoorl and Holt, 1980). This accords well with the ellipsoidal shape of cocoa pods to be about 51%.

For compression between rigid parallel plates, the radii of curvature of the flat plates are assumed to be infinite, so that $1/R_2 = 0$ and $1/R_2 = 0$ in Eqn. 3, giving;

$$D = \frac{3K}{2}\left[\frac{F^2A^2}{2}\left(\frac{1}{R_1}+\frac{1}{R_1}\right)\right]^{\frac{1}{3}} \quad (5)$$

For the particular case of a rigid plate, made of steel, in terms of the elastic modulus E,

$$A = \frac{1-\nu^2}{\pi E_1}$$

and Eqn. 5 becomes (Moshenin, 1986);

$$E = \frac{0.338K^{\frac{3}{2}}F(1-\nu^2)}{D^{\frac{3}{2}}}\left(\frac{1}{R_1}+\frac{1}{R_1}\right)^{\frac{1}{2}} \quad (6)$$

2.2 Basic Hertz Theory Equations for a Cocoa Pod

In order to adapt the hertz equation to the loading of a cocoa pod, the stiffness modulus is used in place of the elastic modulus. hence Eqn. 6 for the parallel loading case translates to:

$$S = \frac{0.338K^{\frac{3}{2}}FA_o(1-\nu^2)}{2R_1D^{\frac{3}{2}}}\left[\frac{1}{R_1}+\frac{1}{R_i'}\right]^{\frac{1}{2}} \quad (7)$$

where S = stiffness modulus, and A_o is the contact area on which the force is acting. For loading with a spherical indenter, a similarly analysis gives;

$$S = \frac{0.338K^{\frac{3}{2}}F(1-\nu^2)A_o}{2R_1D^{\frac{3}{2}}}\left[\frac{1}{R_1}+\frac{1}{R_1'}+\frac{4}{d_i}\right]^{\frac{1}{2}} \quad (8)$$

Eqns. 7 and 8 are the basic Hertz theory equations for a cocoa pod under parallel plate and spherical indenter loading respectively, based on the assumptions made in section 2.1

3. EXPERIMENTAL WORK

3.1 Experimental materials

Pod samples of the two common and commercially grown varieties of Nigerian cocoa, namely, Amelonado and F_3 Amazon, were harvested from the Obafemi Awolowo University Teaching and Research Farm in Ile-Ife, Nigeria. The samples were selected to ensure that various sizes of the different varieties were represented, and only ripe healthy pods were used.

3.2 Test equipment and methodology

Quasi-static, uniaxial parallel plate compression test was pertormed on whole pod sample of the two varieties. Loading was done on the lateral axis. The machine used was the universal testing machine (proving ring model ELE 1152 - 8082), as shown in Fig. 1. Before the tests, the axial length and diameter of each pod was measured. After loading to breakage, the contact areas of the pod surface with the plates were determined from an impression stained on sheets of white paper placed in-between them. An analog planimeter (ARISTO model) was used for evaluating the area. The force-deformation curves obtained were subsequently analyzed to obtain the stiffness modulus, and the toughness - as the area under the curve.

4. RESULTS AND DISCUSSION

The basic breaking characteristics of cocoa pods are presented in Table 1. The mean values of the maximum breaking force, the deformation at failure, the toughness and the stiffness modulus are 0.715 ± 0.038 kN, 7.6 ± 0.37 mm, $2.74 \pm 0.27J$ and $94.1 \pm 6.3kN/m$ respectively for F_3 Amazon cocoa pods. The corresponding values for Amelonado cocoa pods are $0.553 \pm 0.034kN$, 6.38 ± 0.44 mm, 1.70 ± 0.16 J and 89.8 ± 6.44 kN/m. F_3 Amazon cocoa pods offer greater resistance to breakage than Amelonado pods. This must be related to the higher thickness of F_3 Amazon pod husks (Maduako and Faborode, 1990).

Tables 2 and 3 summarize the application of Hertz theory to cocoa pod deformation. First the measured values (S_r), and the values obtained from the basic hertz theory (S_c) were compared, using a two sample t-test. Stiffness modulus values S_c were obtained from Eqn. 7. by substituting the various values of the pods physical dimensions, radii of curvature at the point of contact with loading plates, contact area at failure, the deformation of the pod, and the maximum load, and using a poison ratio of 0.30.

