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Physical and Mechanical Properties of Jatropha curcas L. Seeds

by

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DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated. Wherever contributions of others are involved, every effort is made to indicate them clearly, with due reference to the literature.

Signature ……………………………………….
Date ……………………………………………

ABSTRACT

The purpose of this study was to investigate the moisture- dependant physical and mechanical properties of *jatropha curcas* L seed. And the other aim was to find the optimum moisture content which requires minimum energy. The physical properties investigated include post-harvest moisture content, seed dimensions, sphericity, 1000 seed mass, surface area, volume, bulk density and porosity. The mechanical properties such as rupture force, deformation at rupture point, hardness, energy used for rupture and unit energy were also investigated and reported. To measure each parameter in the laboratory, researcher's recommended laboratory procedures were seriously followed. And all the above mentioned properties of seeds have been evaluated as a function of moisture content in the range of 7.14–47.83 % w.b.

In the moisture range average seeds length, width, thickness, arithmetic mean diameter and geometric mean diameter increased linearly from 17.19 to 19.12mm, 11.03 to 11.41mm, 8.55 to 9.15mm, 12.26 to 13.23mm and 11.74 to 12.59mm respectively as the moisture content increased; while on the contrary sphericity and porosity decreased from 0.68 to 0.66 and 59.70 to 45.85% respectively; the surface area and volume increased from 434.05 to 499.43 mm^2 and 594.68 to 719.53mm^3 respectively; 1000 seed mass and bulk density increased from 391.29 to 525.80 kg/m^3 and 606.06 to 934.78 g respectively. The rupture force and hardness decreased non–linearly from 98.09 to 96.74 kN, and 3.77 to 3.49 kN/mm respectively as the moisture content increased. On the other hand deformation energy, unit energy and maximum deformation increased non–linearly from 328.54 to 415.66 J, 773.26 to 915.91 kJ/m^3 and 25.98 to 27.75 mm respectively as the moisture content increased. The optimum moisture content was 17.60% w.b.

Keywords: *compression; deformation; jatropha curcas (jatropha)*; *wet basis (w.b); total energy*

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1. INTRODUCTION

Jatropha curcas is a species of flowering plant in the spurge family, Euphorbiaceae, which is native to American tropics, most likely Mexico and Central America (Jules Janick et al., 2008). It is able to thrive in a number of climate zones with rain fall of 250–1200 mm (P. Sirisomboon et al., 2007). It is well adapted to arid and semi-arid conditions and has low fertility and moisture demand. Now days it is cultivated in tropical regions around the world, becoming naturalized in some areas.

Jatropha curcas is a multipurpose plant with a variety of applications and enormous economic potentials. All parts of *jatropha* (seeds, leaves, bark etc) have been used in traditional medicine and for veterinary purpose for a long time (Ashwani Kumar and Satyawati Sharma, 2008).The seeds of *jatropha curcas* contain 27-40 % of oil that can be processed to produce a high-quality biodiesel fuel, usable in a standard diesel engine (Achten WMJ et al., 2007). Depending on the variety, *jatropha* seed kernels contain 40–60% of oil (H.P.S. Makkar et al., 1997). Seed cake which is the by-product of oil extraction has potential to be used as a fertilizer or biogas production (G.M Gubitz et al., 1998). Being rich in Nitrogen, the seed cake is an excellent source of plant nutrients (Ashwani Kumar and Satyawati Sharma, 2008). The glycerin that is a by-product of the biodiesel can be used to make soap, and soap can be produced from jatropha oil itself. The oil and aqueous extract from oil has potential to be used as an insecticide (N. Kaustik et al., 2007).

Various *jatropha curcas* oil extraction methods have been identified and used. The two main methods of extracting the oil from *jatropha curcas* seed are the chemical extraction method using solvent extraction with n-hexane and the mechanical extraction method using either a manual ram-press or an engine driven expeller (G.M Gubitz et al., 1998). Use of aqueous oil extraction at various temperatures found to yield 38 % (Hanny Johanes Berchmans and Shizuko Hirata, 2007). Shweta Shah et al., 2003 reported that the aqueous enzymatic extraction method gave a yield of 44g oil/100g *jatropha* seed kernels. Ultrasonication is emerging as a powerful tool to accelerate many chemicals and physical processes. It has also been used to increase the oil yield during aqueous oil extraction in some cases (Shweta Shah et al., 2003). In general, the recoverable oil fraction is clearly affected by pressing technology.

In the process of extracting the *jatropha* oil and its derivatives, the seeds undergo a series of unit operations. Knowledge of the physical and mechanical properties and their dependency on the moisture content is essential to facilitate and improve the design of equipments for processing and storage of seeds. Various physical properties of seeds are dependent on moisture content, and appear to be important in the design of planting, harvesting, handling operation, transportation, storing and processing equipments. Various types of cleaning, grading, separation, oil extraction equipment are also designed on the basis of the physical properties of seeds.

The size and shape of the seeds are important for designing the dehulling or nut shelling machine, and data on the can be used to determine the lower size limit of the conveyor such as belt conveyor, bucket elevator and screw conveyor. Bulk density is used when determining the size of the storage bin and solid density is necessary parameter in the design of a pneumatic conveyor system. Porosity (calculated from bulk density and solid density), surface area and specific surface area affect the resistance to air flow through the bulk material bed and also data on them are necessary in designing the drying process (P. Sirisomboona et al.,2007).

Mechanical properties such as rupture force, hardness and energy used for rupturing the seeds are useful parameters in designing the dehulling or nut shelling machine and oil extractor. The rupture force indicates the minimum force required for dehulling the fruit or shelling the nut and to extract the oil from kernel. The deformation at the rupture point can be used for the determination of the gap size between the surfaces to compress the fruit or nut for dehuuling or shelling (P. Sirisomboona et al., 2007).

1.1 Objective of Study

The aim of this study was to investigate the physical and mechanical properties of *jatropha curcas* seeds. The parameters investigated moisture content, linear dimensions, arithmetic mean, geometric mean, sphericity, surface area, bulk and solid density, porosity, rupture force, deformation at rupture point, energy used for rupture.

2. LITERATURE REVIEW

This literature review briefly explores factors affecting *jatropha curcas* production, cultivation methods, fruit harvesting methods, various use of the plant as a whole and its fruits and seeds in particular, oil extraction methods, and moisture dependant physical and mechanical properties of its seeds. On each topic published scientific journals as well as standard books have been reviewed and presented.

2.1 Factors Affecting Jatropha Curcas L. Production

Among many species, which yield oil as a source of energy in the form of biodiesel, *jatropha curcas* L. has been identified as most suitable oil seed bearing plant due to its various favorable attributes. However, there are some key factors which affect its productivity. The following factors are some of the key factors that can influence *jatropha curcas* production in general, and oil yield of its seed in particular.

2.1.1 Climate

Jatropha curcas grows in tropical and sub tropical regions, with cultivation limits at 30ºN and 35ºS. It also grows in lower altitudes of 0-500 meters above sea level. *Jatropha curcas* is not sensitive to day length and may flower at any time of the year (Heller, 1996). It is a succulent shrub (water-retaining plant) which is adapted to arid climate.

While *jatropha curcas* can survive with as little as 250 to 300 mm of annual rainfall, at least 600 mm are needed to flower and set fruit. The optimum rainfall for seed production is considered between 1 000 and 1 500 mm (FACT, 2007), which corresponds to sub-humid ecologies. While *jatropha* has been observed growing with 3 000 mm of rainfall (Achten, 2008), higher precipitation is likely to cause fungal attack and restrict root growth in all but the most free-draining soils.

Optimum temperatures are between 20˚C and 28˚C, and very high temperatures can depress yields (Gour, 2006). *Jatropha curcas* has been seen to be intolerant of frost. The plant is well adapted to conditions of high light intensity, and is unsuited to growing in shade.

2.1.2 Soil type

Unless there are waterlogged conditions, *jatropha curcas* can be grown in any type of soil. However, the productivity is less in heavy clay soils, particularly where drainage is impaired, as jatropha is intolerant of waterlogged conditions. The best soils for *jatropha* are aerated sands and loams of at least 45 cm depth (Gour, 2006).

Jatropha is known for its ability to survive in very poor dry soils in conditions considered marginal for agriculture, and can even root into rock crevices. However, survival ability does not mean that high productivity can be obtained from *jatropha* under marginal agricultural environments (Jongschaap et al, 2007).

2.1.3 Plant Nutrient, Water and Pesticide Requirements

Jatropha cucas is often described as having a low nutrient requirement because it is adapted to growing in poor soils. However, growing a productive crop requires correct fertilization and adequate rainfall or irrigation. Equally, high levels of fertilizer and excessive irrigation can induce high total biomass production at the expense of seed yield (Jongschaap et al, 2007). Unfortunately, there is insufficient data on response to fertilizer under different growing conditions for it to be possible to make specific recommendations for optimal crop nutrition.

The optimum levels of inorganic fertilizers have been seen to vary with the age of the tree (Achten, 2008). Site-specific fertilizer trials need to be established for trees of different ages and over a number of seasons.

There is little quantitative data available on the water needs, water productivity and water-use efficiency of *jatropha*. It is believed that optimal rainfall is between 1 000 and 1 500 mm (FACT, 2007).

Because of its toxic nature, it is often reported pests and diseases do not pose a significant threat to *jatropha*. However, incidence of pests and diseases is widely reported under plantation monoculture Observed diseases, such as collar rot, leaf spots, root rot and damping-off, may be controlled with a combination of cultural techniques (for example, avoiding waterlogged conditions) and fungicides (Jongschaap et al, 2007).

2.2 Plant Cultivation Methods

Jatropha curcas grows readily from seeds or cuttings; however, trees propagated by cuttings show a lower longevity and possess a lower drought and disease resistance than those propagated by seeds (Heller, 1996) this might have been due to trees produced from cuttings do not produce true taproots (hence less drought tolerant), rather they produce pseudo-taproots that may penetrate only 1/2 to 2/3rd the depth of the soil as taproots produced on trees grown seed.

There are various methods to cultivate *jatropha*, which vary from region to region and also on climatic conditions. These are: direct seeding, pre-cultivation of seedlings (nursery rising), transplanting of spontaneous wild plants and direct planting of cuttings. An important noticeable difference between cuttings and seedlings however is that cuttings are yielding earlier than seedlings, due to the fact that cuttings usually come from adult plants, (with the exception of soft cuttings) (Ab van Peer, 2010). Vegetative propagation has been achieved by stem cuttings, grafting, budding as well as by air layering techniques.

Generally, *jatropha curcas* L. starts producing fruit in about one year and reaches a stable harvesting stage after five years. It has a lifespan of about 50 years and an estimated economically productive period of 25-30 years. After 5 years the plant is said to produce 3-12 tones of seeds per hectare per year depending on weather and management condition. But the production curve is practically unknown since there are no actual production results on a commercial basis (IEEJ, 2009).

2.3 Fruit Harvesting

Poor harvesting has been the major retarding factor for commercialization of this crop and has been highlighted in many publications. The harvesting of the *jatropha* seeds is a difficult process due to the ripening characteristics of the *jatropha* fruit. *Jatropha* fruits mature heterogeneously which leads to laborious and time consuming harvesting because the fruit harvesters have to select only the fruits that are of the right ripening index for latter processing and have to be harvested manually at regular intervals. Due to these ripening issues, the harvesting of *jatropha* is mainly done by hand. The harvesting process becomes a very labor-intensive process, and has a high impact on the production costs of *jatropha* oil (Heller, 1996).

