DESIGN OF A SHAKER-CLAMP SYSTEM FOR INERTIAL SHAKERS OF COFFEE TREES

Federico García Uribe[1];
Carlos Eugenio Oliveros Tascón[2]

ABSTRACT: *The trunk shaking is a promising alternative for the selective mechanical harvesting of coffee. In studies carried out in Cenicafé, was observed that it is possible to detach more than 60% of ripe coffee berries with less than 10% immature coffee berries in the harvested mass in less than 15 s, represents 6,3% of the time required by a picker in the traditional manual harvesting. In those studies it was also observed that mechanical damage in the coffee bark, in the shaker-clamp zone, in the majority of the shaking trees could facilitate the entrance of diseases such as* Ceratocystis *fimbriata fungus which causes the tree's death a high percentage of the time. This research has generated the necessary information for the design and operation of trunk shaker-clamp systems to efficiently transmit the vibration yet avoids the mechanical damage in the bark of the coffee tree. The research was divided into two parts. In the first, in the laboratory, the admissible radial stress [$\sigma_{R\ Adm.}$] of the coffee bark for three ages of trees (48, 60 and 72 months), using a universal machine (INSTRON 5569®) for controlled deformation and by means of histology studies (at the tissue level) was determined. The second part on the shaker-clamp system evaluation, consisted of: the measuring the vibration transmission in the shaker-clamp system using accelerometers, hardware and software to acquire and process the vibration signals. To evaluate tissue damage in normal operating conditions, films sensitive to pressure, developed by S.P.I. Inc. were used to know the pressure exerted on the tree's bark and its distribution. The obtained results, for the shaker-clamp system show that the radial admissible stress [$\sigma_{R\ adm}$] for the ages of trees considered was 2068,2 kPa (300 psi), the visible mechanical damage and at tissues level was 0% and the transmission of the vibration with the shaker-clamp system developed was higher than 80%.*

Keywords: *Coffee (Coffea arabica), mechanical harvest, inertial trunk shakers, shaker-clamp system, mechanical damage, transmission of vibrations*

TRUNK shakers are used in the United States and Europe to diminish the costs of harvesting diverse fruits, among them citric, olive trees, cherries, almonds and nuts. The required force to shaking the trunks is generated by the rotation of unbalanced masses driven by hydraulic motors. The shaker is subjected to the trunk of the tree by means of a shaker-clamp system device designed to transmit the vibration efficiently and to avoid damages in the bark.

The main observed physiological and phytosanitary problems associated with the use of trunk shakers, which represent important economic, are the reduction of productivity and the premature death of the trees (BROWN *et al*. 1988).

According to ORTIZ-CAÑAVATE (1989), greater mechanical damage of trees appears with the use of trunk shakers than with the manual harvesting. As pointed out by ADRIAN and FRIDLEY

[1] Agricultural Engineer, Centro Nacional de Investigaciones de Café (CENICAFÉ), Chinchiná, Caldas, Colombia. Federico.Garcia@cafedecolombia.com
[2] Principal Researcher I. Centro Nacional de Investigaciones de Café, Cenicafé. Chinchiná, Caldas, Colombia. Carlos.Oliveros@cafedecolombia.com.

(1964), CARGILL *et al*. (1982) and ORTIZ-CAÑAVATE (1989), the mechanical damage is also associated to land-climatic factors, human and designs factors.

At the National Center of Coffee Research of Colombia (CENICAFE), vibrations (circular and multidirectional) applied to the trunk of the coffee trees in harvesting have been evaluated since 1996. According to ARISTIZÁBAL (1998), RAMIREZ (1999), and GRANJA (2000)), mechanical vibrations applied to the trunk are very promissory for the mechanized harvest of the coffee in Colombia, in terms of increasing the yielding of the hand labor and the quality of harvesting, measured by the proportion of ripe fruits in the harvested mass, close to observed in the traditional hand picking.

Additionally, by the technical characteristics of the machinery utilized (such as dimensions, power, height of the center of gravity, weight, among others), this technology could be used in high density coffee plantations, in wet grounds with slope of up to 60%.

