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Evaluation of Impact Hammer Mill for Limestone Crushing for Acidic Soil

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Abstract: Soil acidity becomes a serious threat to crop production in most highlands of Ethiopia particularly in Western parts of Oromia. Frequent tillage, removal of crop residues and mono-cropping and heavy rainfall contributes to soil acidification by leaching of cations. Agricultural limestone raises soil pH and reduces solubility of potentially toxic elements such as hydrogen, aluminum (Al^{3+}) and manganese (Mn) at optimum nutrient uptake by crops. To elucidate problems associated with soil acidity, a motorized agricultural limestone crusher was fabricated and evaluated. Performance of the prototype hammer mill machine, in terms of crushing capacity (kg/h), crushing efficiency (%), mean particle size (mm), fuel consumption (ml/kg) or energy consumption (wh/kg) was evaluated. Tests were carried out at engine speeds of 540, 720, 900 rpm, screen hole diameter of 2, 4, 6 mm and feed rates of 3.50, 7.00, 10.50 kg/min. The highest crushing capacity 630.32 kg/hr was recorded at 900 rpm engine speed, 6mm screen hole diameter and at 10.50 kg/min feed rate whereas the minimum 65.62 kg/h was observed at 540 rpm hammer mill speed, 2 mm screen hole diameter and at 3.50 kg/min feed rate. The mean consumed energy ranged from 15.47 to 149.16 Wh/kg with hammer rotor speed of 540 to 900 rpm, screen hole diameter of 2 to 6 mm and the feeding rate of 3.5 to 10.5 kg/min. The mean particle size ranged from 0.121 to 0.448 mm with hammer rotor speed of 540 to 900 rpm, screen holes diameter of 2 to 6 mm and the feeding rate of 3.5 to 10.5 kg/min. It could be noticed that the lowest values of mean particle size were obtained at engine speed of 900 rpm, screen hole diameter of 2 mm and feed rate of 10.5 kg/min.

Keywords: Hammer Mill, Limestone, Particles Size and Crushing

1. Introduction

Agriculture contributes about 37% of the national (GDP), 73% of rural employment, and 70% of export earnings for the Ethiopian economy [5]. However, soil acidity becomes a severe crop production tricky and affects 43% of arable land in the country. Soils around Asosa and Welega in aggregate:- 2.2% extremely acidic, 4% very strongly acidic, 32.8% strongly acidic, 27% moderately acidic, 3% slightly acidic and 1% neutral [1].

Major causes that speeds up soil acidification include [11, 14, 15]: Frequent tillage, Removal of crop residues, Mono-cropping, Frequent application of urea. Soil acidity restricts crop production by impairing root growth and limiting nutrient and water uptake. Crops that are grown in acidic soils have a significantly stunted growth rate and are not very responsive to fertilizers [4, 8]. It also creates toxic soil solution that hinders the growth of roots and micro-organism activity**.** Lime can shift soil acidity towards neutral state and render nutrients more available to crops. Lime amounts of 2-5t/ha are typically needed to neutralize acid soils sufficiently for crop production, depending on the type of soil and levels of acidity [12]. Ethiopian government is planned to rehabilitate 226,000 ha of agricultural land by the end of the GTP II period. To achieve this, it is planned to produce 450,000-900,000 t of lime but, the achievement is quite low. Limestone is a geological nutrient asset that could sustain and enhance crop production is necessary for soil amendments. To improve on the effectiveness of these systems, the option of using locally available geological nutrient resources needs to be tested. Agro-minerals are physically modified by grinding and hammer mill is used because of its ability to handle a wide variety of raw materials, handle hard stray objects and its robustness [2]. To know the machine performances at different engine speed, feed rate and screen hole diameter, existing motorized limestone grinder should be evaluated**.** Therefore, this research study was intended to evaluate impact hammer mill for limestone grinding for acidic soil.

2. Materials and Methods

2.1. Materials Used

Instruments such weighing balance, oven dry, tenso-meter, impact tester, different aperture size of sieve and basic manufacturing tools and equipment were used during prototype construction, data collection and evaluation.

