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DEVELOPMENT OF A CENTRIFUGE FOR HIGH-SPEED CENTRIFUGAL EXTRACTION OF MOISTURE FROM MACERATED WATER HYACINTH

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ABSTRACT

Rapid mechanical dewatering of fibrous vegetative materials like water hyacinth requires separation of the process into two steps of maceration (cell breakage) and moisture extraction, to allow individual optimization for speed and efficiency. To fulfill the second step, centrifugal moisture extraction was explored. Centrifugal moisture extraction characteristics were determined using a fabricated batch loading centrifuge to determine its potential for rapid moisture extraction. A continuous-loading conical centrifuge was designed, fabricated and tested for continuous high-capacity moisture extraction from macerated of water hyacinth.

Batch centrifuge tests were conducted to establish the performance parameters for centrifugal moisture expression from macerated water hyacinth. The tests showed the following basic trends:

- *Percent moisture extraction, weight reduction, and vegetable matter loss significantly increased with increasing degree of maceration.*
- *Percent moisture extraction, weight reduction, and vegetable matter loss increased as centrifugal acceleration was increased.*
- *Percent moisture extraction, weight reduction, and vegetable matter loss increased with increasing spin duration.*

Moisture and weight reduction were observed to exponential functions of spin duration and a critical spin duration of 5 seconds was determined for all treatments. Moisture and weight reduction were also found to be a linear function of centrifugal acceleration. Little change, however, resulted from increasing levels of centrifugal acceleration. Greater moisture and weight reduction resulted from increasing degree of maceration (through extrusion in a die ring with small hole diameter or several maceration passes). The target moisture reduction was attained at a centrifugal acceleration of 1341-g, 5 seconds spin duration and with the hyacinth macerated in a 6.35 mm die ring or twice macerated in a 12.70 mm die ring.

To achieve higher throughput and better efficiency, a cone type continuous-loading centrifuge was designed, constructed and tested. The prototype, however, did not function properly due to the inherent difficulty of controlling the flow of fibrous macerated material up the conical screen surface. The material tended to form a mat that was difficult to break and which remained fixed on the cone surface. A system for controlled and positive displacement of the material along the conical screen surface should solve the problem, but will complicate the design, require high fabrication tolerances and increase machine costs considerably.

I. Introduction

Water hyacinth (Eichornia crassipes) is one of the most successful colonizers of the plant world. This free-floating fresh water plant has spread from the tropical South America to at least fifty countries around the world (Wolverton and McDonald, 1979). It has proved to be a persistent and expensive aquatic weed problem costing millions of dollars to control and unaccounted millions of dollars mere in damages to the environment, irrigation systems and crops.

Over the years, various control methods have been studied and tried including chemical, mechanical, biological means but with no lasting success. Water hyacinth persists and continues to spread. The problem is often aggravated by the ever increasing nutrient enrichment (eutrophication) of our water bodies brought about by excessive use of fertilizers, industrialization, population growth simultaneous with the rising demand for clean water (Baruah, 1983).

Of the control methods mentioned, harvesting by manual or mechanical means offers many advantages. Control by manual and mechanical harvesting has been widely practiced in many countries but the enormity of the hyacinth problem is staggering and the current harvesting and disposal techniques are so inadequate that it is often abandoned in favor of chemical control. Nevertheless, it is still used in many places because of its many advantages; it is target specific and has predictability of weed removal and more importantly, it is environmentally sound (Hasler, 1969; Baruah, 1983). It does not involved potentially hazardous chemical or biotic agent. Harvesting helps reduce or control eutrophication of water bodies through the removal of nutrients in the harvested plants. It is the only method of control, which allows utilization of the harvested plants and, thus, has the potential for an economically self-sustaining operation.

Despite the advantages of mechanical harvesting, it has serious bottlenecks which limit productivity and, consequently, increase harvesting costs. Brunh et.al. (1970). Aboaba et.al. (1973) and Baruah (1983) pointed out two main problems which contribute to low productivity: first is the low forward speed attainable by the harvester when pushing a large conveyor through the water and second, the great bulk and weight of materials to be handled and transported. Since water hyacinth leaves the water with more than 90 percent moisture content, it means that for every kilogram of dry matter handled and transported, nine or more kilograms of water must also be carried along. In addition, this water content has little value to any of the ways in which water hyacinth can be utilized. In fact, this high moisture condition limits the ways of utilizing hyacinth and adversely affects the economics of its utilization.

It is obvious, therefore, that to make mechanical harvesting an acceptable and effective control measure for water hyacinth, substantial improvements in harvesting rates must be achieved. A major step in this direction would be the development of a high capacity processing system onboard the harvester to reduce the bulk and weight of harvested materials (by chopping and dewatering) while in operation. Previous work by Brunh et.al. (1970) on the harvesting of water milfoil and filamentous algae have shown that the harvesting operation can be made four to six times more productive by providing the processing equipment on the harvester barge. It is also expected that processing will improve the utility of hyacinth and thus, further improve the economic viability of harvesting.

The development of a system for rigid dewatering of water hyacinth is, therefore, the critical task at hand. From a review of various devices for dewatering vegetative materials, the following conclusions were made.

- The dewatering process is facilitated by separating it into two sub-processes of maceration (cell rupture) to release liquid from the plant cells, and fractionation (liquid expression) to remove the liquid from the macerated matrix.
- Rotary extrusion devices appear to be the best type of equipment for efficient and rapid maceration of vegetative materials, as was demonstrated on alfalfa.
- Liquid expression from macerated material, on the other hand, can best be done using cone press or roller press. Cone press, however, requires a complicated drive system because of its geometric configuration.
- Centrifugal dewatering is also a viable alternative, as it offers high throughput and efficient operation, particularly for continuous loading systems. Its performance on macerated vegetative materials, however, has yet to be demonstrated.

The work reported in this paper concerns moisture expression from macerated water hyacinth using centrifugal devices.

II. Main Objectives

The major goal of the study was to identify, design and test a processing system capable of rapid dewatering of water hyacinth to at least 50 percent moisture reduction, and demonstrate its potential.

This paper presents the results of an investigation on the potential of centrifugal moisture expression from macerated water hyacinth, with the following specific objectives:

- Evaluate the centrifugal moisture expression performance for macerated water hyacinth, using a batch-loading centrifuge while varying the degree of maceration, centrifugal acceleration and spin duration.

- Design, fabricate and test a continuous-loading centrifuge for water hyacinth and evaluate its performance.

III. Materials and Methods

3.1 General Aspects

The basic approach followed in developing a system for rapid mechanical dewatering of water hyacinth was to separate the process into two sub-processes of maceration (cell rupture) and fractionation (moisture expression), and design separate devices for each. The rationale behind this approach is that the two sub-processes have different physical requirements which have to be met individually, otherwise, excessive energy requirements can result (Basken et.al., 1977). Maceration is an instantaneous and energy-intensive process, while moisture expression is a time-dependent process. Separation of these two sub-processes would allow individual optimization to achieve the goal of rapid, efficient dewatering on the whole.

The main design objectives and criteria followed were:

- Capable of at least 50 percent moisture reduction from initial moisture content
- Minimum loss of solids and nutrients to the extracted juice
- Capable of high throughput (30 Tons/hr) within practical scale-up limits
- Reasonable power and energy requirements
- Reasonable space and weight requirements to allow mounting on a harvester boat

3.2 Centrifugal Moisture Extraction from Macerated Water Hyacinth

The second phase of the dewatering process is the expression of released fluids from the macerated matrix. Moisture expression is a time-dependent process, and a given amount of liquid can be expressed over a wide range of applied pleasure levels, provided the holding time is altered accordingly (Koegel, 1972).

Numerous devices are available for moisture expression, examples of which are screw press, belt press, cone press, and batch press. However, for the particular requirements of this study, premium was placed on a machine which is simple, efficient, capable of high throughput, and a moisture extraction of at least 50 percent of initially available moisture. A viable alternative was centrifugal moisture expression which offered high throughput and efficient operation particularly for continuous-loading systems. Centrifugal equipment are much utilized in the food processing industry. Centrifugal dewatering machines are extensively used in the sugar industry for removing moisture from sugar crystals, and in the fruit juice processing industry for juice extraction from crushed fruit. Performance of these machines on fibrous materials such as macerated hyacinth, however, have yet to be demonstrated.

To assess the potential of centrifugal moisture expression, a simple batch-loading centrifuge was designed and fabricated, and basic experiments on centrifugal dewatering were conducted.

3.3 Centrifugal Moisture Extraction Experiments

3.3.1 Variables Considered and Experimentation Strategy

The primary factors affecting centrifugal moisture extraction performance that were studied included:

- Centrifugal acceleration
- Degree of material maceration
- Spin duration
- Batch load

Centrifugal acceleration determines the magnitude of centrifugal force that the material is subjected to, and corresponds to applied pressure in roller, screw, and belt presses. Centrifugal acceleration can be varied by changing the speed of rotation, or the distance of the material from the center of rotation.

Observations made by Brunh et.al. (1971) on centrifugal dewatering of unprocessed aquatic weeds, indicated that within practical limits of centrifugal acceleration, centrifugal dewatering does not rupture plant cells and removes only the surface free moisture. Consequently, moisture expression by centrifugal means is possible only after prior maceration or rapture of plant cells. The degree of initial material maceration is, thus, an important factor in determining the amount of moisture that can be extracted by centrifugal force. The degree of water hyacinth maceration was varied by macerating the sample plants at different die ring hole diameters or by increasing the number of maceration passes.

Since moisture extraction is a time-dependent process, another important parameter that was considered was spin duration or holding time. Holding times considered did not exceed 30 seconds as longer times would mean significant reduction in throughput. Experiments were also conducted to determine the effect of batch load or material thickness. The experiments conducted are summarized in Table 3.1

3.3.2 Test Set-up, Measurements and Instrumentation

The batch centrifuge utilized in the tests consists of a 150 mm diameter perforated sheet metal cylinder (vertically mounted on a shaft) with an open top and closed bottom and a sheet metal outer casing with bottom drain (Figure 3.1). The perforated cylinder is driven by a variable speed motor through a double-sheave V belt drive up to a maximum speed of 4000 RPM. A removable lining of 1.5 mm aluminum wire mesh as provided inside the cylinder to prevent smaller bits of macerated water hyacinth from escaping through the perforated walls of the centrifuge, and for easy removal of dewatered material. As electronic timer switch was also provided to control the spin duration of the centrifuge.