In the tests carried out by the above-mentioned authors, mechanical damage at the clamping zone and premature death of the trees produced by the attack of *Ceratocystis fimbriata* (CASTRO, 1999), at a high percentage of the vibrated trees (up to 81%) was observed. The inadequate design and operation (clamping pressure) of the shaker-clamp system and the use of unsuitable materials were considered to be the main factors involved in the generation of the mechanical damage.

The objective of this research was to generate the mechanical properties of coffee tree bark as required for the design of shaker-clamp systems for trunk shakers of coffee trees with high vibration transmission efficiency and low damage to the bark of the vibrated trees.

MATERIALS AND METHODS

Mechanical properties of the bark of coffee trees were measured at the laboratories for harvest research and at field conditions, at the experimental station Naranjal (located in the municipality of Chinchiná (Caldas-Colombia) at an altitude of 1310m (over sea level), average temperature of 20,6º C. and average relative humidity of 75%. The selected coffee trees for this study were taken from plots of red Colombia variety of third, fourth and fifth harvest (48, 60 and 72 months age), planted 2m x 1m (2m between rows and 1m between plants and one trunk by site).

The experiment was divided into two stages: 1) Determination of the admissible radial stress of the bark of the coffee plant; and 2) Evaluation of the efficiency of transmission of vibrations of the shaker-clamp system designed and evaluation of the caused mechanical damage to the trunk.

1. Determination of the admissible radial stress of the coffee tree.

The radial stress [σ_r], are the resulting of the loads applied in the radial direction to the coffee stem. The relation that defines this stress is given by the equation:

$$\sigma_r = \frac{F}{A} \qquad (1)$$

Where:

σ_r is the resulting radial stress [Pa]

F: Applied force in the radial direction [N].

A: Area on which the force F acts [m^2].

A universal testing machine INSTRON 5569 and a steel indenter of $1cm^2$, placed in the frame of the machine, were used to measure the admissible radial stress of the coffee bark.

The logs used in the tests, of 50cm of length, were cut 10cm from the base of the trunk, were immediately painted on their ends, placed in plastic bags and stored at 5°C. The logs were loaded in the radial direction on a section of bark of 1 cm^2 adhered to the trunk (Figure 1).

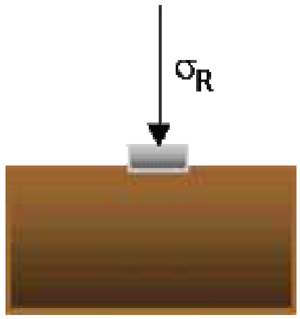


Figure 1 -- Experimental determination of the admissible radial stress of the coffee bark. (Picture source García, 2001)

In each test, a graph of radial stress [σ_r] versus the strain [ε] for the coffee bark was obtained.

The admissible radial stress was determined considering the changes that happen when breaking the cytoplasm of the cells and liberation of phenols occurs, producing easily visible dark tonalities in the zones under stress. With observations under a microscope (optical microscopy of translight), tissue analysis, it was verified the occurrence of damages at the level of trunk structures, mainly at the phloem.

This method allowed for the creation of a scale of color oxidation of the sections of the bark subjected to different values of radial stress. The sections of bark obtained for each one of the considered ages of trees, were subjected to radial stress of 2068.2 kPa (300 psi), 3447 kPa (500 psi), 4825.8 kPa (700 psi), 6204.6 kPa (900 psi), 7583.4 kPa (1100 psi) and 10341 kPa (1500 psi). Sections of bark at each stress value were extracted and its oxidation allowed. In addition, from each one of the logs a section of non-loaded bark, without oxidation, was extracted and was taken as a control.

The minimum value of radial stress, in which the track was clearly observed on the loaded sections, was determined. By means of hystological analysis, the occurrence of mechanical damage was verified. The loaded sections with same or higher values than this radial stress were considered as affected by mechanical damage at macro and micro levels.