The tests show that the difference between the pairs of value was significant at the 99% confidence level. The difference could be attributed to some of the assumptions of hertz which were not quite justified for cocoa pods. Firstly, a cocoa pod is not a homogeneous isotropic material. Rather, it has been shown to be a composite fruit consisting of three distinct constituents, namely the beans, the central placenta with mucilage and the enclosing pod husk (Maduako and Faborode, 1990). Secondly, the surface of the pod

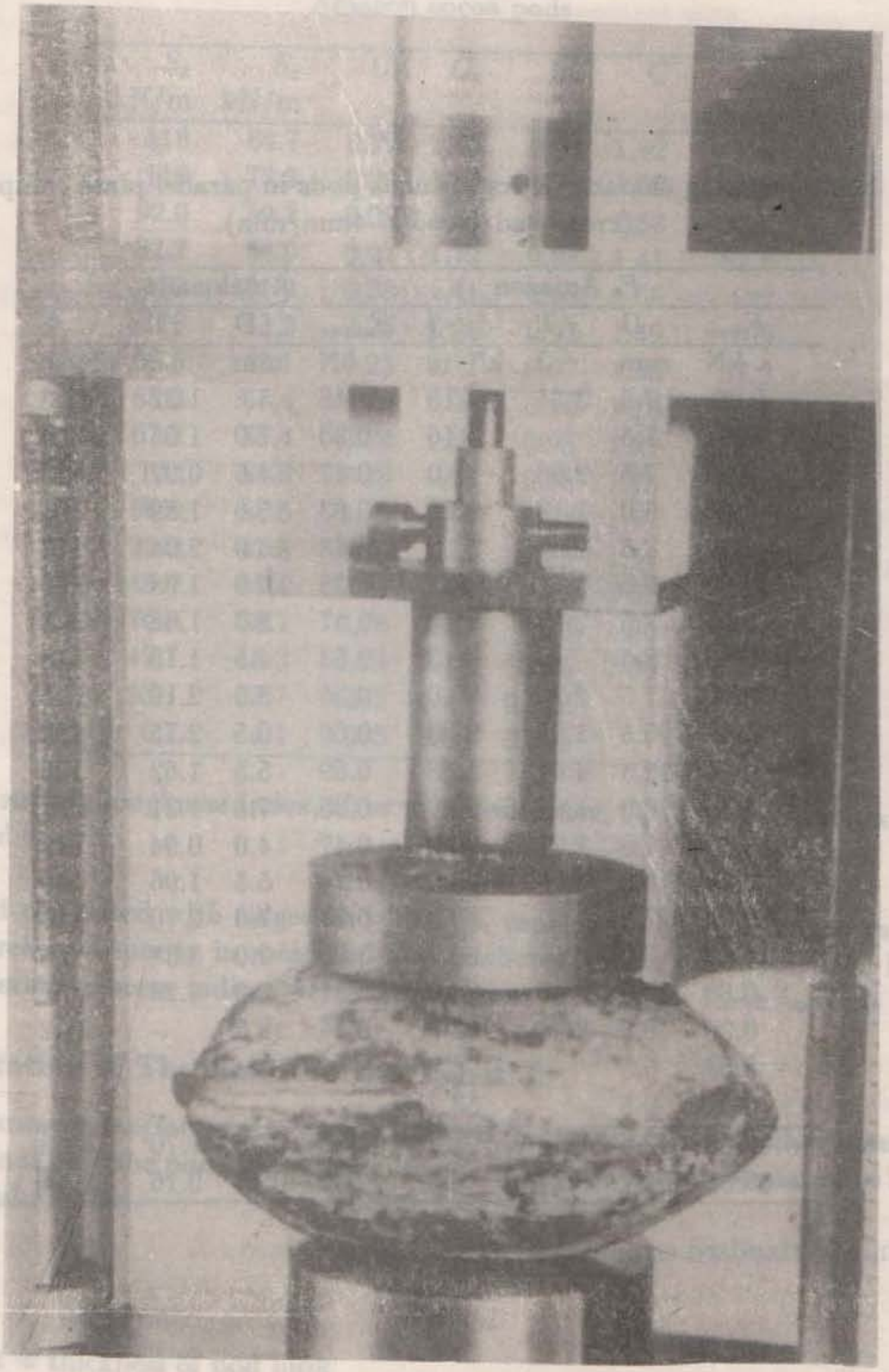

Figure 1: Compression test rig with a pod loaded in the lateral axis

Table 1: Some breaking characteristics of cocoa pods in parallel plate compression test (crosshead speed = 4mm/min).