In operating the centrifuge, macerated material is placed inside the centrifuge while it is at rest and with the wire mesh lining installed. As the centrifuge spins, the macerated material is thrown outward by centrifugal force and is distributed uniformly on the inside surface of the centrifuge. Separation of juice from the fibrous solids is effected as juice is free to pass through the fibrous matrix and through the perforated wall of the centrifuge, while the solids are retained inside. Separated juice is caught by the outer casing and drains by gravity at the bottom.

During the tests, only weight and moisture content changes were observed so that no special instrumentation or procedures were needed. Moisture content before and after moisture expression were measured by oven drying method, while weight changes were measured using a precision 5-kg capacity digital electronic balance. Centrifuge speed was determined using a dial-type tachometer, while spin duration setting was checked using a digital stopwatch.

Table 3.1
Main centrifugal dewatering experiments conducted and variables considered.

Experiment No.	Independent Variables	No. of Levels	Level Values	Statistical Design
I	Centrifugal Acceleration	3	335g, 657g, 1341g	Factorial, 3 reps.
	Degree of Maceration	4	6.35, 9.52, 12.70, 2-pass 12.70 mm die ring	
	Spin Duration	6	2, 4, 6, 10, 20, 30 seconds	
II	Degree of Maceration	4	6.35, 9.52, 12.70, 2-pass 12.70 mm die ring	Factorial, 3 reps.
	Centrifugal Acceleration	5	483g, 657g, 858g, 1087g, 1341g	
III	Batch Load	6	100, 200, 300, 400, 500, 600 g	Factorial, 3 reps.
	Degree of Maceration	3	1-pass, 2-pass, 3-pass 12.70 mm die ring	

3.2.3 Test Procedure

Material preparation and the test procedures followed are summarized and shown in Figure 3.2. Freshly collected mature water hyacinth was first chopped and macerated to the required degree of maceration using a rotary extrusion macerator. Macerated material was the carefully mixed for even moisture distribution and covered with plastic sheet to conserve moisture.

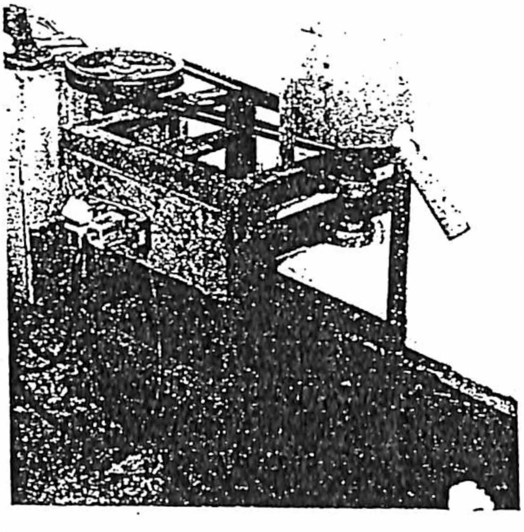

Figure 3.1 Batch-holding dewatering centrifuge utilized in centrifugal moisture extraction experiments

Test batch loads of 400 g each and 100 g samples for moisture content determination were weighed before each test run. Required centrifuge speed and spin duration were set before the test load is placed inside the centrifuge. After dewatering, the material was carefully collected and weighed. A 100 g sample was then taken for moisture content analysis.

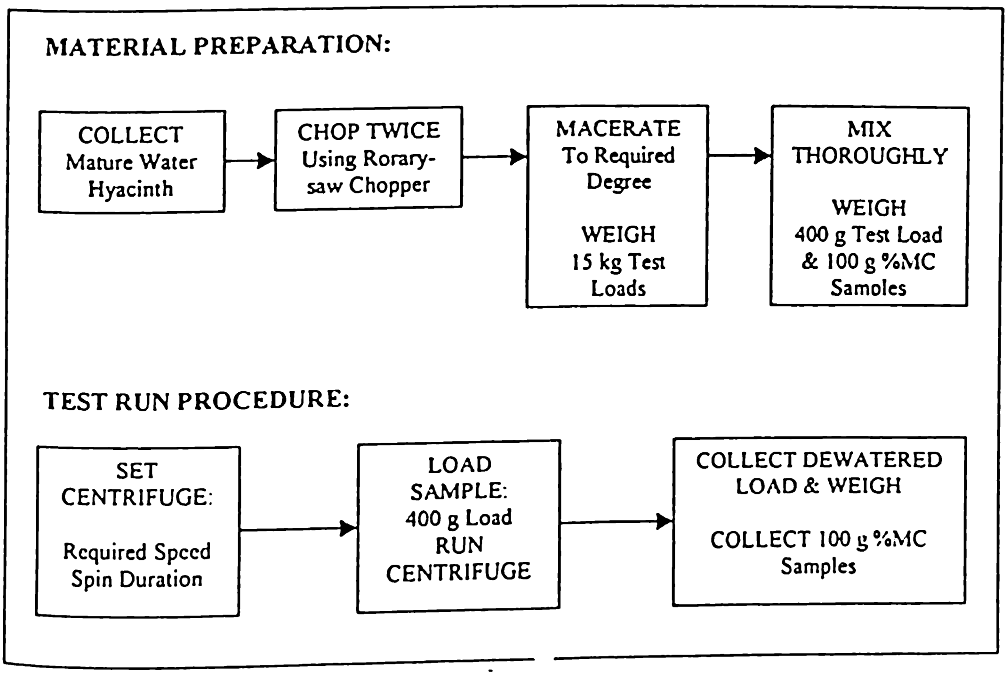

Figure 3.2 Test procedure used in centrifugal moisture extraction experiments

3.2.4 Analysis of Centrifugal Dewatering Performance

Moisture expression performance was evaluated based on the following parameters derived from measured data:

- Percent weight reduction
- Percent moisture extraction
- Percent vegetable matter loss

Regression analysis was done on the computed values for percent weight reduction and moisture extraction against main factors considered like spin duration, centrifugal acceleration, and batch load.

Percent weight reduction indicates the portion of the original weight of material that was expressed as liquid together with included solids. It was computed based on the following equation:

$$WR = ((W_i - W_f) / W_i)100\% \tag{3.1}$$

where:

WR = Percent weight reduction
W_i = Initial weight of sample, kg
W_f = Sample weight after dewatering, kg

Percent moisture extracted, on the other hand, shows part of the original moisture content that was expressed during the centrifugal moisture expression process. It was computed as:

$$MX = (1 - (W_f MC_f) / (W_i MC_i))100\% \qquad (3.2)$$

where:

MX = Percent moisture extraction
MC_i = Initial moisture content, percent (wb)
MC_f = Moisture content after moisture expression, percent (wb)
W_i = Initial weight of sample, kg
W_f = Sample weight after moisture expression, kg

Some solids or vegetable matter are normally expressed along with the juice, and this portion of the original vegetable matter content is given by percent vegetable matter loss. This parameter was derived using the following equation:

$$VML = (1 - (W_f(100 - MC_f) / (W_i(100 - MC_i)))100\% \qquad (3.3)$$

where:

VML= Percent vegetable matter loss
MC_i = Initial moisture content, percent (wb)
MC_f = Moisture content after moisture expression, percent (wb)
W_i = Initial weight of sample, kg
W_f = Sample weight after moisture expression, kg

IV. Results and Discussion

4.1 Results of Centrifugal Moisture Expression Experiment 1

The main objective of this experiment was to find out the moisture extraction behavior as a unction of spin duration (holding time) and, subsequently, identify the minimum holding time required for satisfactory moisture expression performance. The experiment was performed at four levels of maceration (12.70 mm, 9.52 mm, 6.35 mm, and 2-pass 12.70 mm die ring macerated material) and three levels of centrifugal acceleration (335 g, 757 g, and 1341 g).

Both moisture extraction and weight reduction data fitted well to exponential curves as indicated by r^2 values of 0.96-0.99 and as shown in Figures 4.1 - 4.4. Multiple range comparison of result means is shown in Table 4.1 and gives the following trends:

- Moisture extraction, weight reduction, and vegetable matter loss increased with increasing degree of maceration.
- Moisture extraction, weight reduction, and vegetable matter loss increased as centrifugal acceleration increased.
- Moisture extraction, weight reduction, and vegetable matter loss increased with increasing spin duration
- Moisture extraction and weight reduction varied exponentially with spin duration.