Sections of bark subjected to lower radial stress were histologically analyzed in order to establish at tissue level the value of the radial stress that does not produce mechanical damage in the structures of the coffee trunk, which was defined as the net admissible radial stress of the bark of the coffee plant.

2. Field evaluation of the efficiency of transmission of vibrations at the shaker-clamp system and mechanical damage.

This stage was proposed to measure the efficiency of transmission of the vibration generated by the trunk shaker through the shaker-clamp system designed and verify the possible occurrence of internal damages in the bark of the vibrated coffee trees. In addition, it was also corroborated if the radial stress applied [$\sigma_{Rapplied}$] by the shaker was smaller than the admissible radial stress [σ_{Radm}], defined in the previous stage.

The equipment used to evaluate the shaker-clamp system was a trunk shaker operated by a hand tractor (10 kW) developed at CENICAFE, called VITAC-1 (Figure 2). The shaker was operated at the following conditions: clamping pressure 9992.18 kPa (1450 psi), shaking frequency 1500 cpm, eccentricity of the unbalanced masses 56.4 mm, shaking pattern of 10 loops (speed ratio of 7:3), clamping point of the shaker in the trunk 40 cm over the ground, during 10 seconds.

For the design of the shaker-clamp system, the information reported in consulted literature, the experiences gathered in works at CENICAFE, the recommendations of professionals with experience in the design of shaker-clamp systems for trunk shakers and the study of diverse materials (like rubber) were considered.

Figure 2 -- Trunk shaker with multidirectional pattern for coffee trunks (VITAC-1) developed at CENICAFE (2001). (Picture source García, 2001)

The cylindrical form for the pads was chosen for the facility of construction and installation in the shaker

The shaker-clamp system was designed with two elements: a movable body, operated by means of a hydraulic cylinder, and a second fixed body, welded to the structure of the shaker. Each element was made up of a cylinder of rubber of hardness 55° Shore A, of 100 mm of diameter and 200 mm in length assembled on a calibrated steel axis 1020 of 25.4 mm of diameter. On each rubber roller, a pair of bands or aprons elaborated in foamy rubber of hardness 30° Shore A reinforced with canvas ribbing of 350 mm in length, 220 mm wide and 10 mm of thickness, were placed. The aprons of the mentioned material were used for the reduction of damages in the bark of the coffee plant at the subjection zone produced by the tangential stresses generated during the vibration. The function of the rubber rollers is to transmit the loads generated in radial sense.

The dimensions of the shaking head and the average diameter of the coffee trunks were also considered to determinate the size of the shaker-clamp system. The equation obtained by ARISTIZABAL was used (1998), for the red Colombia variety, ($Y = 55.1136 - 0.2354 X$, where Y is the diameter of the trunk [mm], and X is the height of the trunk measured from the ground [cm]), obtaining, to 40cm of the ground, a value of 4,6cm to diameter of the trunk (required to define the minimum distance between internal and external edges of the rubber rollers).

During manufacture of the shaker-clamp system, the gap between the cylindrical pads of rubber was adjusted to 5,0cm, allowing for extensions if necessary. Sufficient contact area between the foamy rubber aprons and the trunks of the coffee trees were sought with acceptable distance to diminish high stress level zones.

The rubber used in the manufacture of the aprons (a combination of synthetic rubber and nitrile) is resistant to contact with hydrocarbons, the outdoors and dynamic loads.

In Figure 3 is shown the shaker-clamp system designed for coffee trees.

In order to evaluate the efficiency of transmission of vibrations, 5 trees of each of the established ages were selected (48, 60 and 72 months) and measured signals of vibration at the inlet, using a biaxial accelerometer ±100 g (previously calibrated), placed on the shaker-clamp system, and at the outlet, using a triaxial accelerometer ±100 g (previously calibrated), placed on the coffee trunk at 40cm of high over the ground, as shown in Figure 4.