Manual picking of *jatropha* fruits is not a good choice for planting for a country where the labour costs exceed approximately US$4/day. This rule of thumb is based on experience in several projects over the period 1996-2009. The alternative is mechanical picking, and although not fully developed, this might bring down costs in the future. There have been many attempts to improve this process by mechanization. These mechanical improvements are still under development, however, and have been applied only in pilot projects (Winfried Rijssenbeek Handbook) .

Mechanical harvesting of this crop was considered impossible due to heterogeneous maturity of fruits. Currently, however, some mechanical methods such as *Tree or stem shakers*, *Robots with picking arms* , *Strippers, Nets to prevent fruits falling on the ground* etc have been practiced in some countries (Winfried Rijssenbeek handbook) . But in almost all farms, today, *jatropha* fruits are still harvested by hand in small and plantation scale farms. In permanent humid areas, weekly harvest in *jatropha* field was required all year through but in dry areas harvest is recommended over a period of two months, which implies daily or weekly harvests. The indeterminate reproductive habit of *jatropha* is thought to be related to this problem but little information exists on these characters.

2.4 Various Uses of Jatropha Curcas Products

Jatropha curcas (Linnaeus) is a multipurpose bush/small tree belonging to the family of *Euphorbiaceae*. It is a plant with many attributes, multiple uses and considerable potential. The wood and fruit of *jatropha* can be used for numerous purposes.

2.4.1 Soil conservation and Protection Benefits

The primary conservation benefits to be derived from production of *jatropha* relate to improved soil restoration and management. The findings of Meena Misra and Amarendra N. Misra (2010) have shown that the heavy metal contaminated soil can be restored by using combination of industrial wastes and suitable bioinoculants strain (*Azotobacter*). *Jatropha* in addition to protecting crops from livestock; it reduces wind erosion and pressure on timber resources and increases soil moisture retention. Nevertheless, *jatropha* does mine soil nutrients. *jatropha* oil projects are expected to provide income and organic fertilizer to increase crop yields, as well as being an ecologically friendly source of alternative energy to rural farmers.

2.4.2 Food Source

Jatropha curcas can be toxic when consumed, however, a non-toxic variety of *jatropha* is reported to exist in some provenances of Mexico and Central America, said not to contain toxic Phorbol esters (Makkar et al., 1998). This non-toxic variety of *jatropha* could be a potential source of oil for human consumption, and the seed cake can be a good protein source for humans as well as for livestock (Becker et al, 1999).This variety is used for human consumption after roasting the seeds/nuts, and "the young leaves may be safely eaten, steamed or stewed. Generally, *jatropha curca's* use as a food source is limited due to the toxic nature of the plant, and it is not a competent crop for food stuff.

2.4.3 Medicinal uses

All parts of *jatropha* (seeds, leaves and bark) have been used in traditional medicine and for veterinary purposes for a long time (Duke, 1985b) and (Duke, 1988) Some compounds (Curcacycline A) with antitumor activities were reportedly found in this plant (Van den Berg et al., 1995). Substances such as phorbol esters, which are toxic to animals and humans, have been isolated and their molluscicidal, insecticidal and fungicidal properties have been demonstrated in lab-scale experiments and field trials (G.M Gubitz et al., 1998). The seed oil can be applied to treat eczema and skin diseases and to soothe rheumatic pain (Heller, 1996). The oil has a strong purgative action and is also widely used for skin diseases and to soothe pain such as that caused by rheumatism.

2.4.4 Biological pesticide

The oil and aqueous extract from oil has potential as an insecticide. For instance it has been used in the control of insect pests of cotton including cotton bollworm and on pests of pulses, potato and corn (Ashwani Kumar and Satyawati Sharma, 2008). Methanol extracts of *jatropha* seed (which contains biodegradable toxins) are being tested in Germany for control of bilharzia-carrying water snails.

2.4.5 Biodiesel Production

The growth in energy demand in all forms is expected to continue unabated owing to increasing urbanization, standard of living and expanding population. Currently due to gradual depletion of world petroleum reserves and the impact of environmental pollution of increasing exhaust emissions, there is an urgent need o develop alternative energy resources, such as biodiesel fuel. Biodiesel has many advantages include the following: its renewable, safe for use in all conventional diesel engines, offers the same performance and engine durability as petroleum diesel fuel, non-flammable and nontoxic, reduces tailpipe emissions, visible smoke and noxious fumes and odors. The use of biodiesel has grown dramatically during the last few years. Feedstock costs account for a large percent of the direct biodiesel production costs, including capital cost and return (Emil kabar et al., 2009).

Jatropha curcas has a great potential as biodiesel and it would be best alternative energy source for the global energy crises. The fact that *jatropha* oil can not be used for nutritional purposes without detoxification makes its use as energy or fuel source very attractive as biodiesel. The fatty acid, methyl ester, of the oil of *jatropha curcas* was found most suitable for use as biodiesel and it meets most of the specifications of biodiesel standards of USA, Germany and European Standard Organization (Mohibbe Azam et al., 2005). The high viscosity of the *jatropha curcas* oil, which is considered as a potential alternative fuel for the compression ignition (C.I.) engine, is decreased by blending with diesel. Pramanik (2003) reported that significant improvement in engine performance was observed, compared to vegetable oil. Acceptable thermal efficiencies of the engine were obtained with blends containing up to 50% volume of *jatropha* oil. From the properties and engine test results, it had been established that 40–50% of *jatropha* oil could be substituted for diesel without any engine modification and preheating of the blends (P. Sirisomboon et al 2007).

2.4.6 The By-product of Oil Extraction as Frtilizers

Seed cake or press cake is a by-product of oil extraction. *Jatropha* seed cake contains curcin, a highly toxic protein similar to ricin in castor, making it unsuitable for animal feed. However, it does have potential as a fertilizer or biogas production (Staubmann et al., 1997) and (Gubitz et al., 1999), if available in large quantities; it can also be used as a fuel for steam turbines to generate electricity. Being rich in nitrogen, the seed cake is an excellent source of plant nutrients. In a green manure trial with rice in Nepal, the application of 10 tones of fresh physic nut biomass resulted in increase yield of many crops.

2.4.7 Other Uses

It is a woody plant and, therefore, its various parts can be used for a number of purposes, especially as fuel, sticks and poles. In some countries, the live pole is used to support vines such as the vanillin plant. Bees pollinate their flowers, thus it is possible to have apiaries in association with *jatropha* areas. A varnish can be made from the oil and the leaves could be feedstock for silk worms but not everywhere. For example, the experiments conducted by the authors, on rearing of *Philosamia ricini* on *Jatropha* leaves, concluded 100% mortality of erisilk worm *P. ricini* on leaf biomass. *Jatropha* is an excellent hedging plant generally grown in some part of the Africa and Asia as live fence for protection of agricultural fields against damage by livestock as unpalatable to cattle and goats. Thus in addition to seed yields it serves the purpose of bio fence with respect to cost effectiveness as compared to wire fence.

2.5 Oil Extraction Methods

It is reported that a dry seed of *jatropha curcas* contains about 55% of oil. However, the maximum amount of oil that can be extracted from a given sample of the seed depends on the method of extraction and perhaps the quality of the feedstock.The determination of oil content in biodiesel feed stocks can be performed using several methods, including mechanical press, solvent extraction, and Nuclear Magnetic Resonance. For the feedstock quality control in terms of oil content, it is important that the applied method is universally accepted so as to obtain results that can be compared with those reported from alternate sources (Gubitz GM 1997).

2.5.1 Mechanical Method

Mechanical extraction is the oldest method used for oil extraction. Three well practiced ways of mechanical means of extraction. These are manual ram press (e.g. Yenga or Bielenberg ram press), an engine driven screw press and hydraulic press. R.K. Henning (2000) stated that engine driven screw presses extract 75–80% of the available oil, while the manual ram presses only achieved 60–65%. The advantages of a screw press compared to a hydraulic press are its slightly higher yield and its continuous mode of operation. Mechanical expression results in high quality oil, but has a relatively low yield. Oil extraction efficiencies calculated from data reported in more recent studies are found to generally correspond to these ranges, although the efficiency range of engine driven screw presses can be broadened to 70–80% (W.M.J. Achten et al 2007). This broader range corresponds to the fact that seeds can be subjected to a different number of extractions through the expeller. Up to three passes is common practice. Pretreatment of the seeds, like cooking, can increase the oil yield of screw pressing up to 89% after single pass and 91% after dual pass.

2.5.2 Solvent Extraction Method

The most common chemical method of extraction is the solvent extraction method which uses *n*-hexane as a solvent. Kpikpi (2002) has reported that solvent extraction with n-hexane could produce about 41% yield by weight of oil per kg of the jatropha seed. The solvent extraction of *jatropha* seed kernels gave a yield of 44 g oil/100 g *jatropha seed kernels*. *Jatropha* oil is reportedly present in the range of 40–60 g oil/100 g *jatropha* seed kernels (Makkar et al., 1997). A value of 44 g oil/100 g *jatropha* seed kernels was taken as 100% recovery of oil while calculating the oil recovery by aqueous -enzymatic extraction method.

2.5.3 Aqueous -enzymatic Extraction Method

In aqueous-enzymatic oil extraction method, enzymes are used to facilitate release of oil from oil bodies enmeshed in protein and cellulosic/ hemicellulosic networks (Rosenthal et al., 1996). In this method the use of alkaline protease gave the best results for both available studies. Furthermore, it was shown that ultrasonication pretreatment was a useful step in aqueous oil extraction (Shweta Shah et al 2004).

Aqueous enzymatic oil extractions greatly reduce the environmental impacts which would occur if conventional *n*-hexane solvent extraction is used. Adriaans, 2006 concludes that solvent extraction is only economical at a large-scale production of more than 50 t bio-diesel per day. Furthermore he does not recommend the conventional *n*-hexane solvent extraction because of environmental impacts (generation of waste water, higher specific energy consumption and higher emissions of volatile organic compounds) and human health impacts (working with hazardous and inflammable chemicals).

2.5.4 Supercritical oil extraction method

Biodiesel production from *jatropha* oil via non-catalytic supercritical methanol had also been proven to be more superior in terms of reaction time, product separation, FAME yield and process complicity compare to conventional biodiesel processing (Hawash et al., 2009). Fluid in a supercritical phase can be considered as an intermediate between liquid and gas. This special state has attributed to several distinctive characteristics such as low viscosity, high diffusion coefficients, variation of density and dielectric constant as a function of pressure. Consequently, supercritical fluids (SCF) are excellent extraction solvents as well as chemical reaction reagents. Therefore, it will be interesting to investigate the potential of SCFs in direct contact with the oil-bearing solid materials for biodiesel production.

In general, the oil extraction efficiency of *jatropha curcas* L. seeds increased with increasing temperature and pressure as higher temperature and pressure typically favoured the expulsion of oil from the shell (Berchmans and Hirata, 2008). The minimum oil extraction efficiency at lower temperatures (200–240 °C) was higher than 65% v/v for all solid fractions due to the contribution of n-hexane in the pre-stirring stage. Higher increment rate for oil extraction efficiency was discovered at temperature above 240 °C since supercritical fluid extraction began to take effect. Thus, it can be concluded that the effect of co-solvent is rather significant at the beginning of the process while supercritical fluid extraction dominates at higher temperatures to bring the total oil extraction efficiency to 100%. For different solid particle sizes, smaller particle size generally exhibited higher oil extraction efficiency because of the higher surface area in contact and less hindrance from the outer hard shell covering the oil seeds (Shuit et al., 2010).