Particle-size distribution, crushing efficiency and capacity: Weight retained in grams for each sieve size, (% weight retained for each sieve size, and cumulative weight % passing) for each sieve size of the particle size analysis of the limestone product from the grinding test were determined.

$$C_{eff} = \left(\frac{M_r}{M_i}\right) \times 100$$

$$\text{Crushing capacity} = \frac{crushed\ limestone}{time\ taken}\left(\frac{kg}{h}\right)$$

where:

C_{eff}=Crushing efficiency

M_i=mass of input material

M_r=mass of recovered material

$$Losses = \left(\frac{M_b - M_a}{M_b}\right) \times 100$$

where:

M_b=mass before grinding

Ma=mass after grinding

2.2. Sieving Method and Analysis of Lime Powder

Sample of 500g was used for conducting sieve analysis and test sieves "nest" together to form a "stack" of sieves. In this work 20 cm diameter sieve was used and test sieve shaker provides both circular and tapping the energy and uniform mechanical motion. It is performed using a mechanical shaker for 10 minutes [7]. The test was carried out as per ASTM D44 using standard sieve analyzer "Tylers" make. After the shaking was completed, the material on each sieve was weighed. The weight of the sample of each sieve was then divided by the total weight to give a percentage retained on each sieve. The size of the average particles on each sieves were analyzed to get the cut-point or specific size range captured on the sieve. The effectiveness of agricultural lime (i.e. ground geological limestone) was accepted base on particle size to be 100% effective for particles <0.3mm; 60% effective between 0.3mm to 0.850 mm and; 10% effective for particles >0.850 mm [13]. To find the percent of crushed limestone passing through each sieve, the following equation was used,

$$\%\,\text{Re}tained = \frac{W_{sieve}}{W_{Total}} \times 100$$

where:

W_{Sieve} is the weight of crushed limestone in the sieve

W_{Total} is the total weight of crushed limestone

To find the cumulative percent of crushed limestone retained in each sieve, add up the total amount of crushed limestone that was retained in each sieve and the amount in the previous sieves. The cumulative percent passing of the crushed limestone was found by subtracting the percent retained from 100%.

%Cumulative Passing=100% - %Cumulative Retained

The values were then plotted on a graph with cumulative percent passing on the y axis and sieve size on the x axis.

2.3. Experimental Design

The full factorial design was used for continuous grinding. For continuous grinding, an experimental plan comprising of three independent variables namely speed of mill (540, 720 and 900 rpm) and screen size having three levels (2, 4 and 6 mm) and feed rate having three levels (3.5, 7 and 10.5 kg/min) and dried Senkele limestone was selected purposely for evaluation. The ground product coming out of the grinding chamber was collected in a polythene bag, fastened directly under the mill to reduce the loss of fine particles. After the grinding operation, particle size distribution was determined by sieve analysis by taking a 500g from each representative sample. Split plot experimental design was used for analysis of data [6].

3. Results and Discussion

Performance Evaluation of the Machine.

3.1. Crushing Capacity

The mean crushing capacity and analysis of variance were presented in (Table 1). Analysis of variances clearly indicated that the crushing capacity of hammer mill limestone grinder was significantly ($P < 0.05$) affected by hammer mill speed, screen hole diameter and feed rate. The maximum crushing capacity of 630.32 kg/hr was recorded when the hammer mill speed was 900 rpm, the screen hole diameter 6 mm and the feed rate 10.50 kg/min. Generally, crushing capacity increased by increasing the hammer mill speed, feed rate and screen holes diameter. [9] Showed the relationships between drum speed and machine productivity (ton/h) at different sieve diameters and feed rates. Increasing the speed increased the product with increasing the treatments of both the sieve diameter and feed in direct relationships.

Table 1. *Crushing capacity (CC in Kg/hr) of limestone crusher at various hammer mill speeds, screen hole diameter and feed rates.*

Treatments		**Feed rates (Kg/min)**			
Velocity (rpm)	**Screen hole (mm)**	**3.50**	**7.00**	**10.50**	**Grand mean**
540	2	65.62^{g}±4.12	134.29^{f}±9.37	180.39^{de}±6.25	
	4	148.76^{ef}±4.87	222.62^{d}±2.11	356.97^{b}±7.48	
	6	279.42^{c}±62.67	344.55^{b}±54.87	489.64^{a}±5.76	
720	2	80.16^{f}±2.05	163.55^{e}±5.72	196.46^{e}±6.38	
	4	198.82^{e}±42.00	313.87^{d}±12.18	404.45^{c}±2.97	
	6	441.73^{c}±22.00	521.21^{b}±12.62	596.66^{a}±8.22	
900	2	88.56^{i}±2.14	168.33^{h}±3.30	212.87^{g}±12.67	
	4	259.13^{f}±3.97	338.57^{e}±2.74	419.41^{d}±12.44	
	6	469.89^{c}±23.48	548.12^{b}±14.19	630.32^{a}±2.65	306.46
SEM	24.78				
LSD	13.52				
CV (%)	8.09				

SED: Standard errors of differences of means; LSD: Least significance difference; CV: Co- efficient of variation; (Two means are said to be similar or homogeneous if they are not significantly different from one another and those with different superscripts across the row are significantly different statistically at ($p<0.05$). Values were means±standard deviation.