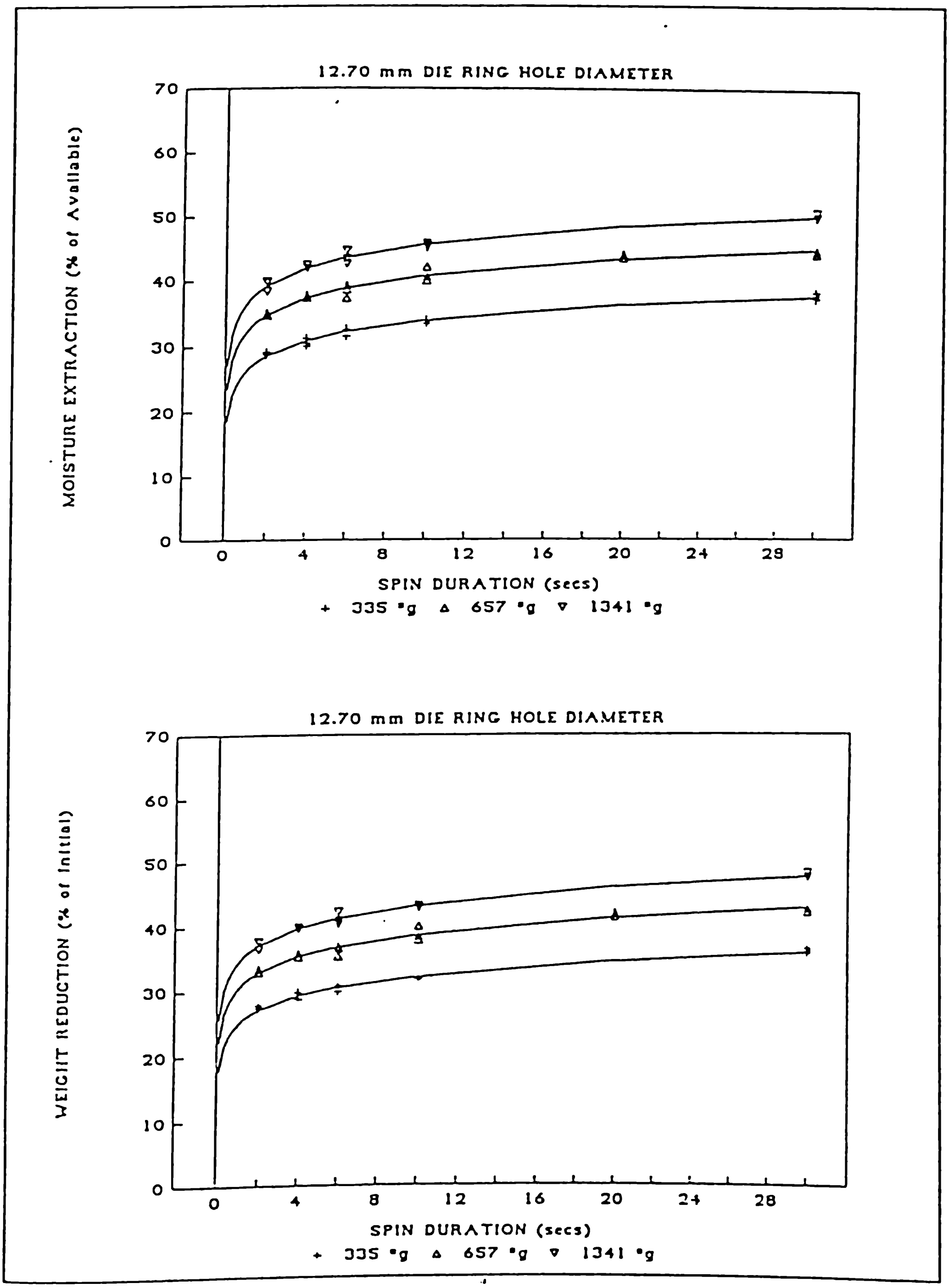

Figure 4.1 Centrifugal dewatering performance characteristics for water hyacinth macerated in a 12.70 mm die ring, at varying centrifugal acceleration and spin duration.

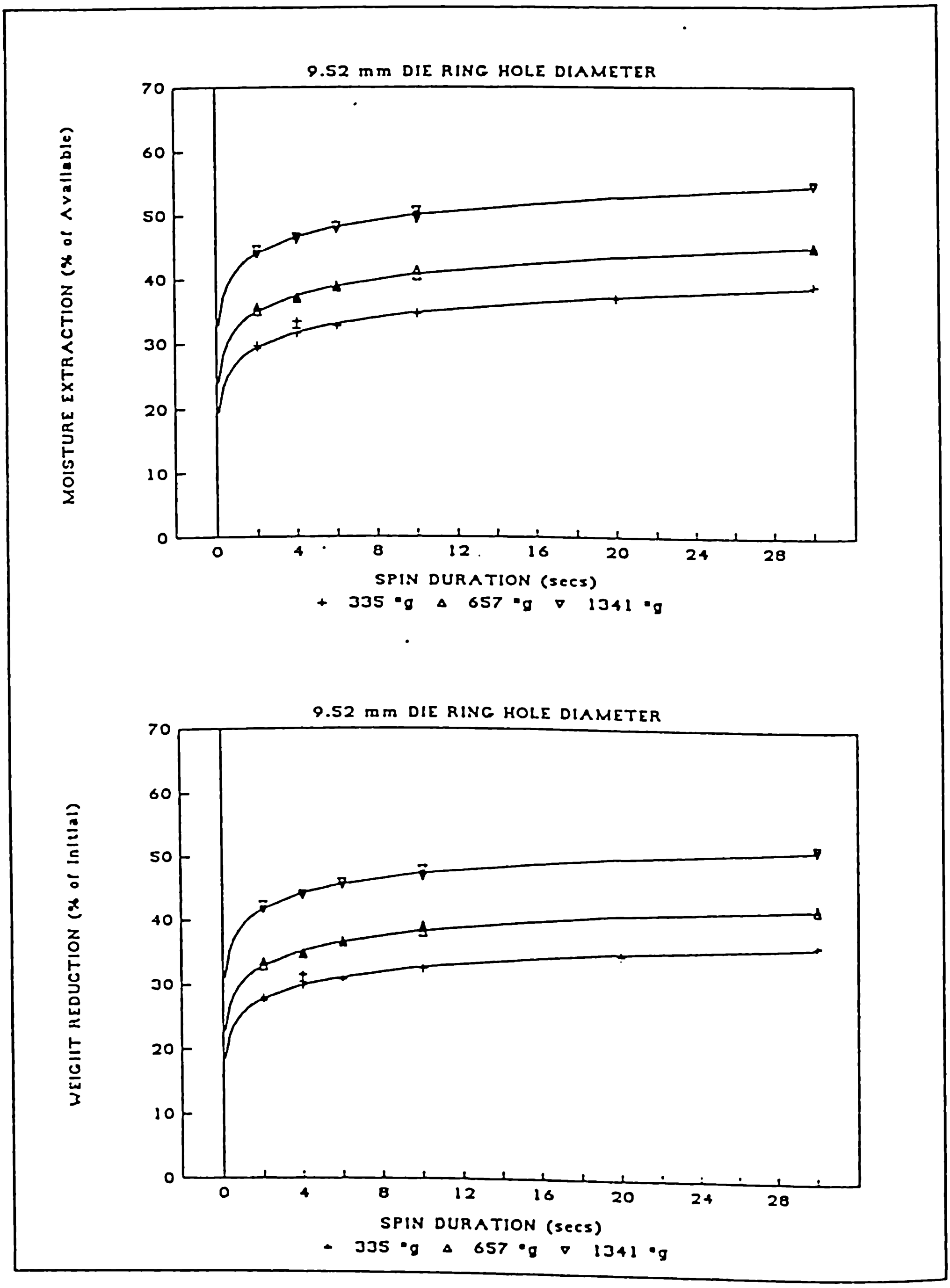

Figure 4.2 Centrifugal dewatering performance characteristics for water hyacinth macerated in a 9.52 mm die ring, at varying centrifugal acceleration and spin duration.

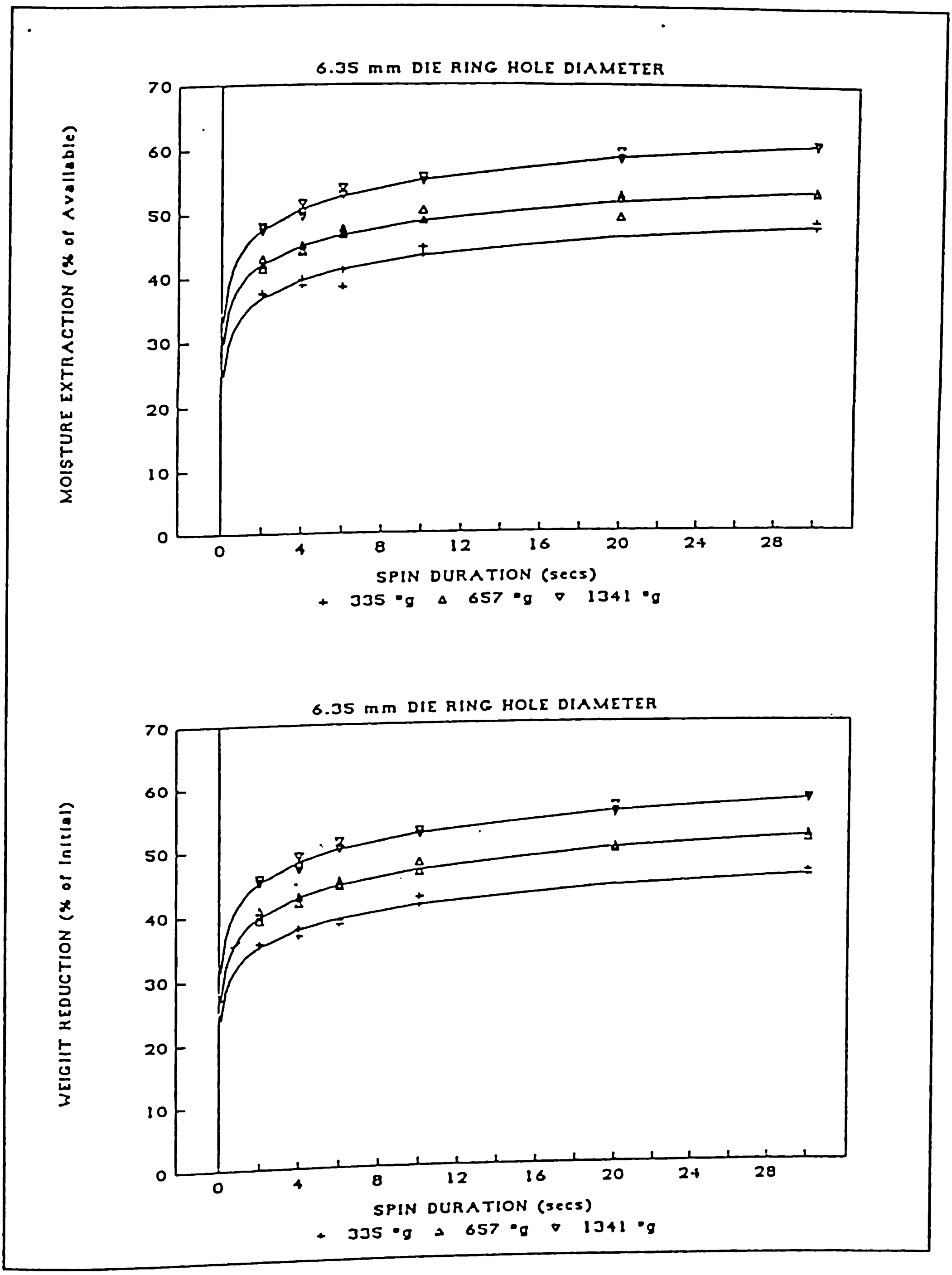

Figure 4.3 Centrifugal dewatering performance characteristics for water hyacinth macerated in a 6.35 mm die ring, at varying centrifugal acceleration and spin duration.