2.6 Physical and Mechanical Properties of Jatropha Curcas Seeds

In the oil extraction process of *jatropha*, there are series of unit operations that *jatropha* seeds must pass through. Each unit operation requires a specific machine or equipment and the design of these equipments requires deep knowledge and understanding of both physical and mechanical properties of *jatropha curcas* seeds. Review of the literatures shows that limited researches have been conducted on the physical and mechanical properties of *jatropha* seeds.

2.6.1 Physical Properties

The physical properties of *jatropha curcas* seeds and their dependency on moisture contents have been studied by some researchers. Seed moisture content is one of the most important factor influencing seed quality and sortability. Therefore, its estimation during seed quality determination is important. According to Danida Forest Seed Center (2003), the *jatropha curcas* seeds are orthodox and should be dried to low moisture content (5-7% d.b) and stored in air tight containers. Experimental measurement shows that the moisture content of the kernel is < 6% and the shell <10% (Gubbitiz et al., 1997). RL Worang (2008) reports the initial moisture content of *jatropha curcas* seeds value from 7.9-8.4%. But this range seems very small and E Winkler

(1997) makes the range a bit wider i.e. 8-10%. And also various experimental values are reported by various researchers and generally the results agree regardless of a slight differences (Sirisomboon et al., 2007, Noyak and Patel., 2010 etc).

D.K. Garnayak et al., (2008) showed that the mean dimensions of 100 seeds were: length 18.65±0.62 mm, width 11.34±0.44 mm and thickness 8.91±44 mm ($P<0.05$). Also the researchers showed that each principal dimension was linearly dependant on the moisture content, and the observed correlation coefficients between the three principal dimensions and moisture content were positive (+). Similar experiments have been done by other researches. For instance, Sirisomboon et al., (2007) demonstrated that the mean dimensions of 100 *jatropha curcas* seeds were: length 21.02±1.03 mm, width 11.97±0.30 mm and thickness 9.58±0.28 mm. For some seeds, like coriander seeds, the relationship between principal linear dimensions and moisture content is a bit complex. Coskuner Y et al., (2006) demonstrated that length of coriander seeds decreased linearly with moisture content in the moisture range of 7.10–18.94% (d.b.). But the relationships between the width and thickness of coriander seeds and moisture content were polynomial.

The surface area of *jatropha curcas* seeds were calculated from their linear dimensions and reported by (D.K. Garnayak et al., 2007). The report shows that the surface area *jatropha curcas* seed increased linearly from 476.78 to 521.99 mm^2 as the moisture content increased from 4.75 to 19.57 % on d.b. A similar trend has been reported by Eşref IŞIK and Halil ÜNAL (2007) for a red kidney bean grains.

Almost all the experimental values of sphericity that have been measured agree and the results seem reliable. Garnayak et al., 2008 observed that sphericity increased from 0.66 to 0.67 as moisture content increased from 4.75 to 19.57% d.b. According to Sirisomboon et al., 2007, the sphericity value of *jatropha curcas* fruit is 0.94 which is closed to a sphere its nut (0.64) and kernel (0.68) both of which are close to ellipsoid. And also sphericity of *jatropha curcas* seeds varied between 0.82 and 0.83 as moisture content increased from 7.97% to 23.33% d.b. Later Sirisomboom and Kitchaiya(2009) concluded that the sphericity of dried kernels was between 0.65 to 0.66 and 0.53 for steamed kernels. Similarly Shkelqim Karaj and Joachim Müller (2009) carried out experiment and found that the sphericity of *jatropha curcas* seeds was between 0.66 to 0.67 and 0.54 to 0.64 for kernels.

The surface area of *jatropha curcas* fruits, nuts and kernels were 3139.21, 534.12 and 306.48 mm^2 respectively (Sirisomboon et al., 2007). But the researchers didn't show us the variation of the surface areas as the moisture content is changed. Later (Garnayak et al., 2008) demonstrated that the surface area of *jatropha curcas* seed was increased 476.78 to 521.99 mm^2 as the moisture content increased from 4.75 to 19.57% d.b.

Arithmetic and geometric mean of *jatropha curcas* seeds have been measure by a few researchers. The arithmetic and geometric mean increased linearly from 12.97 to 13.51mm and 12.32 to 12.89 mm respectively as the moisture content increased 4.75 to 19.57% d.b (Garnayak et al., 2008). The geometric diameter of *jatropha curcas* fruits, nuts and kernels were 31.51, 13.40 and 10.55mm respectively (Sirisomboon et al., 2007). Similarly (Karaj and Muller, 2009) reported the arithmetic and geometric mean values 11.41 to 12.91 mm and 10.87 to 12.32 mm respectively.

The bulk and solid density of *jatropha curcas* seeds were in the range of 0.25 to 0.44 g/cm^3 and 0.408 to 0.786 g/cm^3 respectively (Karaj and Muller., 2009). The bulk densities of *jatropha curcas* fruits, nuts and kernels were0.47, 0.45 and 0.42 g/cm^3 and the corresponding solid densities were 0.95, 1.04 and 1.02 g/cm^3 respectively (Sirisomboon et al., 2007). In the moisture content range of 4.75 to 19.57% d.b, the bulk density decreased from 0.492 to 0.419 g/cm^3 , but the true density increased from 0.679 to 0.767 g/cm^3(Garnayak et al., 2008).

The true density defined as the ratio between the mass of *jatropha* seed and the true volume of the seed, is determined using the toluene (C7H8) displacement method. Toluene is used in place of water because it is absorbed by seeds to a lesser extent. The volume of toluene displaced is found by immersing a weighted quantity of *jatropha* seed in the toluene (Sacilik et al., 2003). In this report true density experiment has not done. However, previously determined value of true density of Jatropha curcas seeds has been used for the calculation of porosity.

The value of porosity of *jatropha curcas* seeds increased linearly from 27.54 to 45.37% as the moisture content increased from 4.75 to 19.57% d.b (Garnayak et al., 2008). Keraj and Muller

(2009) reported porosity in the range between 34.6 to 43.3 %. According to (Sirisomboon et al., 2007) the porosity of *jatropha curcas* fruits, nuts and kernels were 50.53 %, 56.73% and 58.82% respectively.

Static friction coefficient of various surfaces affects the maximum inclination angle of conveyor and storage bin. The magnitude of frictional force affects the amount of power required to convey the materials (Sirisomboon et al., 2007. The static coefficient of friction of *jatropha* seed on three surfaces (plywood, aluminum and mild steel sheet) against moisture content in the range of 4.75–19.57% d.b was investigated by (Garnayak et al., 2008). They have observed that the static coefficient of friction increased linearly with increase in moisture content for all contact surfaces.

2.6.2 Mechanical Properties

Mechanical properties such as rupture force, hardness and energy used for rupturing fruit, nut and kernel are useful information in designing the dehulling or nut shelling machine and oil extractor. The rupture force indicates the minimum force required for dehulling the fruit or shelling the nut and to extract the oil from kernel. The deformation at rupture point can be used for the determination of the gap size between the surfaces to compress the fruit or nut for dehulling or shelling (P. Sirisomboon et al, 2007). Literature review shows that moisture dependant mechanical properties of *Jatropha curcas* have not deeply investigated yet.

In view of these, present research was designed to study the physical and mechanical properties of *jatropha curcas* seed from Sumatra, Indonesia.

3. MATERIALS AND METHODS

3.1 Sample

Sun dried *jatropha curcas* seeds were obtained from Sumatra, Indonesia. The seeds were cleaned manually to remove all foreign materials and broken seeds. The initial moisture content of seed was determined by using the standard hot air oven method at 105±1°C for 24h (Brusewitz, 1975; Gupta and Das, 1997; O¨zarslan, 2002; Altuntases et al., 2005; Coskun et al., 2005).

In order to observe the moisture dependant physical and mechanical properties of *jatropha curcas* seed, four samples of the seed were taken and moistened for four consecutive days. The samples were kept in refrigerator, and after each day the physical and mechanical properties were investigated.

The rewetted samples were kept at 5 °C in a refrigerator, and the moisture contents were determined after one day, two days, three days and four days. Before starting the tests, the required quantities of the samples were taken out of the refrigerator and allowed to warm to room temperature for about one hour.

3.2 Physical Properties

Seed moisture content is expressed as percentage of moisture based on wet weight (wet basis) or dry matter (dry basis). Wet basis moisture content is generally used by researchers to investigate moisture dependant properties of seeds, and it was used in this paper too. But the dry basis moisture content is equally important for other researchers. The formulae for the two basis are as follows:

$$M_w(\%) = \left(\frac{W_w - W_d}{W_w}\right) \cdot 100 \qquad (1)$$

$$M_d(\%) = \left(\frac{W_w - W_d}{W_d}\right) \cdot 100 \qquad (2)$$

Where, W_w = wet weight

W_d = dry weight

M_w = moisture content on wet basis(%) and

M_d = moisture content on dry basis (%)

For both natural and further wetted conditions, measurements of the three major perpendicular dimensions of the seed (length, width and thickness) were carried out with a vernier caliper with an approximate accuracy of 0.02mm.

The average diameters of seeds were calculated using the formulae of arithmetic and geometric means taking the three axial dimensions as input parameters. The arithmetic mean diameter, D_a and geometric mean diameter, D_g of the seed were calculated by using the following relationships (Mohsenin, 1970):

$$D_a = \frac{L + W + T}{3} \tag{3}$$

$$D_g = (L \cdot W \cdot T)^{\frac{1}{3}} \tag{4}$$

Where, L, W and T are length, width and thickness respectively

The sphericity (Φ) of *jatropha* seed was calculated by using the following relationship (Mohsenin, 1970):

$$\Phi = \frac{(L \cdot W \cdot T)^{\frac{1}{3}}}{L} \tag{5}$$

Again here, L is the length, W the width and T is the thickness, all in mm.

The surface area of *jatropha* seed was found by analogy with a sphere of the same geometric mean diameter, using the following relationship (Sacilik et al., 2003; Tunde-Akintunde and Akintunde, 2004; Altuntases et al., 2005):

$$S = \pi \cdot D_g^{2} \qquad (6)$$

Where D_g is the geometric mean diameter in (mm), and S is the surface area (mm2).

The bulk density was calculated from the mass of the seeds and the volume of the pressing vessel. The mass (M_b) of the seeds was measured by an electronic balance and the volume of the pressing vessel was calculated from the following relationship.

$$V = \frac{\pi D^2}{4} \cdot H \qquad (7)$$

$$\rho_b = \frac{M_b}{V} \qquad (8)$$

Where, ρ_b is bulk density, M_b is mass of the seeds, V is volume of seeds, D is the diameter of the pressing vessel (D=72.15mm) and H is height of seeds in the pressing vessel (H=40mm).

Porosity is a parameter indicating the amount of pores in the bulk material. And it could be calculated from bulk and true densities using the following relationship (Mohsenin, 1970):

$$\psi = \left(1 - \frac{\rho_b}{\rho_t}\right) \cdot 100 \qquad (9)$$

Where ψ is the porosity (in %), ρ_b the bulk density (in $kg.m^{-3}$), and ρ_t is the true density (in $kg.m^{-3}$). The true density ρ_t is defined as the mass of individual material divided by the volume of the material. Sirisomboon et al. 2007 has determined the true density of *jatropha curcas* seeds by weighing the seeds in toluene, and found the value of 971 $kg.m^{-3}$. In this paper this previously determined value (i. e = 971 $kg.m^{-3}$) was used for the calculation of porosity using equation (9) above.