Figure 3 -- General view of the shaker-clamp system designed for the trunk shaker “VITAC-1” (Picture source García, 2001)

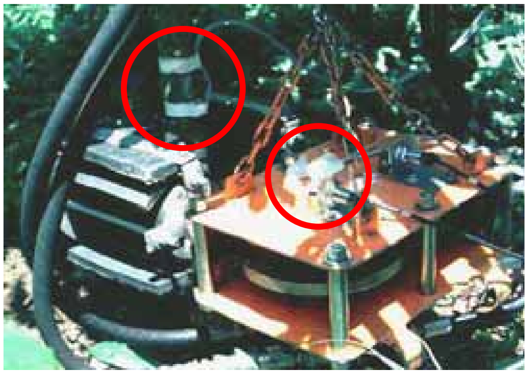


Figure 4 -- Placement of the accelerometers used for the measurements of vibration transmission. (Picture source Ramírez, 2001)

The efficiency of transmission (ET), in percentage, was obtained as,

$$ET(\%) = \frac{Outlets}{Inlets} \qquad (2)$$

The inlet and outlet signals were registered in a computer at a frequency of sampling of 5000 data per second, during a maximum acquisition time of 10 seconds. For the analysis of the signals it was used a program in MATLAB® developed by DUQUE and HENAO (2001), which allowed to measure the energy dissipation that happens between the generating source (the shaker) and the average receiver (the trunk of the tree).

A confidence interval at 95% and average was considered an acceptable ET value range. It was also determined the inferior limit of the interval had to be >80%.

Evaluation of the mechanical damage produced by the shaker-clamp system under static conditions

To detect the occurrence of injuries in the bark of the vibrated trees, values of applied radial stress (statically) [σ_{Rapp}] and admissible [$\sigma_{R\ adm}$] were compared. Verification of visible injuries in the trees was also sought and compared where possible.

In order to obtain the radial stress applied to the trunk by the shaker-clamp system, according to equation 1, the clamping force and the contact area between the rubber bands and the trunk of the coffee plant are required. For the estimation of the force a free body analysis of the movable element was done, which allowed obtaining an expression to relate the clamping force (in the tree) and the pressure at the hydraulic cylinder.

The image processing technique was used to calculate the contact area between the rubber bands and the trunk. In every single tree used in the efficiency of vibration transmission tests, the bark in the contact zone was impregnated with a thin film of used engine oil. A sheet of paper was inserted in the middle with the purpose of marking the contact area on the sheet, the trunk was clamped during 10s and the sheet retired. The contact area was digitized and an algorithm developed by MATLAB® by GOMEZ (2001) was used to measure it.

With the obtained information of the applied radial stress [σ_{Rapl}], (under static conditions), for age of the evaluated crop, was considered the average and the confidence interval at 95%. If the value of the superior limit of the interval is smaller (descriptively) that the value of the admissible radial stress determined then the shaker-clamp system fulfills the purpose for that was designed.

Evaluation of the mechanical damage under dynamic conditions (shaking)

The Topaq Analysis System®, manufactured by Sensor Products Inc, was used to determine both the pressure distribution and the magnitude at the clamping zone during the shaking. The Topaq® system consists of a scanner as well as specialized hardware and a piece of tactile pressure sensor film "*TPSF*" (in our particular experiments, the Super Low range of *TPSF* was used).

Four trees for each considered age (48, 60 and 72 months) were selected and a band was inserted between the trunk and the rubber bands of the shaker-clamp system. The trees were vibrated for 10 seconds and then the bands were retired. On each band an area of approximately 3 cm^2 was delimited (representing the contact area between the shaker-clamp system and the coffee trunk) and a line parallel to the axis of the trunk was traced, with the purpose of obtaining the corresponding pressures profile.

After the exposed film was returned to Sensor Products Inc. in the United States for analysis, 2D and 3D maps with pressure distribution at the contact area, pressure profiles along the drawn line, histogram of relative frequencies and basic statistics of the defined region (representing the contact area) were obtained (Figure 5). From the analysis of the pressure bands, the average, median and the mode for each one of the representative areas of contact, as well as the 99 percentile and the percentage of area at higher stress than the admissible radial stress [σ_{Radm}], defined in the first stage, were clearly determined. Figure 5 shows a typical test before and after being processed in 2D and 3D with the Topaq® System.