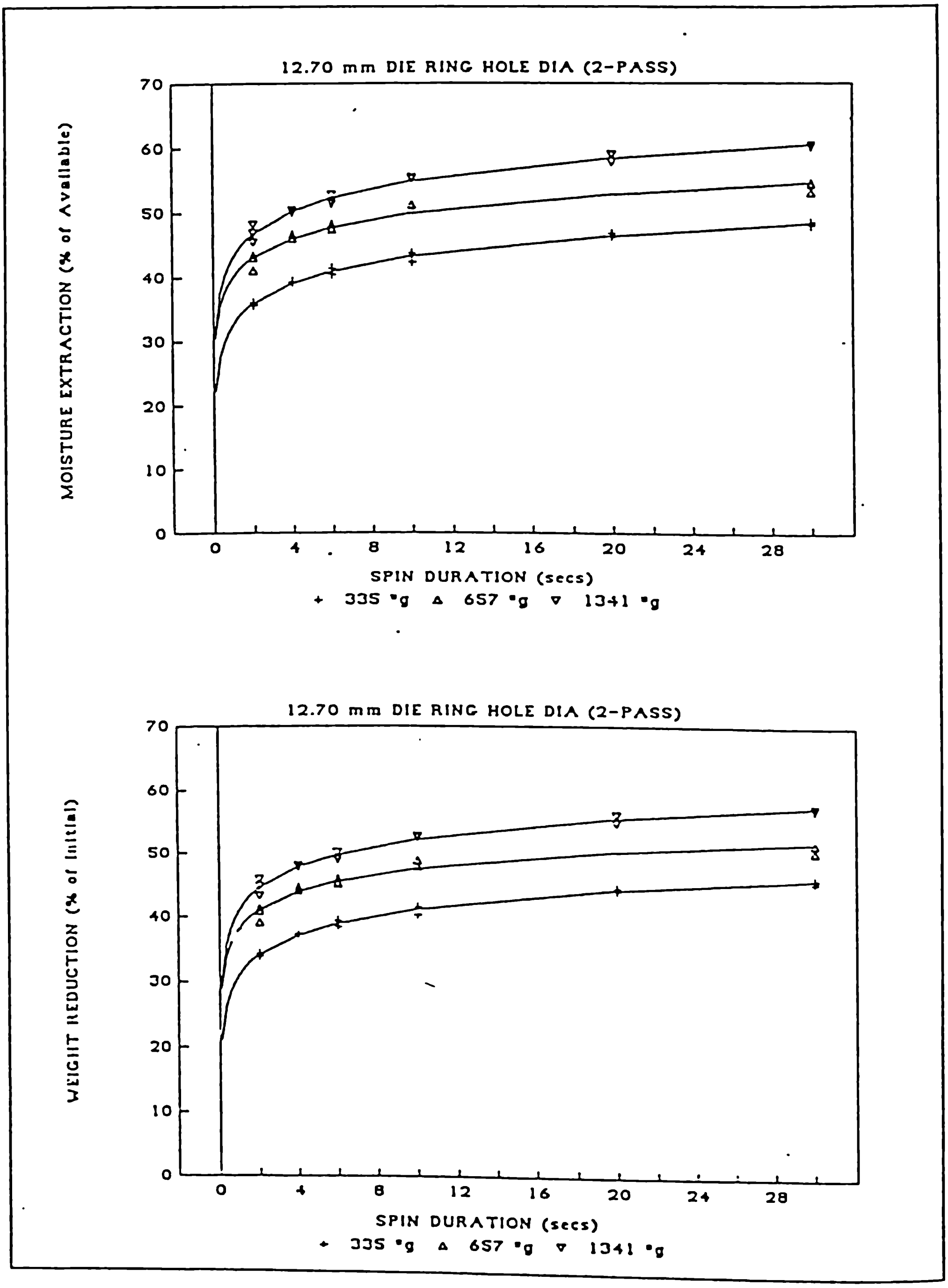

Figure 4.4 Centrifugal dewatering performance characteristics for water hyacinth twice macerated in a 12.70 mm die ring, at varying centrifugal acceleration and spin duration.

Table 4.1 shows that average moisture extraction increased from 39.00 percent to a maximum of 48.12 percent for material macerated in a 12.70 mm die ring and in a 6.35 mm die ring respectively. Moisture extraction for a 2- pass 12.70 mm die ring macerated material was statistically similar to that of 6.35 mm die ring. Similar trend was exhibited by weight reduction which ranged from 36.92 percent for 12.70 mm die ring macerated material to 46.01 percent for 6.35 mm die ring macerated material. Weight reduction for a 2-pass 12.70 mm die ring macerated material was significantly greater than the 6.35 mm die ring macerated material but the value was very close at 46.24 percent. Vegetable matter loss were observed with increasing centrifugal acceleration vegetable matter loss increased with increasing degree of maceration with the 6.35 mm die ring and 2-pass 12.70 mm die ring macerated materials having significantly higher vegetable matter losses at 14.48 and 13.96 percent respectively.

Table 4.1
Statistical multiple range comparison (LSD 95%) of results for centrifugal dewatering experiment 1

Variable	Moisture Extraction (%)	Weight Reduction (%)	Vegetable Matter Loss (%
By Degree of Maceration:			
12.70 mm die ring	39.00 a	36.92 a	10.24 a
9.52 mm die ring	40.32 b	38.06 b	10.21a
6.35 mm die ring	48.35 c	46.01 c	14.48 b
2-pass 12.70 mm die ring	48.12 c	46.24 c	13.96 b
By Centrifugal Acceleration:			
335 g	37.75 a	35.67 a	10.83 a
657 g	43.92 b	41.71 b	12.27 b
1341 g	50.57 c	47.95 c	12.84 c
By Spin Duration:			
2 seconds	38.73 a	36.73 a	11.08 a
4 seconds	41.35 b	39.20 b	11.09 a
6 seconds	42.91 c	40.86 c	11.25 a
10 seconds	45.22 d	42.87 d	12.19 b
20 seconds	49.28 e	46.92 e	13.43 c
30 seconds	49.58 e	47.08 e	13.76 c

Note: Means followed by the same letter are statistically similar at 95% significance level.

Increasing centrifugal acceleration had the effect of increasing moisture extraction, weight reduction, and vegetable matter loss. In particular, moisture extraction increased from 37.75 percent at 335 g acceleration, to 43.92 percent at 657 g, and to 50.57 percent at 1341 g acceleration. Similarly, weight reduction increased from 35.67 percent at 335 g acceleration, to 41.71 percent at 657 g acceleration, and to 47.95 percent at 1341 g acceleration. Small but statistically significant differences in vegetable matter loss were observed with increasing centrifugal acceleration. Vegetable matter loss increased from 10.83 percent at 335 g acceleration, to 12.27 percent at 657 g acceleration, and to 12.84 percent at 1341 g centrifugal acceleration.

Moisture extraction and weight reduction varied exponentially with spin duration as shown in Figures 4.1 to 4.4. Most of the moisture extraction and weight reduction occurred in the first 4-6 seconds holding time. The maximum moisture extraction and weight reduction reached after 30 seconds spin duration was a function of degree of maceration and centrifugal acceleration, and followed trends as discussed previously. Similar performance was observed between 6.35 mm die ring macerated material and double-pass macerated material (in a 12.70 mm die ring).

Vegetable matter loss increased with spin duration and averaged 11.0 percent in the first 6 seconds before increasing to 13.5 percent at 20-30 seconds.

It is clear from the preceding that moisture extraction performance is highly dependent on the degree of maceration for centrifugal machines. This is an indication that the centrifugal moisture extraction process does not rupture additional cells and expresses only available free moisture. Holding time should also be kept at around 4-6 seconds only, as higher holding times resulted in little additional dewatering while substantially decreasing potential throughput.

4.2 Results of Centrifugal Moisture Expression Experiment II

Experiment II examined more closely the effect of centrifugal acceleration on moisture extraction performance. Consequently, centrifugal acceleration was varied at levels of 483 g, 657 g, 858 g, 1087 g, and 1341 g while keeping spin duration constant at 5 seconds. The experiment was also conducted at different degrees of initial maceration (12.70 mm, 9.52 mm, 6.35 mm, and double-pass in a 12.70 mm die ring). A positive linear relationship was found between centrifugal acceleration and both moisture and weight reduction. The regression curves and data points are plotted in Figures 4.5 and 4.6, while a multiple range comparison of result means are given in Table 4.2.

Similar general trends as in experiment 1 were observed. Figures 4.5 and 4.6, however, clearly show that moisture extraction and weight reduction are positive linear functions of centrifugal acceleration. The slopes, though, are relatively flat, which indicate that only little change in moisture extraction and weight reduction occurred as centrifugal acceleration was increased. Greater increases resulted from increasing levels of maceration as shown by the gaps between regression lines. There was little difference, however, between material macerated in a 6.35 mm die ring and material double-macerated in a 12.70 mm die ring.

Referring to Table 4.2, average moisture extraction (across all maceration treatments) increased from a minimum value of 40.85 percent at minimum acceleration of 483 g, to 48.63 percent at maximum acceleration of 1341 g. Likewise, average weight reduction increased from 38.59 percent at minimum acceleration of 483 g, to 45.83 percent at maximum acceleration of 1341 g. Vegetable matter loss also increased from 9.82 percent at minimum acceleration of 483 g. to 13.47 percent at maximum acceleration.

Overall, statistically significant increases in moisture extraction, weight reduction, and vegetable matter loss resulted from increasing centrifugal acceleration from 483 g to 1341 g. The increase, though, was relatively small compared with that resulting from increasing the degree of maceration. The final choice on what combination of centrifugal acceleration and degree of aceration to select, will depend on energy considerations, that is which parameter requires more energy if increased to required level.