3.3 Mechanical Properties

To determine the mechanical properties of *jatropha curcas* seeds, compression testing machine (Compression device-ZDM50-2313/56/18) which has 100kN compression was used. The mechanical properties of *jatropha curcas* seeds including rupture force, deformation at rupture point and energy used for rupture on vertical position were determined.

The plots of applied force versus the resulting deformation that the testing machine produces (For example as shown in figure 1 below) were scanned, and then digitized using engauge digitizer software. The output of this software is a table containing numbers, which correspond to deformation (mm) and force (N).

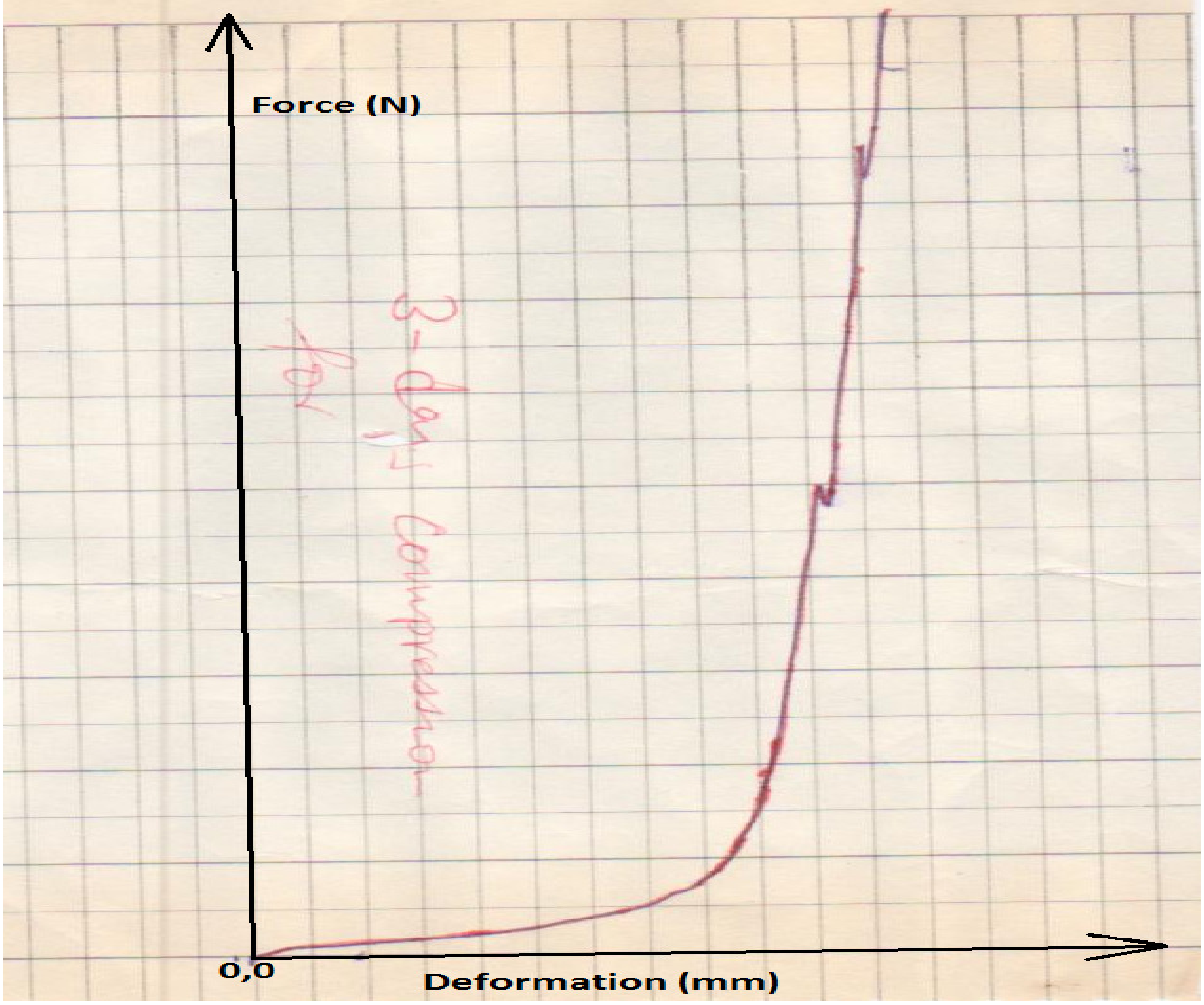

Fig 1. Force-deformation curve from the compression testing machine

Finally analysis was carried out using Microsoft Excel and MathCAD software. While most of the analysis ware carried with excel program, MathCAD was also used to calculate the total energy from the mathematical models generated by the excel program. This is important because it enables us to compare and see the variation between the total energy calculated by finite method (force times deformation), and the corresponding total energy calculated by integrating the mathematical models generated by excel program.

The rupture force, F_r (N) is the minimum force required to break the sample. Whereas deformation at rupture point, δ_{max} (mm) is a point on the force–deformation curve at which the loaded specimen shows a visible or invisible failure in the form of breaks or cracks. This point is detected by a continuous decrease of the load in the force-deformation diagram. While the rupture point was detected, the loading was stopped. These tests were carried out at the loading rate of 1 mm/sec for all moisture levels (ASAE, 2006a).

Maximum deformation

Hardness, H (N/mm) is the ratio of rupture force and deformation at rupture point (maximum deformation). It was calculated as:

$$H = \frac{F_r}{\delta_{max}} \tag{10}$$

Where δ_{max} is maximum deformation (deformation at rupture point) and F_r is the rupture force.

The mechanical behavior of *jatropha curcas* seeds were expressed in terms of rupture force and rupture energy required for initial rupture .Energy for rupture, E_r (N.m) is the energy needed to rupture the sample, which could be determined from the area under the curve between the initial and final points. Energy absorbed by the sample at rupture was determined by calculating the area under the force–deformation curve from the following relationship:

$$E = \sum_{n=0}^{n_{max}} \left[\left(\frac{F_{n+1} + F_n}{2} \right) \cdot \left(X_{n+1} - X_n \right) \right] \tag{11}$$

Where E= Strain energy in joule, (F_{n+1} and $F_{n)}$ are forces applied in Newton and (X_{n+1} and X_n) are values of seed deformation in mm (Braga et al., 1999). The subscript 'n' stands for data point and it ranges from 0 to its maximum value (n_{max}), where the seeds fracture.

Unit energy

The unit energy or energy density is a term used for the amount of energy stored in a given system or region of space per unit volume. Symbolically it is expressed as:

$$U_e = \frac{E}{V} \tag{12}$$

Where U_e is unit energy J/m^3, E strain energy J and V volume m^3 which could be calculated using the following formulae:

$$V_d = \frac{\pi \cdot D^2}{4} \cdot \delta_{max} \qquad \text{Or} \qquad V_i = \frac{\pi \cdot D^2}{4} \cdot H \tag{13}$$

Where: V_d is deformed volume (m^3), V_i is initial volume (m^3), D is diameter of the pressing vessel (72.15 mm), H is height of seeds in the pressing vessel (40mm) and δ_{max}, is the maximum deflection (mm) that obtained after the experiment being done.

The unit energy was calculated using equation number 13. However, two cases were considered for the calculation of the unit energy. In the first case, the height of the sample (H) in the cylinder was taken in place of the maximum deformation, δ_{max} , for the calculation of volume, and then this volume in turn was taken for the calculation of unit energy. In the second case, maximum deformation (δ_{max}) after compression was taken for the calculation of volume and, then it was considered for the unit energy calculation. Nevertheless, the same formula (equation number 13) was used in both cases.

4. RESULT AND DISCUSSION

4.1 Physical Properties

4.1.1 Seed Moisture Content

The moisture content (w.b%) of *jatropha curcas seeds* increased linearly as the time of moistening increased (Fig 2 below). The moisture absorption property of the seed indicates the porosity level of the seed. The seed continues absorbing moisture until all the pores inside the seeds are filled. Table 1 shows how the measurements were undertaken and moisture content was calculated.

Table 1. Moisture content on wet and dry basis (M_a is mass of sample after drying, M_b is mass of sample before drying and M_c mass of container)

Moistening Time (hr)	M_a (g)	M_b (g)	M_c (g)	MC (w.b%)	MC (d.b%)
0	62	64	36	7.14	7.69
24	64	78	36	33.33	50.00
48	62	78	36	38.05	61.54
72	58	76	36	45.12	81.82
96	60	82	36	47.83	91.67

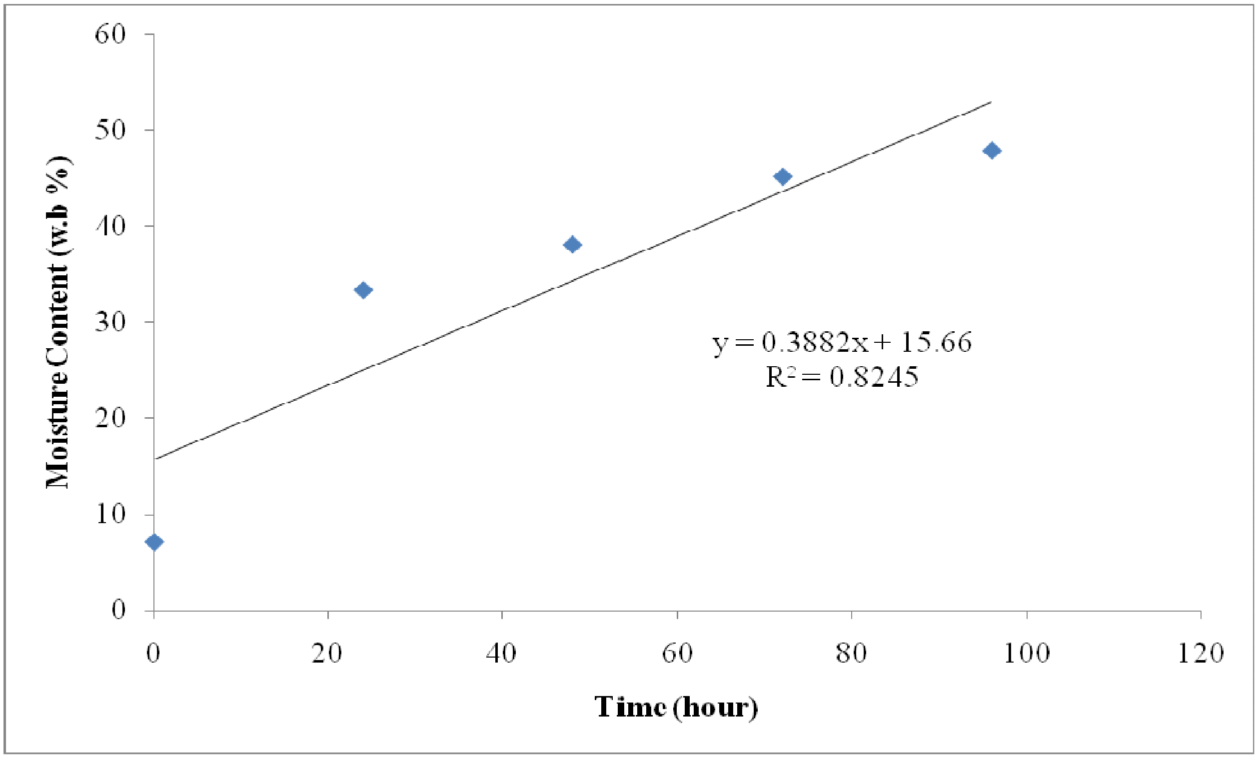

Fig.2 Moisture content (w.b %) versus time (hrs)

4.1.2 Seed dimensions

The average principal dimensions (viz length, width and thickness) and average arithmetic and geometric mean diameters of the *jatropha curcus* seeds at the natural moisture content (7.14 w.b%), were 17.19mm, 11.03mm and 8.55mm and 12.26mm and 11.74 mm respectively.