3.2. Crushing Efficiency

The mean percent crushing efficiency of the limestone crusher prototype and analysis of variance are given in (Table 2). Analysis of variance revealed that hammer mill speeds and screen hole diameter had significant ($p=0.01$) effect on crushing efficiency. As can be seen from (Table 2), increasing engine speed resulted in increased crushing efficiency. At higher hammer mill speed the energy imparted to the limestone was high hence causing higher crushing. The Results obtained showed that crushing efficiency increases with increasing screen hole diameter and hammer mill speed and [3] reported similar findings.

The highest crushing efficiency 99.61% was recorded at 900 rpm engine speed, 6 mm screen hole diameter and at 10.50 kg/min feed rate; whereas the lowest crushing efficiency 95.48% was recorded at 540 rpm engine speed, 2 mm screen hole diameter and at 3.50 kg/min feed rate as can be seen from Table 2.

Table 2. *Crushing efficiency (CE, %) of limestone crusher at various hammer mill speeds, screen hole diameter and feed rates.*

Treatments		**Feed rate (kg/min)**			
velocity (rpm)	**screen hole (mm)**	**3.50**	**7.00**	**10.50**	**Grand mean**
540	2	95.48^{a}±0.05	96.06^{b}±0.06	96.48^{c}±0.08	
	4	97.73^{a}±0.05	98.02^{b}±0.05	98.34^{c}±0.10	
	6	98.67^{a}±0.05	98.95^{b}±0.05	99.17^{c}±0.07	
720	2	96.64^{a}±0.05	97.10^{b}±0.10	97.80^{c}±0.05	
	4	98.22^{a}±0.05	98.39^{b}±0.05	98.70^{c}±0.049	
	6	98.89^{a}±0.05	99.05^{b}±0.05	99.27^{c}±0.05	
900	2	97.97^{a}±0.16	98.56^{b}±0.21	98.86^{c}±0.16	
	4	99.05^{a}±0.17	99.27^{b}±0.17	99.50^{c}±0.16	
	6	99.36^{a}±0.16	99.48^{b}±0.16	99.61^{c}±0.16	98.33
SEM	0.13				
LSD	0.07				
CV (%)	0.14				

SED: Standard errors of differences of means; LSD: Least significance difference; CV: Co- efficient of variation; (Two means are said to be similar or homogeneous if they are not significantly different from one another and those with different superscripts across the row are significantly different statistically at ($p<0.05$). Values were means±standard deviation.

3.3. Consumed Energy

The relationship between consumed energy (CE) and hammer rotor speed (V) at different feeding rates (F) and screen holes diameters (S) were illustrated in (Table 3). The obtained data showed that the consumed energy decreased with increasing feeding rate, screen holes diameter and hammer mill speed. The mean consumed energy ranged from 15.47 to 149.16 Wh/kg with hammer rotor speed of 540 to 900 rpm, screen holes diameter of 2 to 6 mm and the feeding rate of 3.5 to 10.5 kg/min. It could be noticed that the lowest values of consumed energy were obtained at engine speed (V) 900 rpm, screen hole diameter (S) 6 mm and feed rate (Fr) of 10.5 kg/min, however the highest values of consumed energy were obtained at engine speed (V) 540 rpm, sreen hole diameter (S) 2 mm and feed rate (F) 3.5 kg/min and Dabbour *et al.* (2015) reports justify similar findings.