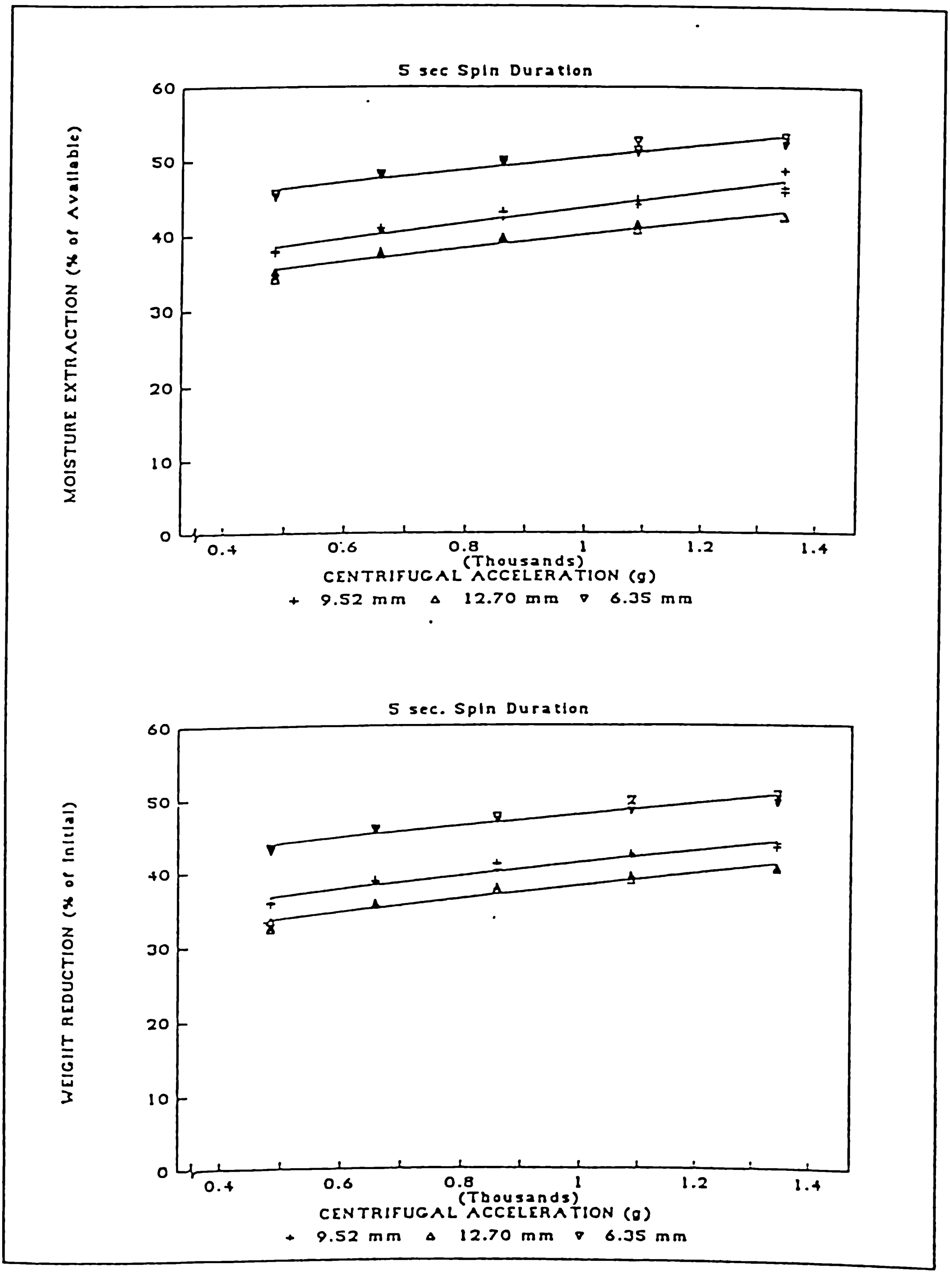

Figure 4.5 Centrifugal dewatering performance characteristics for macerated water hyacinth at varying centrifugal acceleration and degree of maceration for a constant spin duration of 5 seconds.

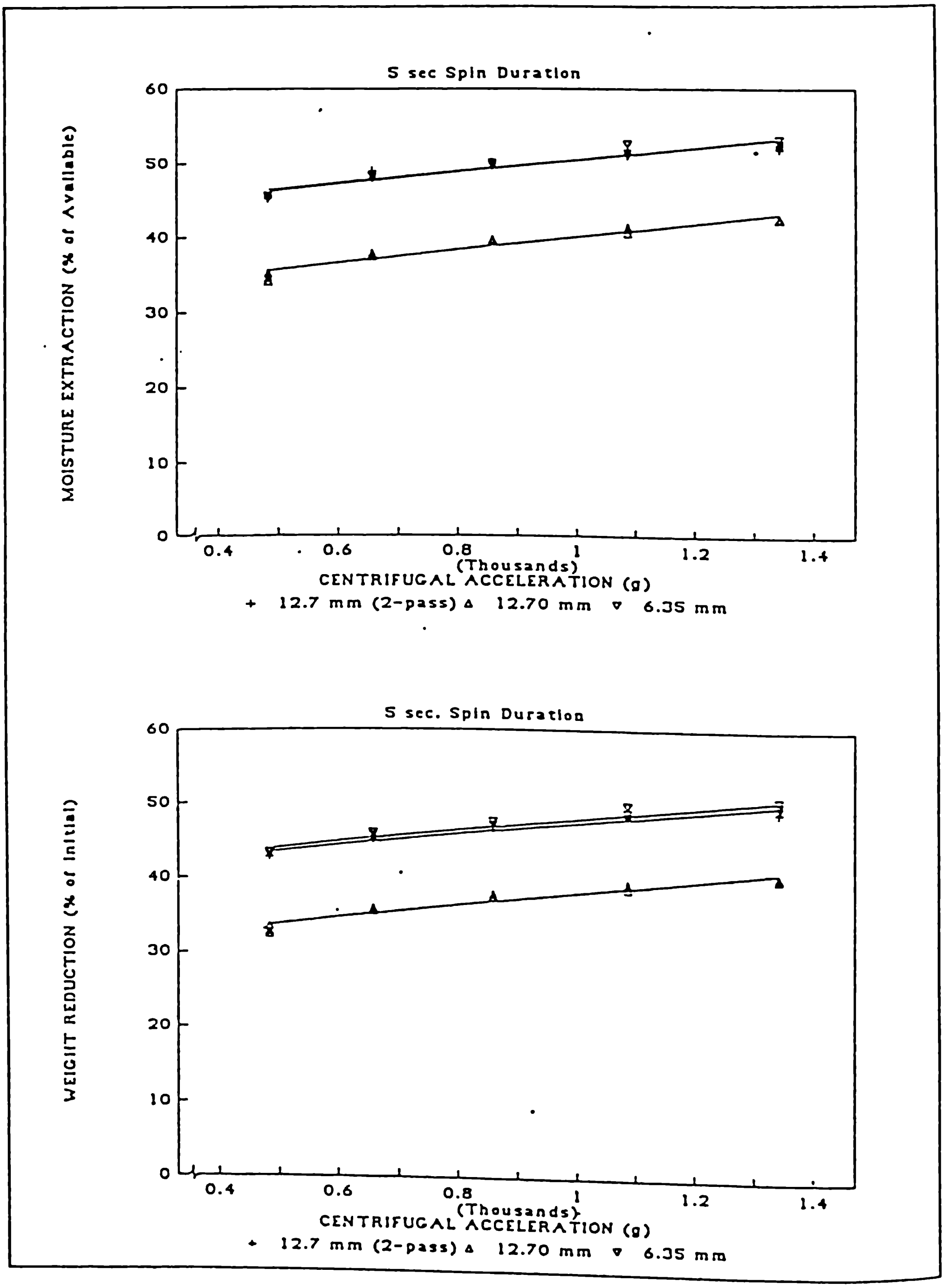

Figure 4.6 Centrifugal dewatering performance characteristics for macerated water hyacinth at varying centrifugal acceleration and degree of maceration for a constant spin duration of 5 seconds.

Table 4.2
Statistical multiple range comparison (LSD 95%) of results for centrifugal dewatering experiment II

Variable	Moisture Extraction (%)	Weight Reduction (%)	Vegetable Matter Loss (%)
By Centrifugal Acceleration:			
483 g	40.85 a	38.59 a	9.82 a
657 g	43.78 b	41.26 b	10.78 ab
858 g	45.57 c	43.04 c	11.49 bc
1087 g	47.24 d	44.61 d	12.74 cd
1341 g	48.63 e	45.83 c	13.47 d
By Degree of Maceration:			
12.70 mm die ring	39.12 a	37.09 a	9.29 a
9.52 mm die ring	42.56 b	40.15 b	10.35 a
6.35 mm die ring	49.53 c	46.44 c	14.75 c
2-pass 12.70 mm die ring	49.65 c	46.99 d	12.24 b

Note: Means followed by the same letter are statistically similar at 95% significance level.

4.3 Results of Centrifugal Moisture Expression Experiment III

The effect of varying the amount of batch load on centrifugal moisture expression performance was studied in experiment III. Batch load was varied from 100 to 600 g at 100 g increments, while degree of maceration was also varied at three levels of 1-pass, 2-pass, and 3-pass maceration in a 12.70 mm die ring. Spin duration and centrifugal acceleration were kept constant at 5 seconds and 1341 g, respectively. The results are plotted in Figure 4.7, a multiple range comparison of result means is presented in Table 4.3.

A linear relationship was found between batch load and moisture extraction and weight reduction. The behavior, however, was different at different levels of maceration. At high levels of maceration (2-pass and 3-pass maceration in 12.70 mm die ring), a slight decrease in moisture reduction and weight reduction (negative slope) resulted as batch load was increased. Conversely, at low level maceration (1-pass in a 12.70 mm die ring), there was a slight increase in moisture and weight reduction as batch load was increased. The above mentioned differences are quite small and may be considered insignificant. A slight decrease in moisture and weight reduction is expected, however, since materials thickness in the surface of the centrifuge increases as batch load is increased, which then offers greater restriction to outward flow of moisture. The above results, however, indicate that even when centrifuge was loaded almost to the brim (at 600 g level), moisture extraction performance was relatively unaffected. Likewise, vegetable matter loss varied little, from a low of 12.4 percent to a maximum of 14.6 percent.