	F_3 Amazon				Amelonado			
	F_{max}	D	T	S	F_{nmax}	D	T	S
	kN	mm	J	kN/m	kN	mm	J	kN/m
	0.89.	7.5	3.34	118	0.48	5.5	1.32	87.3
	0.87	7.5	-	116	0.30	7.0	1.05	42.9
	0.69	7.5	2.58	92.0	0.42	4.6	0.97	91.3
	0.45	5.0	1.13	90.0	0.63	6.0	1.89	105
	0.69	7.5	2.59	92.0	0.68	6.0	2.04	113
	0.69	6.5	3.12	148	0.36	6.0	1.08	60.0
	0.57	7.5	2.14	76.0	0.47	8.0	1.88	58.8
	0.96	8.5	-	113	0.53	4.5	1.19	118
	0.60	7.5	2.25	80.0	0.54	8.0	2.16	67.5
	0.60	6.5	1.95	92.3	0.66	6.5	2.15	102
	0.71	12.5	4.44	56.8	0.59	5.5	1.62	106
	0.54	6.0	1.62	90.0	0.35	7.5	1.31	46.7
	0.63	7.0	2.21	90.0	0.47	4.0	0.94	116
	0.90	9.0	4.05	100.0	0.74	5.5	1.96	140
	0.86	7.5	-	60.0	0.77	7.0	2.70	110
	0.46	7.0	-	65.7	0.75	9.0	3.38	83.3
	0.88	10.0	4.40	88.0	0.51	5.0	1.28	102
	0.90	5.5	2.48	164.0	0.84	12.5	-	67.2
	0.63	6.5	-	96.9	-	-	-	
	0.51	9.5	-	53.7				
x	0.715	7.6	2.74	94.1	0.553	6.38	1.70	89.8
e	0.038	0.37	0.27	6.3	0.034	0.44	0.16	6.44

x = mean, e = standard error

Table 2 Comparison of measured and predicted values of stiffness modulus for F_3 Amazon cocoa pods

	S_e kN/m	S_c kN/m	C_t	C_a	C_r	C	S_h kN/m
	118	64.7	0.29	1.60	0.99	1.92	124
	116	73.3	0.29	1.38	1.99	1.66	121
	92.0	59.2	0.29	1.31	0.98	1.58	93.6
	82.7	58.0	0.27	1.19	0.98	1.41	81.6
	113	71.9	0.28	1.41	0.98	1.69	122
	110	73.2	0.26	1.26	0.97	1.49	109
	58.8	42.1	0.23	1.17	0.97	1.36	57.2
	83.3	61.4	0.29	0.96	0.96	1.19	73.7
	67.2	36.4	0.28	1.52	0.95	1.27	68.7
	102	54.0	0.26	1.60	0.98	1.75	107
	90.0	53.5	0.28	1.45	0.98	1.97	93.6
	92.0	42.8	0.29	1.63	0.98	1.97	84.3
	148.0	59.4	0.29	1.95	0.97	2.39	142
	76.0	38.7	0.26	1.49	0.96	1.80	69.7
	47.7	16.3	0.24	2.12	0.95	2.56	41.7
x	93.1	53.7	0.273	1.47	0.972		92.6
e	6.7	4.1	0.005	0.08	0.003		7.3

Note: C_r = surface roughness index, C_t = thickness index, C_a = shape factor, x = mean, e = standard error.

is rough and contoured with ridges and furrows, especially the F_3 Amazon variety, for which the greater disparity in measured and predicted values were recorded. Based on these considerations some indices were introduced to account for these factors.

4.1 Modification of The Basic Hertz's Equation

1. **A thickness index/factor, C_t, was introduced to account for the hollow nature of the pod, since only the pod husk appears to offer any appreciable resistance to breakage (Maduako, 1989).**

$$C_t = \frac{2t}{d} \tag{9}$$

where t = thickness of pod husk

d = diameter of pod at contact point

2. **A pod shape factor, C_a, was to take care of the deviation of the contact surface between the pod and the loading plates from the theoretical elliptical shape it was**

Table 3 Comparison of measured and predicted values of stiffness modulus for Amelonado cocoa pods.