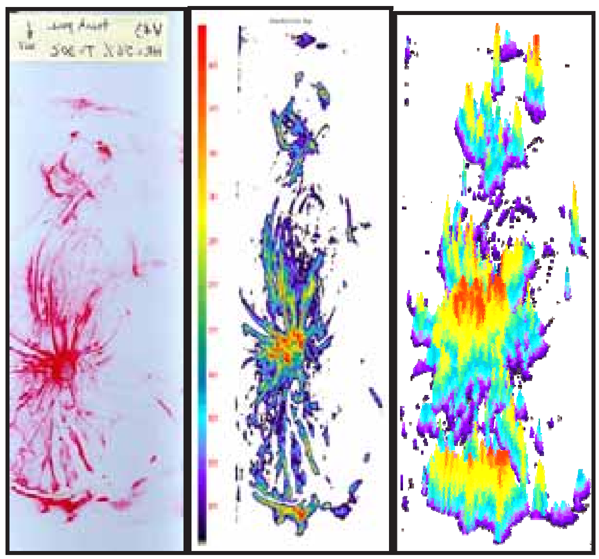


Figure 5-- Typical test before and after being processed in 2D and 3D with the Topaq® system.

RESULTS and DISCUSSION

1. Admissible radial stress for the coffee bark

As shown in Figure 6, curves of radial stress [σ_{Radm}] vs. strain [ε] for the coffee bark for each studied ages (48, 60 and 72 months) exhibit similar trend. On each curve three zones can be identified: Zone A, where great deformations occur at low loads, possibly due to the compression of lignified structures of the bark with macropores filled with air (corky type). Zone B, with greater rigidity than the previous one, where the compression of the phloem and xylem structures begins. (The behavior is almost linear until reaching a breaking point where the structures collapse). Zone C, where the bark structures fail, an apparent increase in the rigidity can be observed, due to the compression of the woody structures of the trunk.

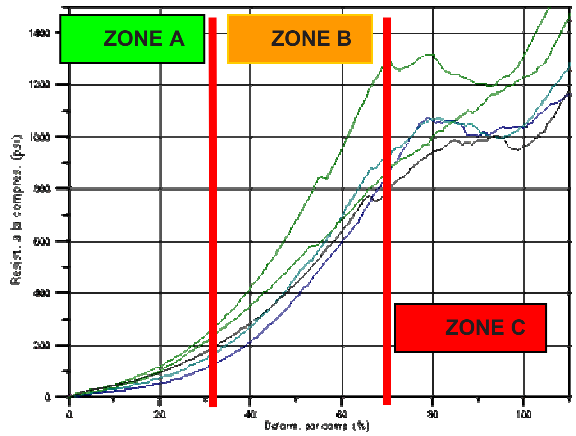


Figure 6 -- Curves of radial stress [σ_{Radm}] versus strain [ε] and identified zones for the coffee bark, obtained in compression tests.

An oxidation colors scale method, similar to that employed by FRIDLEY et al. (1970), was used as a first indicative to determine the admissible radial stress of the coffee bark [σ_{Radm}].

The scale of color oxidation for zones subjected to different values of radial stress was similar for the three studied ages, as shown in Figure 7. For 2068,2kPa (300psi), and for 3447kPa (500psi), no track left by the steel indenter was noted in the loaded sections. For 4825,8kPa (700psi), the track left by the indenter was tenuous. However for the sections loaded to 6204,6kPa (900 psi), 7583,4kPa (1100psi) and 10341kPa (1500psi) the tracks left by the indenter were evident.