Table 2. Axial dimensions of jatropha seeds at various moisture content (± standard deviation

Moisture Content (w.b%)	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**A. Mean (mm)**	**G. Mean (mm)**
7.14	17.19 ±0.31	11.03 ±0.14	8.55 ±0.125	12.26 ±0.16	11.74 ±0.15
33.33	18.37 ± 0.42	11.30 ± 0.31	9.02 ± 0.23	12.90 ± 0.25	12.32 ± 0.24
38.05	18.07 ± 0.57	11.27 ± 0.30	8.93 ± 0.24	12.76 ± 0.31	12.20 ± 0.28
45.12	18.52 ± 0.37	11.73 ± 23	9.27 ± 0.01	13.17 ± 0.17	12.62 ± 0.15
47.83	19.12 ± 0.55	11.41 ± 0.34	9.15 ± 0.25	13.23± 0.35	12.59 ± 0.32

Principal dimensions such as length width and thickness of the seeds varied linearly as the moisture content increased. Analysis of the experimental data shows that moderately linear relationships exist between the principal dimensions mentioned above and moisture content. High values of the coefficient of determination (R^2) were observed.

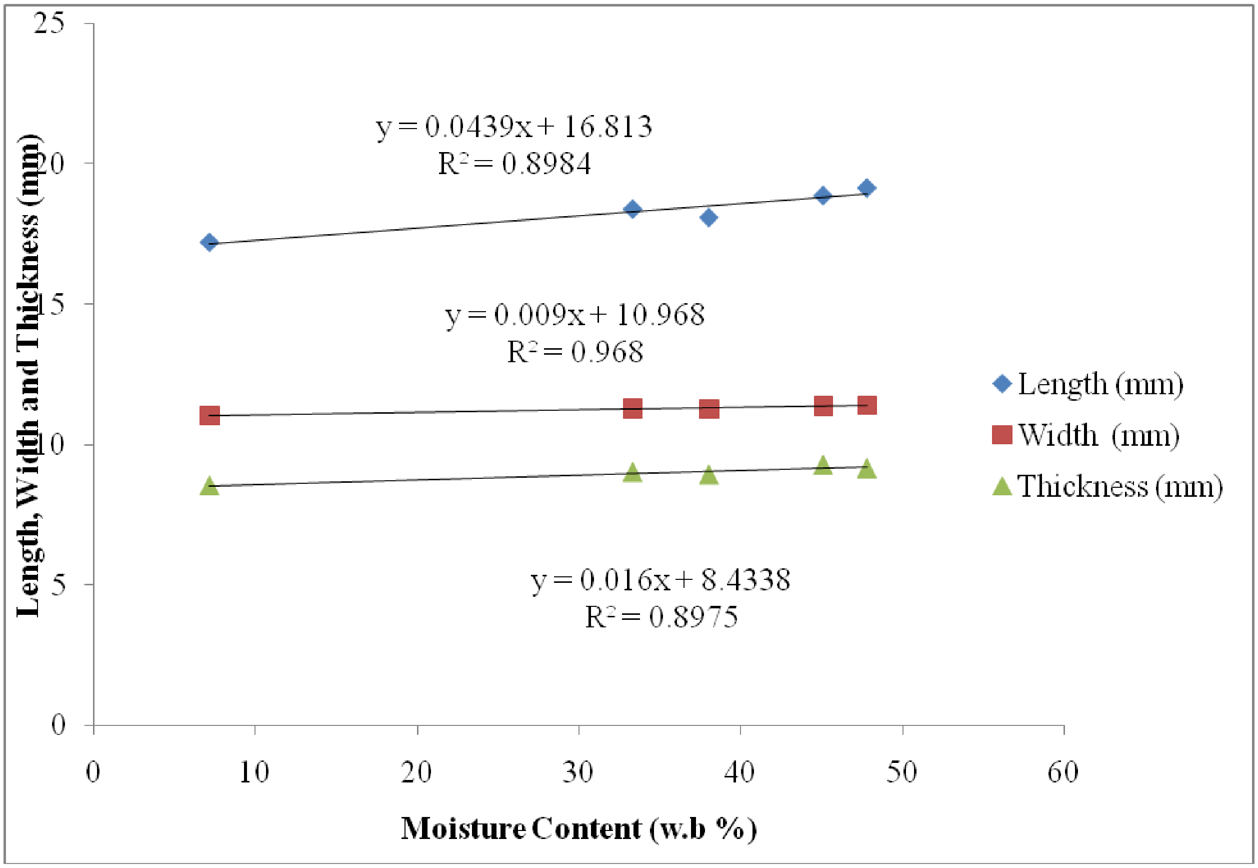

Fig.3 Principal Dimensions (mm) versus Moisture Content (w.b %)

Mean diameters of the seeds were also linearly changing when the moisture content increased from 7.14(w.b %) to 47.83 (w.b %). The relationship between the arithmetic and geometric mean diameters and the moisture content on wet basis were plotted in Fig.4 below. Here also very high values of coefficient of determination were observed which means the linear dependency of the arithmetic and geometric mean diameters on moisture content was strong.

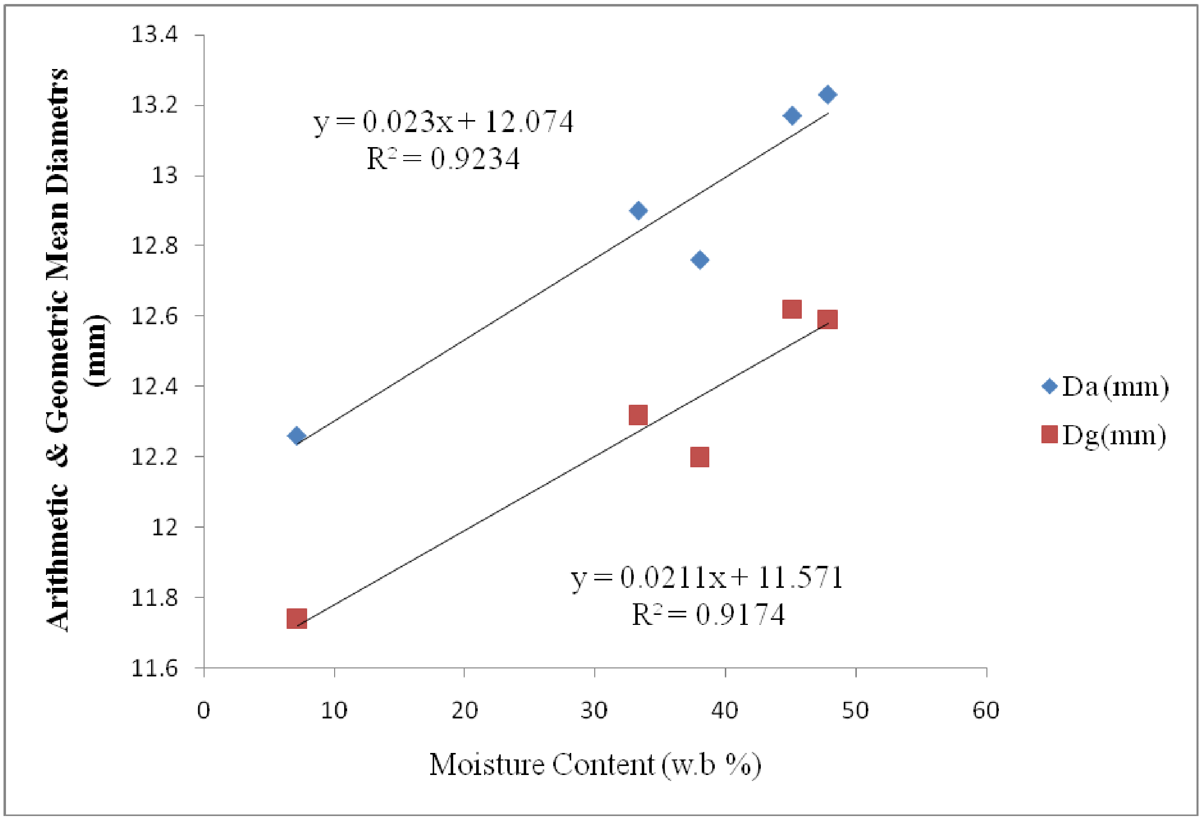

Fig.4 Mean Diameters (mm) Versus Moisture Content (w.b%). The symbols Da and Dg are arithmetic mean and geometric mean respectively.

4.1.3 Sphercity

The sphericity values were calculated using Eq. (4) and plotted against moisture content (Fig.5 below). It was seen that the seeds had mean values of sphericity ranging from 0.66 to 0.68. Mangaraj and Singh (2006) and Sirisomboon et al. (2007) have reported the values for sphericity of *jatropha curcas seed* as 0.61 and 0.64, respectively, which is close to the results of this investigation. Sphericity is a unit-less quantity, and in this particular work it is the ratio of dimensions. The average value of spericity at the natural moisture condition was 0.66. When the moisture content increased, the spericity of the *jatropha curcas* seed also increased (Fig 5 below).