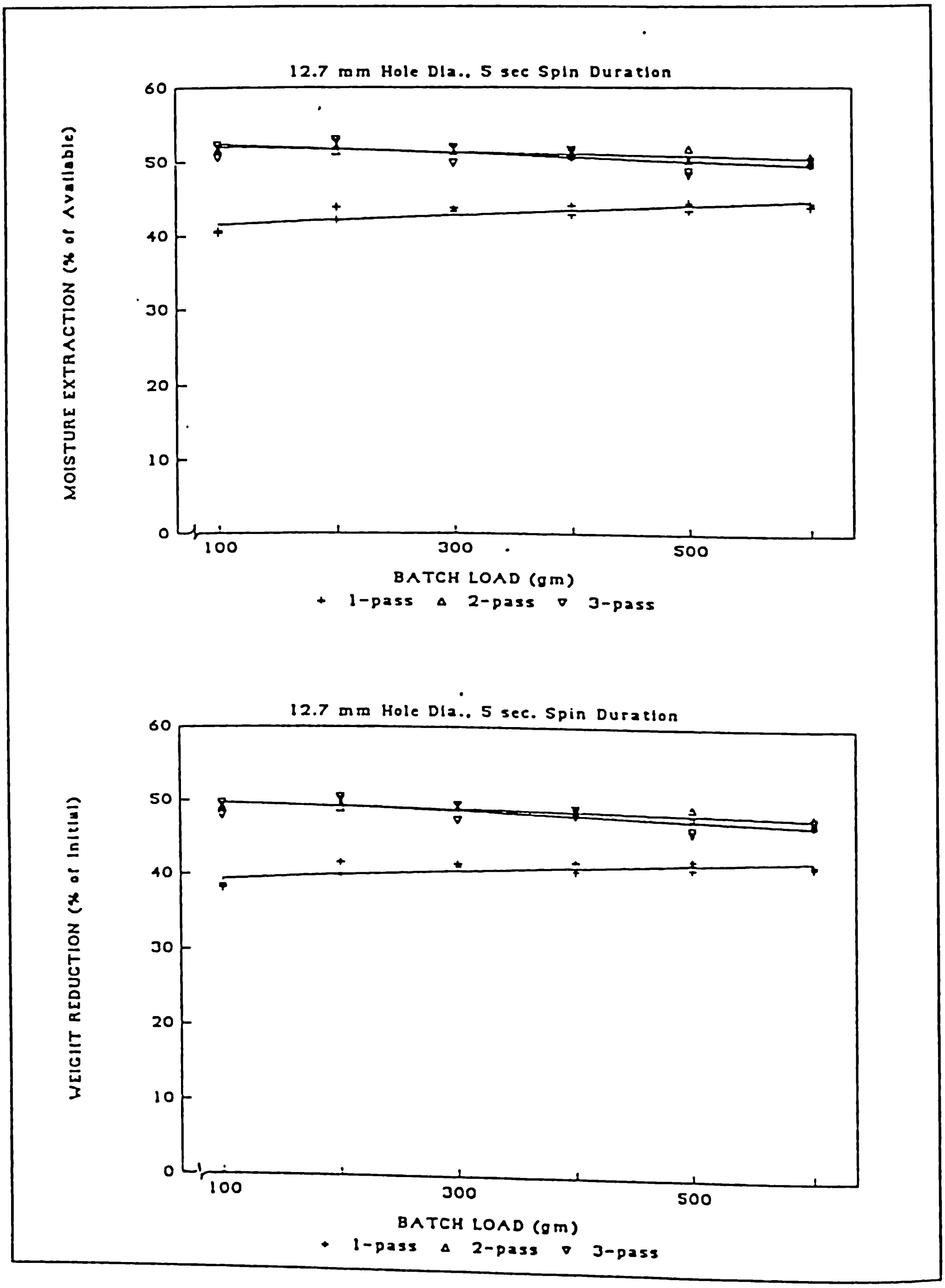

Figure 4.7 Centrifugal dewatering performance characteristics for water hyacinth macerated once, twice, and thrice in a 12.70 mm die ring, at varying batch loading rate.

Table 4.3
Statistical multiple range comparison (LSD 95%) of results for centrifugal dewatering experiment III

Variable	Moisture Extraction (%)	Weight Reduction (%)	Vegetable Matter Loss (%)
By Batch Load:			
100 g	47.90 a	45.51 a	12.39 a
200 g	49.12 c	46.75 b	14.27 c
300 g	48.73 c	46.39 b	14.63 c
400 g	48.54 bc	46.17 b	13.73 bc
500 g	47.90 a	45.56 a	13.84 bc
600 g	47.95 ab	45.56 a	12.99 ab
By Degree of Maceration:			
1-pass 12.70 mm die ring	43.02 a	40.82 a	11.05 a
2-pass 12.70 mm die ring	50.87 b	48.79 c	14.80 b
3-pass 12.70 mm die ring	51.18 b	48.37 b	15.08 b

Note: Means followed by the same letter are statistically similar at 95% significant level.

4.4 Summary of Centrifugal Moisture Extraction Experiments

A summary of the observed trends are presented in Table 4.4 and indicates that moisture extraction, weight reduction, and vegetable matter loss increases as the degree of maceration, spin duration and acceleration are increased. Batch load, on the other hand, had relatively less effect and should be minimized.

Table 4.4
Summary of the results of centrifugal dewatering experiments in terms of trends and optimum values found for the variables considered.

Variable	Moisture Extraction	Weight Reduction	Vegetable Matter Loss	Optimum Value of Variable
Degree of Maceration (↑)	↑	↑	↑	6.35 mm die ring or 2-pass in 12.70 mm die ring
Centrifugal Acceleration (↑)	↑	↑	↑	1341 g
Spin Duration (↑)	↑	↑	↑	5-6 seconds
Batch Load (↑)	-	-	-	600 g

In general, the preceding results were encouraging since the design parameters for moisture extraction, were met at reasonable levels of spin duration and centrifugal acceleration. Specifically, 50 percent moisture extraction was achieved at a spin duration of only 5 seconds when centrifugal acceleration was set at 1341 g and material macerated in a 6.35 mm die ring or double-macerated in a 12.70 mm die ring. The main factor, though, that controls the level of moisture extraction possible was degree of maceration. The primary reason for this, was that centrifugal moisture extraction (within the limits of centrifugal acceleration tested) does not rapture additional plant cells and removes only the moisture previously released during maceration.

In order to make the system viable, however, it has to be made continuous loading to increase throughout, and to reduce and even up the power requirement. The next sections discuss the attempts made at designing a workable continuous loading centrifuge.

4.5 Design of a Continuous Loading Centrifuge

Results of the moisture expression experiments conducted on the batch centrifuge were encouraging. However, batch-loading operation was deemed impractical on actual scale as throughput is low and power requirements are high during starting. Consequently, attempts were made to design and fabricate a simple continuous-loading centrifuge.

A review of existing continuous-loading centrifuge designs, particularly in the sugar processing industry, revealed that typical design (shown in Figure 4.8) consists of a vertically or horizontally-mounted perforated cone which fed at the center and discharges at the outer lip. The feed material climbs the cone surface under the action of centrifugal force and loses its moisture at the same time. The simplicity of this concept was appealing and was, therefore adopted in designing the first continuous-loading centrifuge prototype.

4.5.1 Simplified Theoretical Analysis

A simple analysis of the cone centrifuge concept was done and presented in the diagram in Figure 4.9. The analysis assumed that the particle inside the cone centrifuge was in a state of dynamic equilibrium and impends to move up the cone. It was assumed further that the cone was spinning at a constant angular velocity, ω, and that mass, m, and friction coefficient, μ, remain constant.

By summing all normal forces (normal to the cone surface), Equation 4.1 results:

$$R = m(\omega^2 \rho \cos\alpha + g \sin\alpha) \quad \ldots (4.1)$$

where:

R = Normal reaction by cone surface on the particle, N
m_i = Particle mass, kg
ω = Cone angular velocity, rad/s
ρ = Radial distance of particle from cone center, m
α = Cone angle, rad
g = Gravitational acceleration, m/s^2

From the summation of tangential forces, on the other hand, Equation 4.2 was derived:

$$m\omega^2\rho\sin\alpha = mg\cos\alpha + \mu R \qquad \text{... (4.2)}$$

where:

μ = Coefficient of friction between cone surface and particle

By combining Equation 4.1 and 4.2, an expression for the critical cone α, was derived:

$$\alpha = Tan - 1\left[(g\mu\omega^2\rho)(\omega^2\rho - \mu g)\right] \qquad \text{...(4.3)}$$

It can be seen from Equation 4.3 that the value of the critical cone angle, α, is directly related to the friction coefficient, μ. Thus, the choice of cone material is important in determining the cone angle which would make the particle move-up the cone. Tests were, therefore, conducted to determine the friction coefficient between different screen materials and macerated water hyacinth.

4.5.2 Coefficient of Friction Determination between Macerated Water Hyacinth and Different Cone Materials

Experiments were conducted to determine the friction coefficient between macerated water hyacinth and several screen materials and coatings at two moisture levels of macerated water hyacinth (initial moisture level and moisture level after dewatering). The following materials and coatings were considered:

- Bare perforated steel
- Bare perforated stainless steel
- Enamel painted perforated steel
- Lead oxide painted steel
- Enamel coated steel

Tests were done on the set-up shown in Figure 4.10, which consists of a tray containing the macerated water hyacinth, a small rectangular skid made of the material being tested, a load cell for measuring pulling force, and a motor-driven screw linear displacement mechanism for pulling the skid at a slow uniform speed. The horizontal draft force was measured and recorded through a strain-meter data logger at different normal loads applied on the skid. Linear regression of the average draft force at corresponding applied normal loads was computed to get the coefficient of friction which is the slope of the regression line.

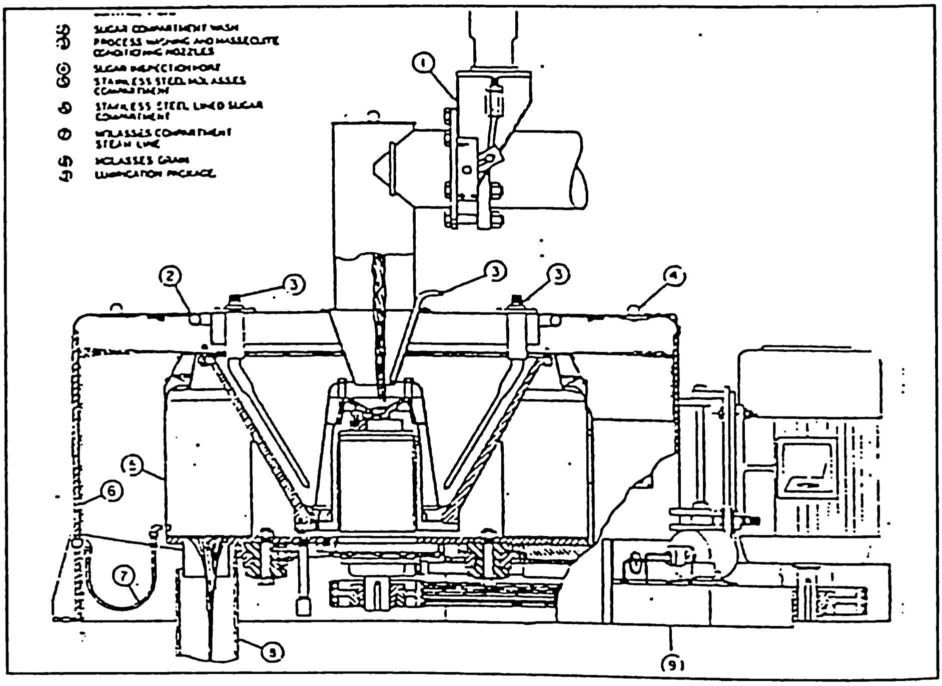

Figure 4.8 Typical continuous-loading centrifuge design.