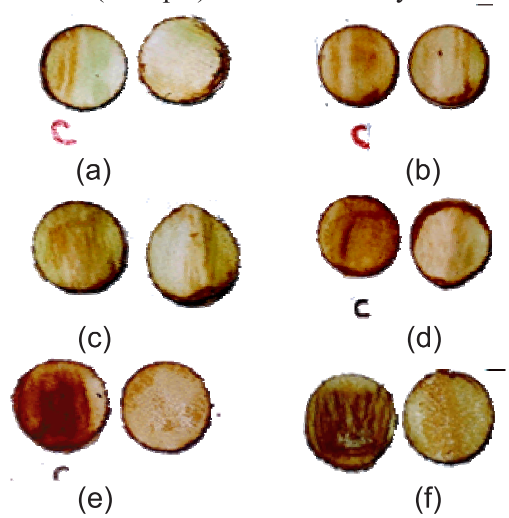
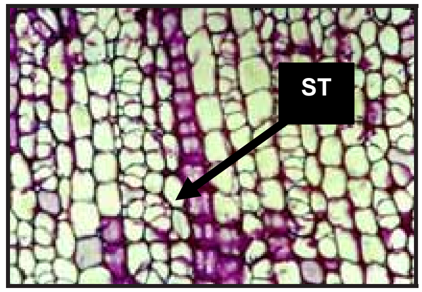
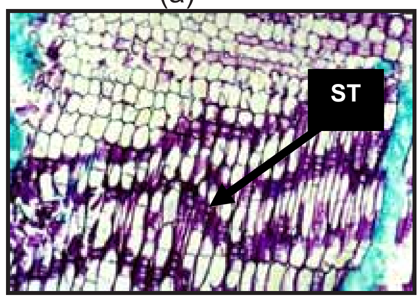


Figure 7 -- Scale of colors oxidation for sections of coffee bark subjected to different values of radial stress: (a) 2068,2kPa (300psi); (b) 3447kPa (500psi); (c) 4825,8kPa (700psi); (d) 6204,06kPa (900psi); (e) 7583,4kPa (1100psi); (f) 10341kPa (1500psi), in comparison with the control (right). (Picture source García, 2001)

Tissue analysis in sections of the coffee bark loaded to 6204,06kPa (900psi) with tracks left by the indenter were carried out. It was observed that at this stress value mechanical damage in internal tissues of the bark appears (Figure 8).



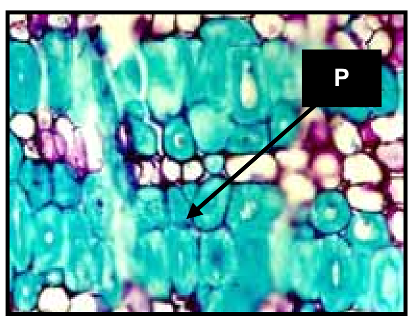
(a)



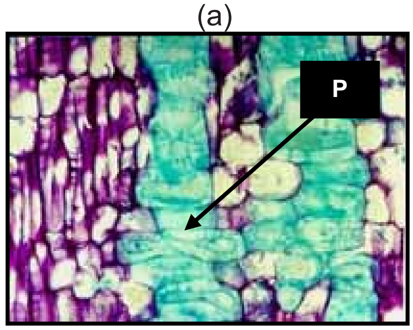
(b)

Figure 8 -- Cross section of the coffee bark: (a) sound tissue and (b) tissue with damage at the sieve tubes (ST), subjected to 6204,6kPa (900psi), Zoom 40x. (Picture source García and Camayo, 2001)

In Figure 9 are shown sound tissue and tissue with damage at the phloem for the same section, characterized by the crushing of these cells. The symmetry that exhibits these cells in comparison with the loaded tissue whose cells are of rectangular shape can be observed.



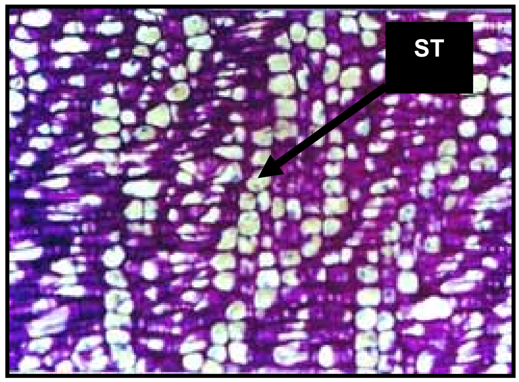
(a)