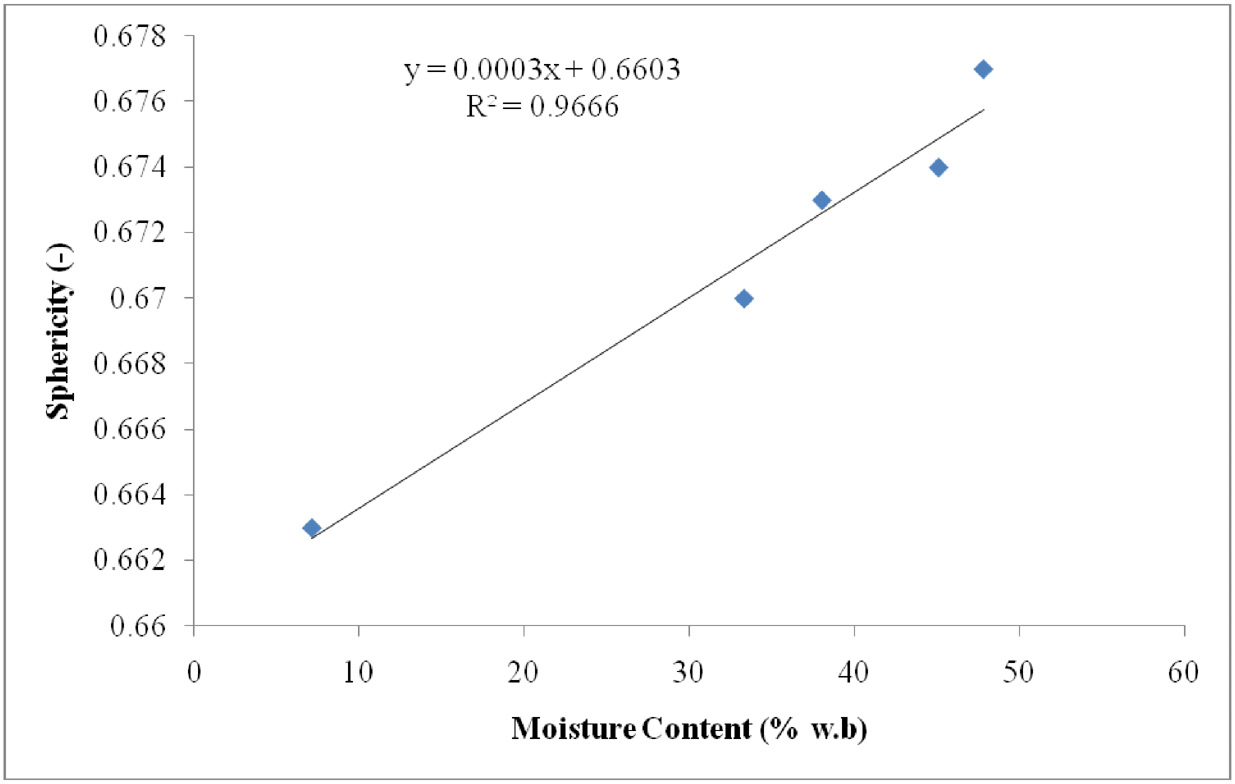

Fig.5 Sphericity (-) versus Moisture content (w.b %)

4.1.4 Thousand seed mass

The 1000 seed mass of *jatropha* seed, M_{1000} (g) increased from 606.06 to 934.78g as the moisture content increased from 7.14 to 47.83% w.b. Fig. 6 below shows a strong linear relationship between thousand seeds mass and moisture content.

Similar trends have been reported by researchers on different seeds. D.K. Garnayak et al (2007) have observed strong linear relationship between thousand seeds mass and moisture content. They have observed that the thousand seeds mass increased from 741.10g to 903.15g as the moisture content changed from 4.75 to 19.57% d.b. And also a similar trend has been reported by Selvi et al. (2006) for linseed and Isik and Unal (2007) for red kidney bean grains.

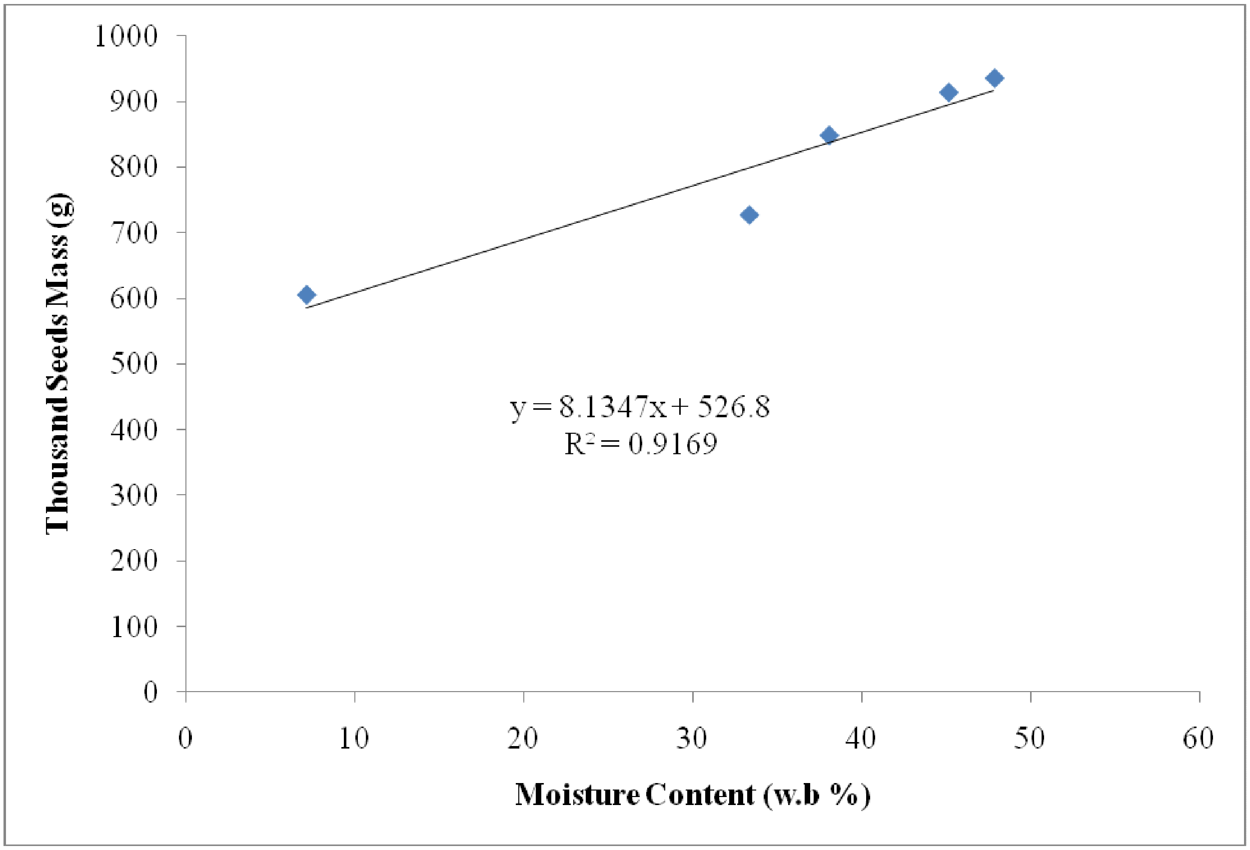

Fig. 6. Thousand seeds mass (g) versus moisture content (w.b %)

4.1.5 Surface Area

The average value the surface area of the *jatropha curcas seed*s at the natural moisture content was found to be 434.05 mm^2. The average surface areas of seeds were determined for each moisture content values and plotted (Fig. 7 below). The surface area of the seeds increased linearly from 434.05mm^2 to 499.43 mm^2 when the moisture content increased from 7.14% to 47.83% (w.b).

Similar trend has been reported by D. K. Garnayak et al (2007) for jatropha curcas. They have shown that the surface area of *jatropha* seed increases linearly from 476.78 to 521.99mm^2 when the moisture content increased from 4.75 to 19.57% d.b. Also similar trend has been reported by Selvi et al. (2006) for linseed and Isik and Unal (2007) for red kidney bean grains.

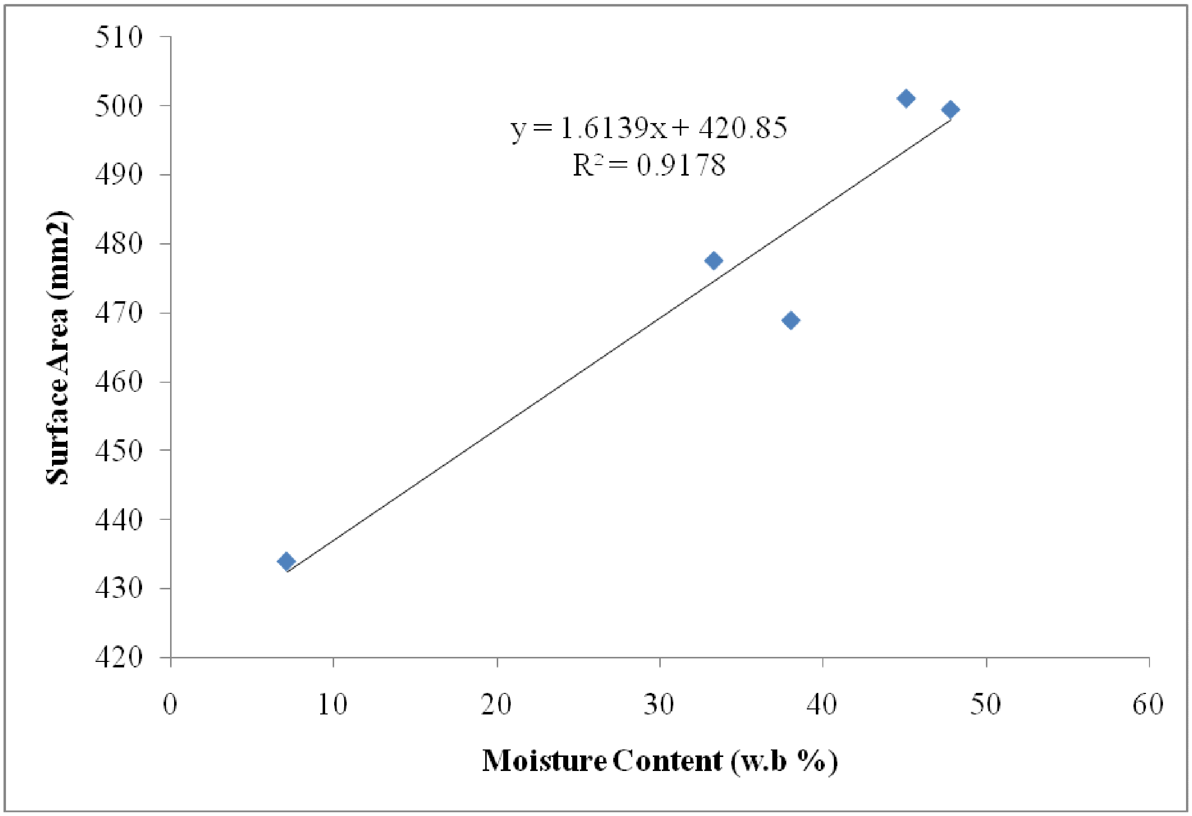

Fig. 7 Surface area of jatropha curcas seeds (mm2) versus moisture content (w.b %)

4.1.6 Seed Volume

The average values of volume of seeds of *jatropha curcas* varied from 594.68 mm^3 at natural condition to 719.53 mm^3 at the fourth day moisture content (Fig.8 below). An increase of 20.99% in volume of single seed was recorded for *jatropha curcas* seed in the moisture range stated. The relationship between moisture content and seed volume was fairly linear. The seed volume increased linearly as the moisture content increased with a high coefficient of determination (R^2=0.90).