	S_r kN/m	S_c kN/m	C_t	C_a	C_r	C	S_h kN/m
	91.3	75.2	0.28	0.94	0.93	1.19	89.5
	88.0	42.2	0.27	1.49	0.92	1.90	80.2
	90.0	52.7	0.29	1.26	0.93	1.61	84.9
	87.3	68.8	0.32	0.91	0.92	1.20	82.5
	105	98.3	0.30	0.85	0.93	1.10	108
	113	83.2	0.30	0.97	0.93	1.38	114
	80.0	55.6	0.27	1.12	0.93	1.40	77.8
	90.0	54.0	0.29	1.35	0.93	1.72	92.8
	60.0	57.0	0.28	0.89	0.94	1.12	61.5
	60.0	36.1	0.28	1.36	0.93	1.72	62.2
	100	90.6	0.27	0.94	0.93	1.17	106
	60.0	33.2	0.29	1.43	0.93	1.83	60.5
	92.3	72.1	0.27	0.94	0.93	1.18	85.1
x	85.9	63.0	0.290	1.11	0.930		85.0
e	4.7	5.7	0.004	0.06	0.001		4.8

Note: C_r = surface roughness index, C_t = thickness index, C_a = shape factor, x = mean, e = standard error.

assumed to be on the basis of the pods being true ellipsoids.

$$C_a = \frac{\text{theoretical elliptic contact area}}{\text{actual contact area measure}} \tag{10}$$

3. A surface roughness index C_r, was introduced to account for the corrugation of the pod surface with furrows and ridges, and is defined as;

$$C_r = 1 - \frac{t_r - t_f}{R} \tag{11}$$

where T_r = thickness of the husk at the ridge

t_f = thickness of the husk at the furrow, and

R = radius of pod at contact point.

The effect of all three correcting indices on the Hertz's equation was analyzed through dimensional analysis and a combined correction factor (C) was developed to improve the Hertz's relation:

$$C = \frac{C_a}{C_r(1 - C_t)^{\frac{1}{2}}} \tag{12}$$

4.2 The modified Hertz Equation

The final form of the Hertz's relation for cocoa pod is as follows;

$$S = \frac{0.242 C_a A_o \left(\frac{1}{R_1} + \frac{1}{R_1}\right)^{\frac{1}{2}}}{R_1 D^{\frac{3}{3}} C_r (1 - C_t)^{\frac{1}{2}}} \tag{13}$$

or

$$S = \frac{0.242 C A_o}{R_1 D^{\frac{3}{2}}} \left(\frac{1}{R_1} + \frac{1}{R_1'}\right)^{\frac{1}{2}} \tag{14}$$

All the symbols are as defined previously.

The values of the correcting indices and overall correcting factor as calculated are given in Tables 2 and 3. The modified prediction of stiffness modulus is also summarized. Statistical analysis confirm the goodness of fit of the predicted values for both cocoa varieties at the 99% confidence level.

An examination of the correcting indices indicate that C_t and C_r are fairly constant, being on the average, 0.273 ± 0.005 and 0.972 ± 0.003 respectively for F_3 Amazon, and 0.290 ± 0.004 and 0.930 ± 0.001 for the Amelonado variety. Using the mean values in Eqn. 12, the combined correction factor (C) can be expressed in terms of only shape factor C_a as follows:

for F_3 Amazon; $C = 1.205C_a$
for Amelonado; $C = 1.276C_a$

This implies that only the shape factor need be determined thus reducing the measurements and computation needed to use the modified hertz relation for analysis of cocoa pod deformation.

5. CONCLUSION

The Hertz contact stress theory was modified for use in the analysis of cocoa pod deformation by incorporating correcting indices which reflect the pods internal hollowness, surface roughness and irregular shape. The modified relation gave good prediction of the stiffness modulus of cocoa pods when subjected to compression between two rigid parallel plates. The shape factor was the most variable as the other two factors appear to be fairly constant for a given cocoa variety.

NOTATION

A = an index which relates the poison ratio of the bodies in contact to their elastic mod
A_o = the contact area on which the force is acting, m^2
A = radius of the contact surface, mm
C = combined correction factor
C_t = thickness index/factor
C_a = pod shape factor
C_r = pod surface roughness index
D = total deformation of the bodies in contact, mm
d = diameter of pod at contact point, mm
d_i = diameter of spherical indenter, mm
E, E_1, E_2 = Young moduli of elasticity of the bodies, N/mm^2
F = applied force between contacting bodies, kN
F_{max} = maximum breaking force, kN
k = shape constant
R = radius of pod at contact point, mm
R_1, R_1' = minimum and maximum radii of curvature of body 1, mm
R_2, R_2' = minimum and maximum radii of curvature of body 2, mm
S = stiffness modulus, kN/m
S_c', S_e = calculated and measured stiffness modulus, kN/m
S_h = improved calculated stiffness modulus, kN/m
t = thickness of pod husk, mm
t_r = thickness of the husk at the ridge, mm
t_f = thickness of the husk at the furrow, mm
Λ_1 = material/property constant of first body (body 1)
Λ_2 = material/property constant of the second body (body 2)

ν, ν_1, ν_2 = poison ratios of the bodies

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