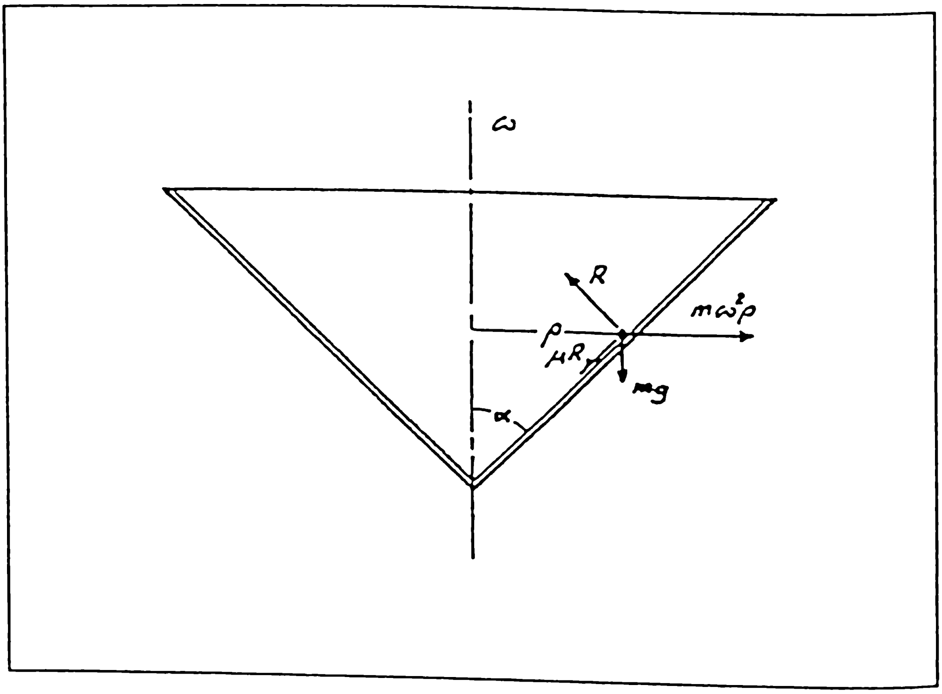

Figure 4.9 Simplified analysis of the cone centrifuge concept.

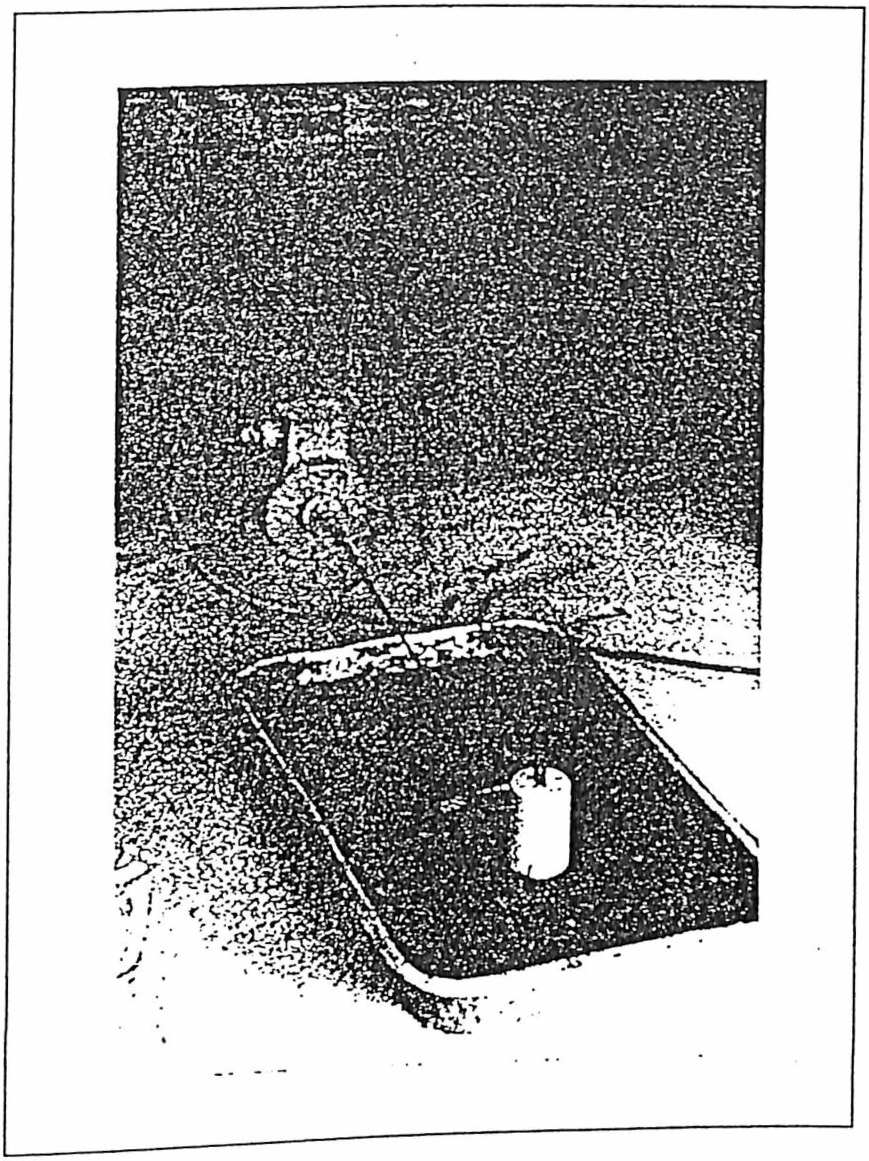

Figure 4.10 Test set-up used in determining the coefficient of friction between water hyacinth and different screen materials and coatings.

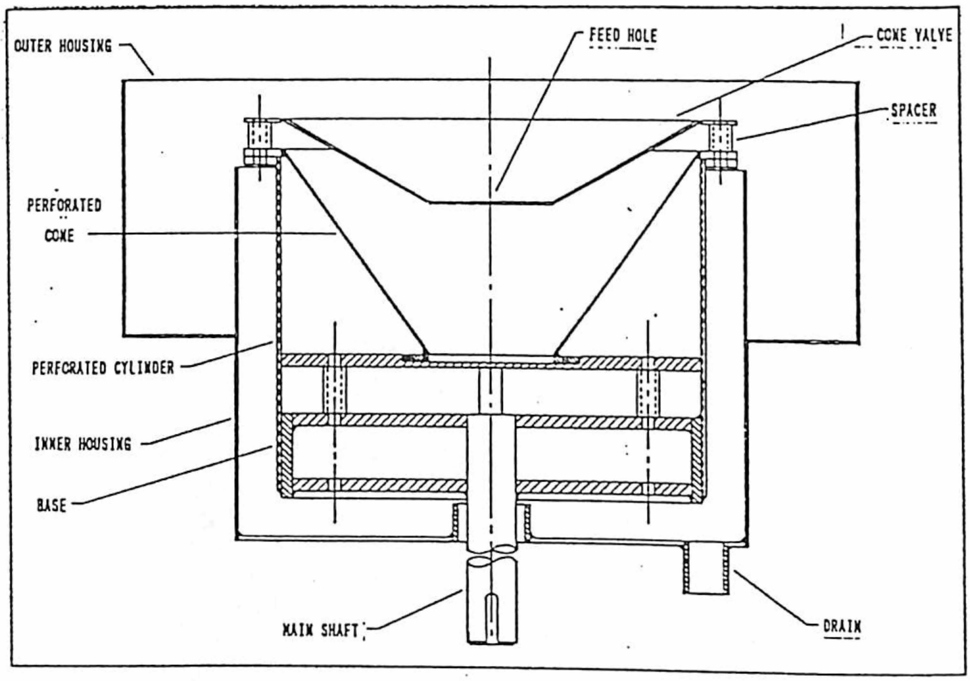

Figure 4.11 Design of the cone-type continuous-loading centrifuge.

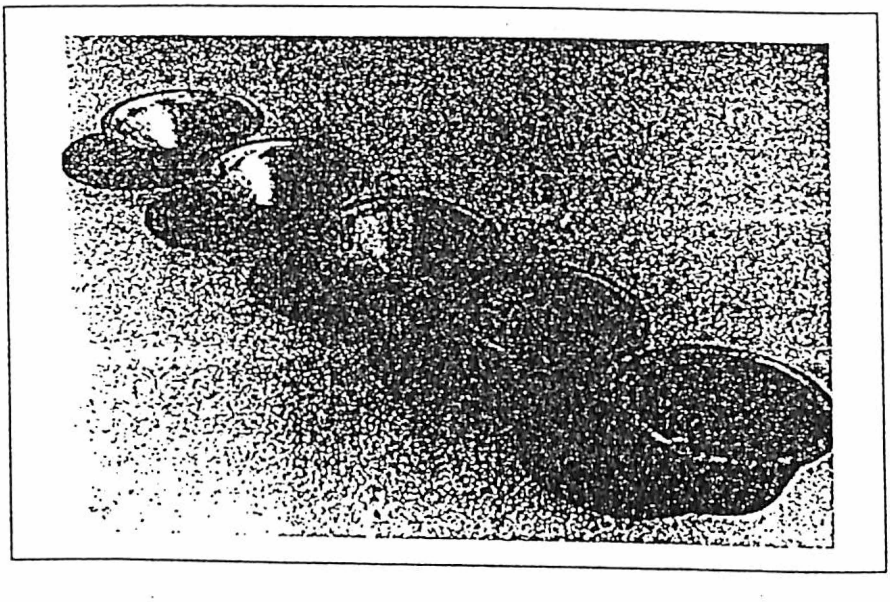

Figure 4.12 Series of cone with increasing cone angles tested in the continuous-loading centrifuge.