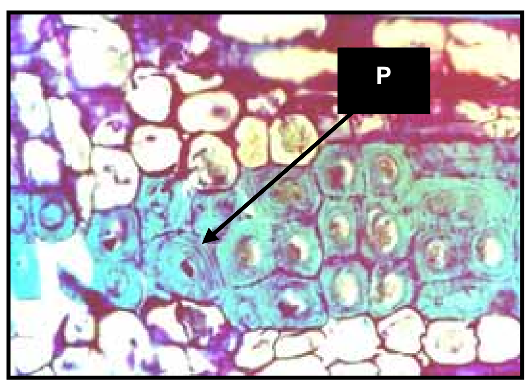
(b)

Figure 9 -- Cross section of the coffee bark: (a) sound tissues and (b) tissues with damages at the phloem level (P), loaded 6204,06kPa (900psi) with damages at the phloem (P). Zoom 40x. (Picture source García and Camayo, 2001)

In the coffee bark sections loaded to 5515,2kPa (800psi), 4136,4kPa (600psi), and 3447kPa (500psi), mechanical damage at the sieve tubes and the phloem level was also observed. In sections loaded to 2068,2kPa (300psi) (Figure 10), evidence of mechanical damage at tissue level was not noted. At the phloem level the cells presented the same configuration observed in a sound tissue. The sieve tubes exhibited the same linear ordering observed in sound tissue.



(a)



(b)

Figure 10 -- Cross section of a coffee bark loaded to 2060,2kPa (300psi): sieve tubes (a) and phloem (b). Zoom 40x. (Picture source García and Camayo, 2001)

At a radial stress of 2060,2kPa (300psi) the oxidation pattern observed was the same as that for the sound tissue for the three coffee plant ages considered (48, 60 and 72 months), therefore this value was assumed as the net admissible stress for the coffee bark.

2. Efficiency of vibration transmission for the shaker-clamp system and mechanical damage evaluation at field conditions.

The lower limit of the confidence interval at 95% for the vibration transmission variable for trees of third harvest (48 months) was 85%, for trees of fourth harvest (60 months) 80% and for trees of fifth harvests (72 months) 79% (Table 1). Considering the previous values and the average (88%) for the three studied ages it was considered that the design is appropriate.

Mechanical damage evaluation under static conditions

By means of a free body diagram of the movable element of the shaker-clamp system the following equation relating the radial stress applied [$\sigma_{Rapplied}$], under static conditions, the pressure of the hydraulic cylinder [P_C] and the contact area [A_R], measured by means of the image processing technique, was obtained:

$$\sigma_{Raplic} = \frac{29{,}439 \cdot P_C}{A_R}, \qquad (3)$$

Where: [σ_{Raplic}] kPa, [P_C] psi, [A_R] cm^2

With equation 3, the applied radial stress for each one of the studied ages was determined (Table 2). For coffee trees of third harvest (48 months), the upper limit of the confidence interval at 95% for the variable applied radial stress was of 881,26kPa (127,8psi), for fourth harvest (60 months) 756,4kPa (109,71psi), and for trees of fifth harvest (72 months) 684,7kPa (99,3psi). The greatest radial stress applied [$\sigma_{Rapplied}$], was obtained in trees of third harvest (smallest diameter) and the smallest value in trees of fifth harvest (greatest diameter).

Considering that the greatest value of applied radial stress for trees of third harvest (881,26kPa; 127,83psi) is notoriously lower than the admissible stress (2068,2kPa; 300psi), it is not hoped to cause internal mechanical damage in the structures of the trunk (at the phloem and sieve tubes level).

Evaluation of the mechanical damage under dynamic conditions (shaking)

The pressure map for each studied age was also obtained with the Topaq® Analysis System.