Table 3. *Energy consumption (Wh/kg) of limestone crusher at various hammer mill speeds, screen hole diameter and feed rates.*

Treatments		**Feed rate (Kg/min)**			
Velocity (rpm)	**Screen hole (mm)**	**3.50**	**7.00**	**10.50**	**Grand mean**
540	2	149.16^{a}±9.31	72.95^{b}±5.04	54.11^{c}±1.87	
	4	65.61^{a}±2.17	43.80^{b}±0.42	27.33^{c}±0.57	
	6	36.48^{a}±7.10	28.96^{b}±4.16	19.92^{c}±0.23	
720	2	121.71^{a}±3.06	59.69^{b}±2.05	49.68^{c}±1.58	
	4	51.03^{a}±9.44	31.11^{b}±1.22	24.11^{b}±0.18	
	6	22.13^{a}±1.18	18.72^{a}±0.45	16.34^{a}±0.23	
900	2	110.16^{a}±2.62	57.94^{b}±1.12	45.96^{c}±2.69	
	4	37.64^{a}±0.58	28.80^{b}±0.23	23.27^{c}±0.69	
	6	20.80^{a}±1.08	17.80^{a}±0.47	15.47^{a}±0.06	46.32
SEM	4.178				
LSD	2.28				
CV (%)	9.02				

SED: Standard errors of differences of means; LSD: Least significance difference; CV: Co- efficient of variation; (Two means are said to be similar or homogeneous if they are not significantly different from one another) Values were means±standard deviation and those with different superscripts across the row are significantly different statistically at ($p<0.05$).

3.4. Mean Particle Size

The relationship between mean particle size of the limestone particle after ground and hammer rotor speed (V) at different feeding rates (F) and screen holes diameter (S) were illustrated in (Table 4). The obtained data showed that mean particle size increased with increasing screen holes diameter and feeding rate and decreased with increasing hammer speed. The mean particle size ranged from 0.121 to 0.448 mm with hammer rotor speed of 540 to 900 rpm, screen holes diameter of 2 to 6 mm and the feeding rate of 3.5 to 10.5 kg/min. It could be noticed that the lowest values of mean particle size were obtained at engine speed (V) of 900 rpm, screen hole diameter (S) of 2 mm and feed rate (Fr) of 10.5 kg/min.

Table 4. *Mean particle size (mm) of crushed limestone at various hammer mill speeds, screen hole diameter and feed rates.*

Treatments		**Feed rate (Kg/min)**			
V (rpm)	**Scr. diameter**	**3.50**	**7.00**	**10.50**	**Grand mean**
540	2	0.28^{a}±0.01	0.28^{b}±0.03	0.28^{a}±0.01	
	4	0.34^{a}±0.00	0.35^{b}±0.00	0.35^{a}±0.01	
	6	0.44^{c}±0.09	0.44^{b}±0.02	0.45^{a}±0.04	
720	2	0.18^{b}±0.01	0.18^{a}±0.01	0.19^{a}±1.58	
	4	0.30^{ab}±0.02	0.30^{b}±0.02	0.30^{a}±0.02	
	6	0.33^{c}±0.04	0.33^{b}±0.05	0.34^{a}±0.05	
900	2	0.12^{a}±0.01	0.12^{a}±0.0	0.12^{a}±0.00	
	4	0.16^{c}±0.05	0.1637^{b}±0.00	0.17^{b}±0.00	
	6	0.20^{a}±0.03	0.20^{a}±0.00	0.21^{a}±0.01	0.26
SEM	0.02				
LSD	0.32				
CV (%)	7.74				

SED: Standard errors of differences of means; LSD: Least significance difference; CV: Co- efficient of variation; (Two means are said to be similar or homogeneous if they are not significantly different from one another and those with different superscripts across the row are significantly different statistically at ($p<0.05$). Values were means±standard deviation.

3.5. Fuel Consumption

The analysis of variance, on fuel consumption of the crushing machine, revealed that hammer mill speed, screen hole diameter and hopper feed rate had highly significant ($P=0.01$) effects on the fuel consumption. In general, fuel consumption increases with in increasing of engine speeds and decrease with increasing screen hole diameter and increase with increasing of feed rates. The mean fuel consumption ranged from 8.62 to 47.99 ml/kg with hammer rotor speed of 540 to 900 rpm, screen holes diameter of 2 to 6 mm and the feeding rate of 3.5 to 10.5 kg/min. It could be noticed that the lowest values of fuel consumption were obtained at engine speed (V) 540 rpm, screen hole diameter (S) 6 mm and feed rate (Fr) of 3.5 kg/min, however the highest values of fuel consumption were obtained at engine speed (V) 900 rpm, screen hole diameter (S) 2 mm and feed rate (F) 10.5 kg/min. (Table 5) indicating that fuel consumption would be increased with increasing rate of work and feed though it appears to decrease with increasing screen hole diameter manifesting the effect of screen hole diameter on fuel consumption during crushing.