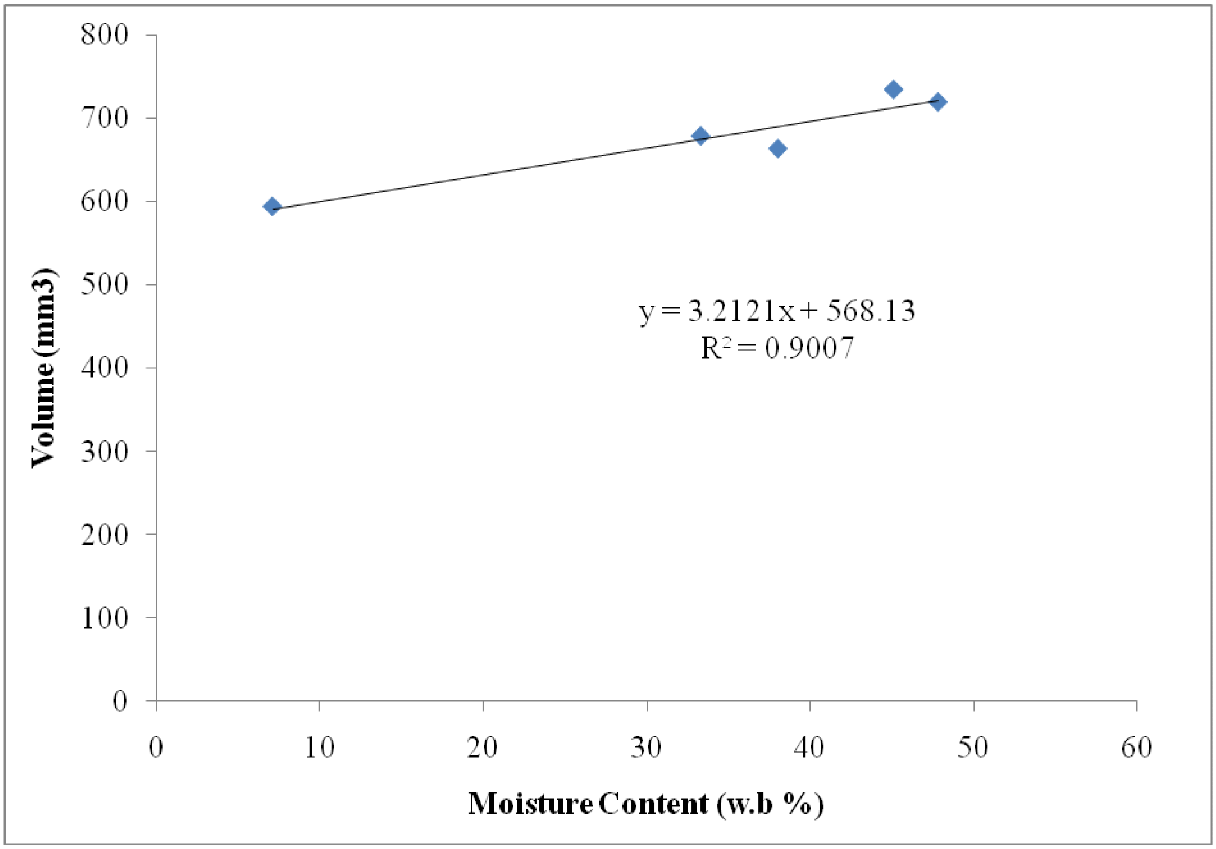

Fig.8 Seed volume (mm3) versus moisture content (w.b %)

4.1.7 Bulk Density

The bulk density of *jatropha curcas* seed, at the natural moisture conten (MC of 7.14%w.b), was 391.3 kgm^{-3}. The seed bulk density at the other moisture levels increased linearly from 403.52 to 525.80 kgm^{-3} (Fig.9 below). This was due to the fact that an increase in mass owing to moisture gain in the grain sample was higher the corresponding volumetric expansion of the bulk.

But a negative linear relationship of bulk density with moisture content was observed by various other research workers (Shepherd and Bhardwaj, 1986; Dutta et al., 1988; Gupta and Prakash, 1990; Carman, 1996). Therefore, further investigation is needed before any conclusion is made.

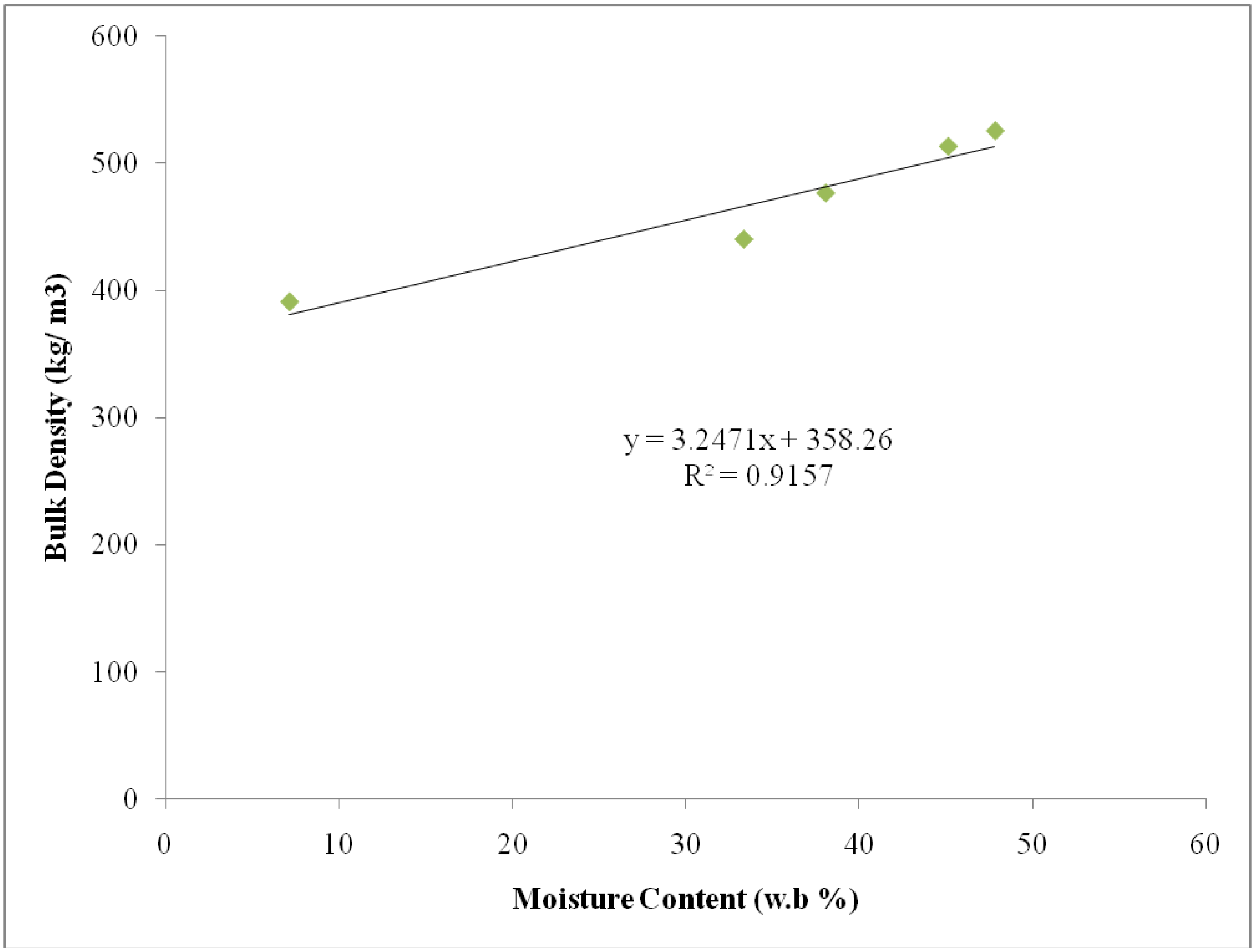

Fig.9 Bulk density (kg/m3) versus moisture content (w.b %)

4.1.8 Porosity

Porosity was calculated using Eq. (6), taking mean values of bulk density and particle density as inputs. The result of the calculation is presented in Table 3 below.

Table 3. Porosity values at each moisture content

MC (w.b%)	Mass (g)	Height (mm)	Diameter (mm)	Volume (m3). 10^{-6}	ρ_b (kg/m^3)	ρ_t (kg/m^3)	ψ $(1-\rho_b/\rho_t)*100$
7.14	64	40	72.15	163.56	391.29	971	59.70
33.33	72	40	72.15	163.56	440.52	971	54.63
38.05	78	40	72.15	163.56	476.89	971	50.89
45.12	84	40	72.15	163.56	513.57	971	47.11
47.83	86	40	72.15	163.56	525.80	971	45.85

The porosity of the seeds decreased linearly from 59.70% (at the natural moisture content) to 45.85 % (at the 4th day moisture content). The reason for decreased porosity could be the increase in bulk density over the specified moisture content range.

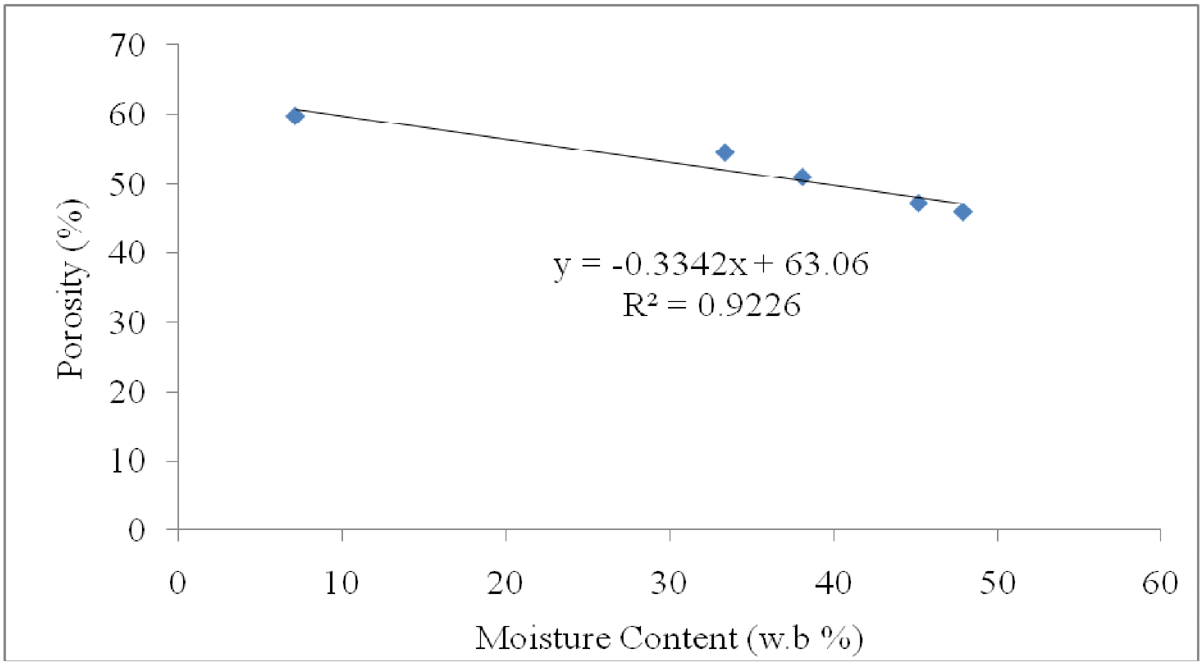

Fig.10. Porosity (%) versus moisture content (w.b %)

4.2 Mechanical Properties

Force- deformation curves obtained from the compression device scanned and digitized to calculate the important mechanical parameters. The curves at the various moisture contents were best approximated using higher degree polynomial. In section 4.2.1 below, force deformation curves for each moisture contents were plotted and important parameters were calculated.

4.2.1 Force-deformation curves at various moisture content

The curves at higher moisture contents had greater irregularities (ups and downs) than the curves at lower moisture contents. As a consequence, different degree polynomials were used to approximate curves at different moisture contents. For instance, force deformation curves for the curves at the moisture contents 7.14 % and 33.33 % (w.b) were fitted using fifth degree polynomial. But the curves at other moisture contents were approximated by fourth degree polynomial. The resulting graphs and the corresponding equations are presented here below.