4.5.3 Continuous-loading Centrifuge for Macerated Water Hyacinth

A simple cone-type continuous-loading centrifuge was designed and fabricated for test. The main working elements of the design are shown in Figure 4.11 and include a perforated cylinder vertically mounted on a shaft and inside which, perforated cones of various angles can be installed.

A conical valve was provided on top to control the flow of material and redirect them towards the collection casing. The outer housing has two annular sections wherein the inner section is for collection of expressed juice, while the outer section catches the spun off dewatered material. The centrifuge was mounted on a rectangular frame and driven by a 4-kW variable speed motor through a double-sheave V-belt-drive.

Macerated material was fed into the center of the spinning cone wherein it is subjected to centrifugal force and is spun outwards to the sides of the cone. The centrifugal force further causes the material to move up the cone and lose moisture through the perforated cone surface at the same time. It is then ejected when it reaches the outer lip of the perforated cone. The conical cover, which is bolted on top of the perforated cone at a certain clearance between the cover and the perforated cone lip is adjustable by changing the length of pipe spacer.

4.5.4 Preliminary Test Results and Modifications

The results of the coefficient of friction tests between macerated water hyacinth and several screen materials and coatings are presented in Table 4.5. Included in the table are the computed values for critical cone angle based on Equation 4.3 . It shows that the coefficient of friction decreased as macerated material moisture content dropped from initial level of 93.3 - 92.2 percent to dewatered level of 88.0 - 87.5 percent for stainless steel, painted steel and bare steel. The reverse was true for lead oxide painted steel and particularly enamel-coated steel, wherein coefficient of friction increased as moisture content dropped. The minimum coefficient of friction, determined was 0.48 for enamel coated steel on high moisture water hyacinth. Maximum coefficient of friction, on the other hand, was 0.84 for bare steel on high moisture water hyacinth. Correspondingly, minimum critical cone angle computed was 26.1° while maximum was 40.5 °.

A series of five perforated cones were fabricated from perforated steel sheet with 1.5 mm diameter perforations, with cone angles ranging from 20 ° to 40 ° at steps of 5° (see Figure 4.12). The cones were tested on the continuous cone centrifuge set-up to identify at which cone angle the material will smoothly flow upwards and out of the centrifuge. It was observed that for cone angles of 20 ° to 35 °, the macerated material tended to form a continuous mat and remain stuck on the cone surface. At the cone angle of 40 °, however, almost all the material inside the cone flew out of the cone, instantaneously, without any moisture being removed. Similar results were obtained, even when the cones were coated with enamel. The use of the cone valve also proved unsatisfactory as it promoted the formation of the material mat and accumulation of material inside the cone. The most probable reason for this problem is the fibrous nature of the material which enhanced mat structure formation. The fibers also tended to go through the perforations and impending the flow of material.

Table 4.5
Friction coefficients and critical angle for different materials and macerated water hyacinth

Materials	Moisture Content (% wb)	Friction Coefficient	Critical Cone Angle
Perforated steel (no paint)	93.3	0.84	40.5
Perforated steel (no paint)	87.5	0.80	39.2
Perforated stainless steel	92.2	0.71	35.7
Perforated stainless steel	87.5	0.65	33.6
Perforated steel (enamel paint)	93.3	0.82	39.7
Perforated steel (enamel paint)	87.5	0.79	38.6
Red oxide painted steel	92.2	0.75	37.3
Red oxide painted steel	88.1	0.80	39.2
Enamel coated steel	92.2	0.48	26.1
Enamel coated steel	88.1	0.64	33.0

Some other ideas were tried to control the flow of material, particularly in the 40° cone. One is the incorporation of helical metal strips on the inside surface of the cone as shown in Figure 4.13, to retard the ejection of material and allow some dewatering to take place. Test results were also not encouraging as material tended to accumulate under the helical metal strips even when the pitch of the helix was increased.

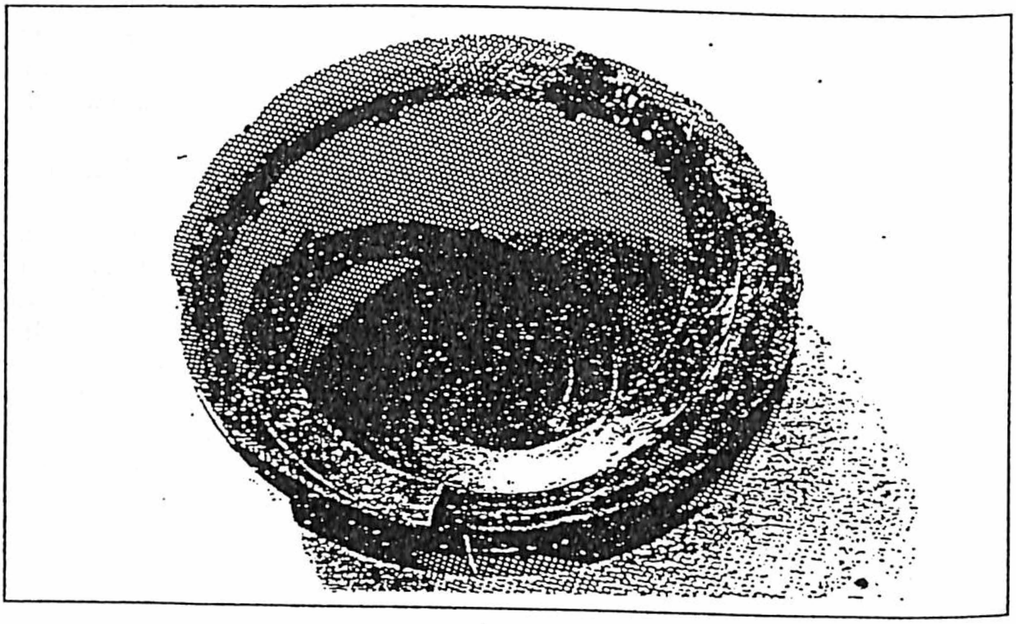

Figure 4.13 Cone with helical guide metal strips.

It was concluded that a more positive mode of displacing the macerated material along the cone surface was needed in order to fully control its holding time in the cone and to prevent accumulation of material. In fact, such a system exists and is used in juice extraction from crushed fruit. A schematic diagram of this machine is given in Figure 4.14 and shows an inner cone with a helical scroll attached to its surface which rotates at a higher relative speed to the perforated outer cone. The speed difference causes the inner cone to scrape and convey the material being dewatered downwards and out of the cone. Residence time is controlled by the relative speed difference between inner and outer cones.

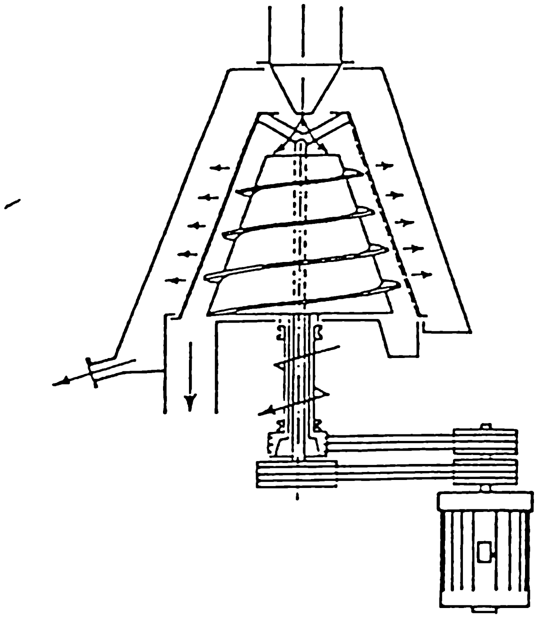

Figure 4.14 Screw-type continuous-loading centrifuge.

Such system may likely solve the problem encountered with the cone centrifuge prototype, but it results in a more complicated and expensive machine. The design also requires very close fabrication tolerances and a complicated drive system. Thus, it was decided a different moisture expression system needs to be tried such as rollers presses which are simpler and easier to design and make.

V. Conclusions

- Centrifugal moisture expression performance varied with degree of water hyacinth maceration, centrifugal acceleration, and spin duration.
- The basic trends observed were:
  - Percent moisture extraction, weight reduction, and vegetable matter loss significantly increased with increasing degree of maceration.
  - Percent moisture extraction, weight reduction, and vegetable matter loss increased as centrifugal acceleration was increased.
  - Percent moisture extraction, weight reduction, and vegetable matter loss increased with increasing spin duration.
- Percent moisture extraction and weight reduction were both found to be positive exponential functions of spin duration. Thus a critical spin duration value is reached, wherein little change in moisture and weight reduction results from its further increase. The observed critical spin duration averaged about 5 seconds for all treatments.
- Percent moisture and weight reduction were observed to be positive linear functions of centrifugal acceleration. The linear slope, however, was quite flat which meant that only little change results from increasing centrifugal acceleration.
- Greater increases in moisture and weight reduction resulted from varying the degree of maceration compared with centrifugal acceleration. This is an indication that the centrifugal moisture expression process does not cause rupture of additional plant cells and expenses only freely available moisture.
- Centrifugal moisture expression performance varied little with increasing size of batch load. Only a slight drop in moisture and weight reduction was noted when batch load was increased from 100 g to 600 g (maximum bulk capacity of the centrifuge).
- The required moisture extraction performance was attained when the centrifuge was set at 5 seconds spin duration, 1341 g centrifugal acceleration, and degree of maceration at 6.35 mm die ring or double-pass in a 12.70 mm die ring.
- In order to achieve better throughout and higher efficiency, the centrifuge must be made continuous-loading. Attempts were made to make a continuous loading centrifuge based on the cone centrifuge concept, but failed to come up with a working prototype. The main problem encountered is the difficulty in controlling the flow of macerated water hyacinth up the cone surface, because of its fibrous nature. The material tended to form a mat which was difficult to break and which remained fixed on the cone surface.
- A system for positive control of displacement of the material along the cone surface is needed to solve the problem, but this will complicate the machine design, require high fabrication tolerances and increase machine costs significantly. Consequently, a new system for expressing moisture from macerated water hyacinth was considered.

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