Table 5. *Fuel consumption of engine (FC, ml/kg) for hammer mill prototype when operated at different speeds, screen hole diameter and feed rates.*

Treatments		Feed rate (Kg/min)			
Velocity (rpm)	**Screen hole (mm)**	**3.50**	**7.00**	**10.50**	**Grand mean**
540	2	$14.66^{c}±1.07$	$16.98^{b}±0.55$	$18.34^{a}±0.75$	
	4	$10.54^{ef}±0.85$	$12.67^{d}±0.94$	$15.26^{c}±0.85$	
	6	$8.62^{g}±0.51$	$9.72^{f}±0.52$	$11.40^{e}±0.70$	
720	2	$29.00^{e}±0.63$	$34.33^{c}±0.76$	$39.33^{a}±0.25$	
	4	$20.98^{h}±0.54$	$27.45^{f}±1.03$	$35.54^{b}±0.94$	
	6	$20.58^{h}±1.35$	$25.85^{g}±1.73$	$31.37^{d}±0.55$	
900	2	$35.81^{d}±0.41$	$39.70^{c}±0.43$	$48.00^{a}±0.68$	
	4	$28.82^{g}±0.45$	$34.92^{e}±0.21$	$42.24^{b}±0.50$	
	6	$27.97^{g}±0.23$	$33.01^{f}±0.31$	$38.99^{c}±0.11$	26.37
SEM	0.85				
LSD	0.50				
CV (%)	3.49				

SED: Standard errors of differences of means; LSD: Least significance difference; CV: Co- efficient of variation; (Two means are said to be similar or homogeneous if they are not significantly different from one another and those with different superscripts across the row are significantly different statistically at (p<0.05). Values were means±standard deviation.

3.6. Sieve Particle Size Analysis

Sample of 500 g was used for conducting sieve analysis and test sieves "nest" together to form a "stack" of sieves. In this work 20 cm diameter sieve was used and performed using a mechanical shaker within 10 minutes and carried out as per ASTM D44 using standard sieve analyzer "Tylers" make. After the shaking was completed, the material on each sieve was weighed and divided by the total weight to give a percentage retained on each sieve. The size of the average particles on each sieve then was analyzed to get the cut-point or specific size range captured on the sieve.

To find the cumulative percent weight of crushed limestone retained in each sieve, add up the total weight of crushed limestone that was retained in each sieve and the amount in the previous sieves. The cumulative percent passing of the weight of crushed limestone was found by subtracting the percent retained from 100%. The values are then plotted on a graph with cumulative percent passing on the y axis and sieve size on the x axis.

Table 6. *Cumulative percent passing through sieve and % retained for engine speed of 900 rpm, screen hole diameter of 6 mm and feed rate of 10.5 kg/mi (at maximum efficiency and crushing capacity).*

Sieve №	Mesh size (mm)	WR	%R	CW	%CUM	%Fine
8	2	0	0	0	0	100
16	1.18	2.71	0.542	2.71	0.542	99.46
30	0.6	17.68	3.54	20.39	4.08	95.92
50	0.3	39.27	7.85	59.66	11.93	88.07
100	0.15	189.15	37.83	248.81	49.76	50.24
200	0.075	228.35	45.67	477.16	95.43	4.57
(Pan)		22.77	4.554	499.93	99.99	0.01

Coefficient of Uniformity (CU) (ASTM D2487)=D_{60}/D_{10}=0.19/0.0825=2.3, D_{30}=0.12

Coefficient of curvature (Cc) (ASTM D2487)=$(D_{30})^2/(D_{10}xD_{60})=(0.12)^2/(0.0825x0.19)$=0.92

D60=Diameter corresponding to 60% finer in the grain size distribution. D30=Diameter corresponding to 30% finer in the grain size distribution. D10=Diameter corresponding to 10% finer in the grain size distribution [13].

4. Conclusion and Recommendations

4.1. Conclusion

In light of the aim and objectives stated, the tested results showed that the machine gave a satisfactory performance in output, energy and fuel consumption. The machine also has room for easy maintenance activities such as replacement of screen, hammers and cleaning of the bottom casing. The utilization of the machine is not limited to only limestone and it can be used in poultry and fish food processing and iodized salt processing and can be milled provided they are dried. Lastly, the fabricated machine was constructed with locally sourced material and has fewer components; hence, the purchase price of the machine can be kept low.

4.2. Recommendations

Based on the finding obtained, the performance of impact hammer mill machine appear to be most efficient at 900 rpm engine speed, 6 mm screen hole diameter and 10.50 kg/min feed rate.

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