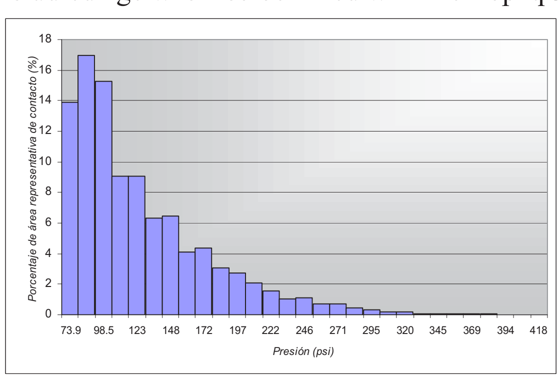


Figure 11 -- Percentage of representative contact area-pressure developed in the contact zone relationship under normal operation conditions of the equipment.

According to the information shown in Figure 11, most of the delimited area or representative contact area (>98%) is subjected to stresses lower than the admissible radial stress [σ_{Radm}] obtained for the coffee bark Therefore no internal damages in the coffee bark at the clamping area during the shaking of the trunk are expected. In Table 3 are shown the measures of central tendency, the 99% percentile and the critical contact area for each of the studied ages (46, 60 and 72 months). In all cases, the mode and the median were always lower than the average and none of the central tendency measures was higher than the admissible radial stress obtained for the coffee bark. In some trees the measured radial stress exceeds the admissible radial stress. This could be due to the effect of protuberances left after the elimination of lower branches. These zones, without bark, are hard and lignified. Therefore they were not considered for analysis in this study. Contact areas with stresses higher than σ_{Radm} were found in only two tests in trees of fourth and fifth harvest, respectively.

Table 1 Confidence Intervals at 95% for the variable efficiency of transmission of the vibration (E.T.) obtained for each one of the studied ages. Red Colombia Variety.

Age		Lower limit	Mean	Upper limit
Harvest	Months			
3[a]	48	85%	91%	98%
4[a]	60	80%	83%	86%
5[a]	72	**79%**	88%	97%

Table 2 Confidence Intervals at 95% for the variable applied radial stress for each of the studied age. Red Colombia Variety.

Age		Upper Limit		Mean		Lower Limit	
Harvest	Months	Psi	kPa	psi	KPa	Psi	kPa
3[a]	48	127,83	881,36	108,5	748,08	89,17	614,79
4[a]	60	109,71	756,40	99,02	682,73	88,33	609,07
5[a]	72	**99,30**	**684,68**	86,89	599,06	74,47	513,45

Table 3 Central tendency measures, percentile 99 and critical area for each of the representative contact areas according to age.

Harvest- tree	Median (kPa)	Mean (kPa)	Mode (kPa)	Percentil 99 (kPa)	% critical area
3-1	651,07	803,63	594,33	1861,45	0,39
3-2	749,72	908,42	679,13	2035,80	0,93
3-3	697,01	886,36	594,33	2290,25	1,65
3 4	725,52	809,15	594,33	1527,09	0
4-1	659,34	789,71	594,33	1527,09	0
4-2	1018,31	1113,38	679,179	2459,85	3,65
4-3	848,72	1070,77	594,33	2799,03	10,8
4-4	1317,44	1310,96	1272,70	2629,44	7,25
5-1	1018,31	1125,86	679,13	2459,85	6
5-2	957,58	1112,62	679,13	2714,24	8,32
5-3	1187,90	1287,38	679,13	2883,83	18,2
5-4	658,86	773,37	509,54	1611,89	0

CONCLUSIONS

1. The method based on the scale of colors is a useful tool to establish, at macro level, the occurrence of mechanical damage in tissues of the bark of the coffee tree. Histological studies, at micro level, can be used to identify the affected structures and the extension of the caused damages.

2. In the studied ages, for a radial stress of clamping to 2068,2kPa (300psi), no mechanical damages were detected in the internal structures of the bark of the coffee tree. Therefore this value is proposed as the permissible radial stress [σ_{Radm}] for the bark of the coffee plant Colombia variety.

3. With the designed shaker-clamp system, in which sliding rubber bands are used to avoid the transmission of tangential stresses to the bark and rubber pads to transmit the generated forces, the maximum radial stress at the clamping zones is 881,26kPa (127,83psi), no mechanical damage is produced in the internal structures of the bark and the transmission of vibrations efficiency is at least 80%.

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