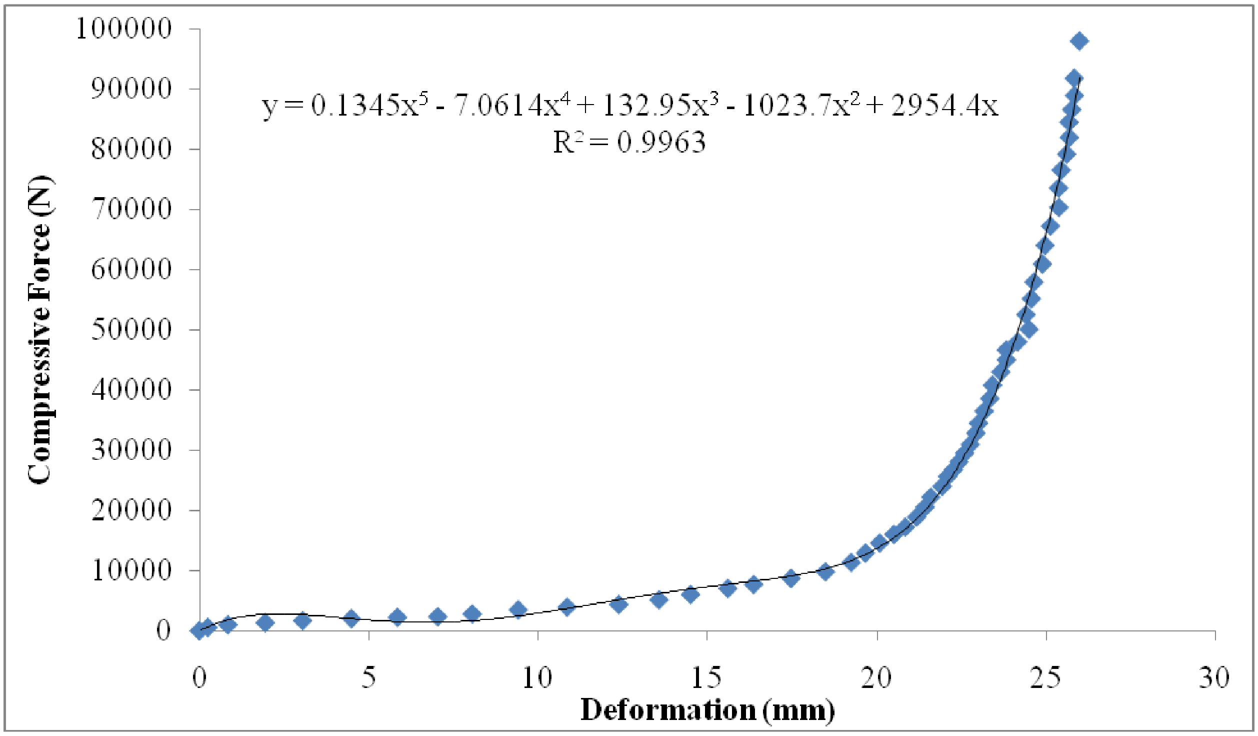

Fig 11. Force-deformation curve at the moisture content value of 7.14 %(w.b).

The approximate force deformation equation derived from the data points was used to calculate the total energy. Using MathCAD software, the force deformation equation was integrated over the deformation range as shown below. The result is total energy consumed (N.mm)

$$\int_{0}^{25.9829} \left(0.1345x^5 - 7.0614x^4 + 132.95x^3 - 1023.7x^2 + 2954.4x\right) dx = 3.333 \times 10^5$$

Therefore, the total energy, E= 333.3 J. But the total strain energy calculated using equation (11) was E=328.54J (at the natural moisture content). The difference is about 1.5% which is not so big.

The force deformation curve at the moisture content value 33.33% (w.b), (Fig 12 below) is not as smooth as the force deformation curve at the moisture content value 7.14 % (w.b), (Fig 11 above). Moreover, the total energy absorbed at the natural moisture content was greater than the total energy absorbed at the first day moisture content.

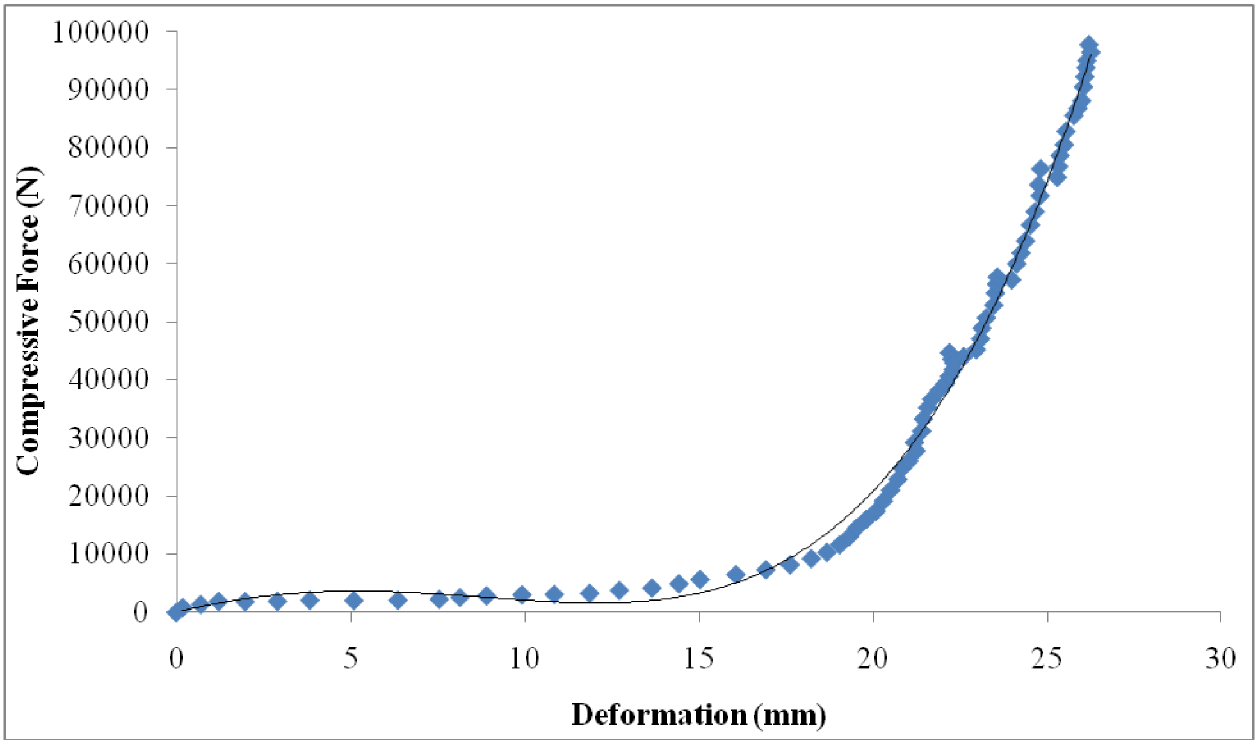

Fig 12. Force-deformation curve at the moisture content value of 33.33 %(w.b)

The total strain energy absorbed was calculated from the mathematical model generated from the data points. The deformation range for the first day moisture content was was 0 to 26.77mm. Therefore, the total energy could be calculated by directly integrating the equation over the deformation range.

$$\int_{0}^{26.77} \left(0.0669x^{5} - 2.3385x^{4} + 27.768x^{3} - 186.1x^{2} + 996.72x\right) dx = 4.059 \times 10^{5}$$

As shown above, the total strain energy, E=405.9 J. But the total energy calculated from equation (11) was E= 405.54J. Here, the mathematical model estimates 0.09% more than the energy calculated from equation (11).

As the moisture content increased further, the force-deformation curves showed zigzag shapes in higher moisture ranges. This characteristic became more apparent at higher moisture content values. The force-deformation curve at the moisture content value of 38.05 % (w.b) is presented in fig 13 below.

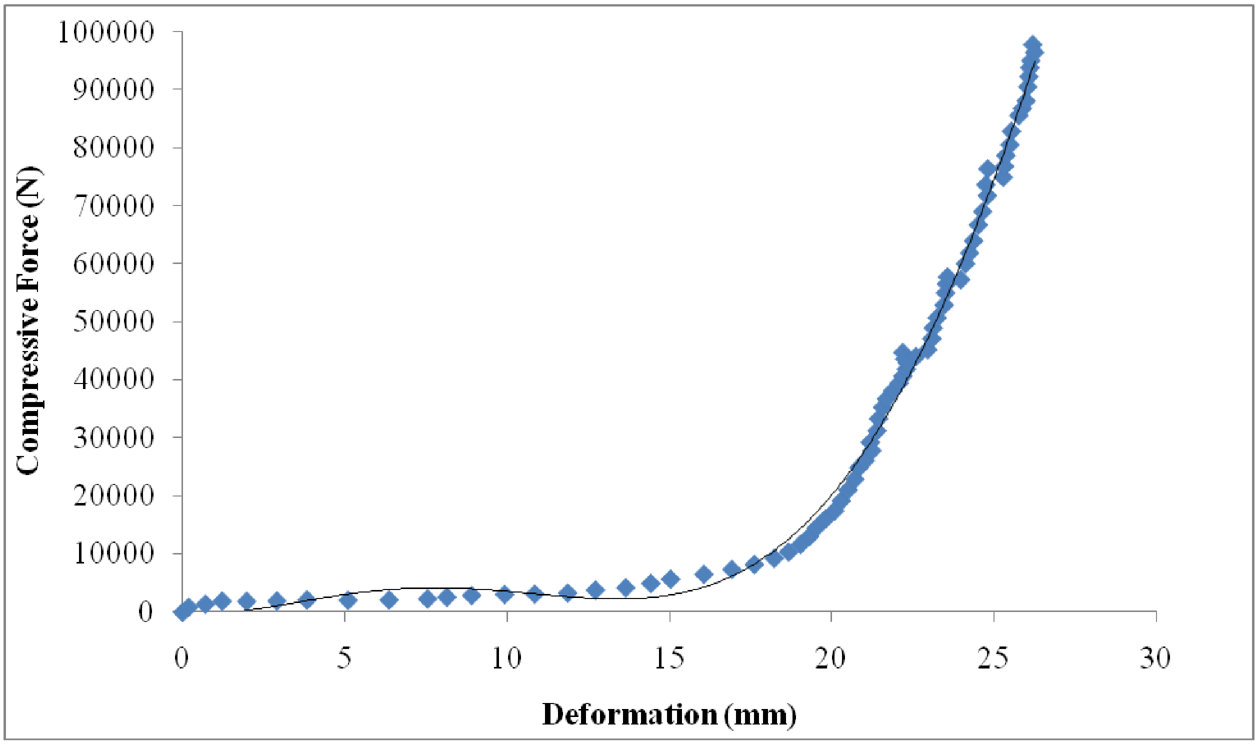

Fig 13. Force-deformation curve at the moisture content value of 38.05 %(w.b)

The polynomial equation representing the graph of the force deformation curve at the 2nd day moisture content was: $y(x) = 0.3489x^4 - 1.0465x^3 - 153.8x^2 + 1478.2x$. And the deformation range was between 0 and 27.19mm. The total energy absorbed would be:

$$\int_0^{27.19} \left(0.3489x^4 - 1.0465x^3 - 153.8x^2 + 1478.2x\right) dx = 4.099 \times 10^5$$

Therefore the total energy from the above calculation is: E=409.9J. The total deformation energy calculated using equation (11) was: E=410.11J. Here also, the difference is insignificant.

Fig 14 below presents the behavior of the force-deformation curve at the moisture content of 45.12% (w.b) . As explained before, the graphs became less smooth at higher moisture content.

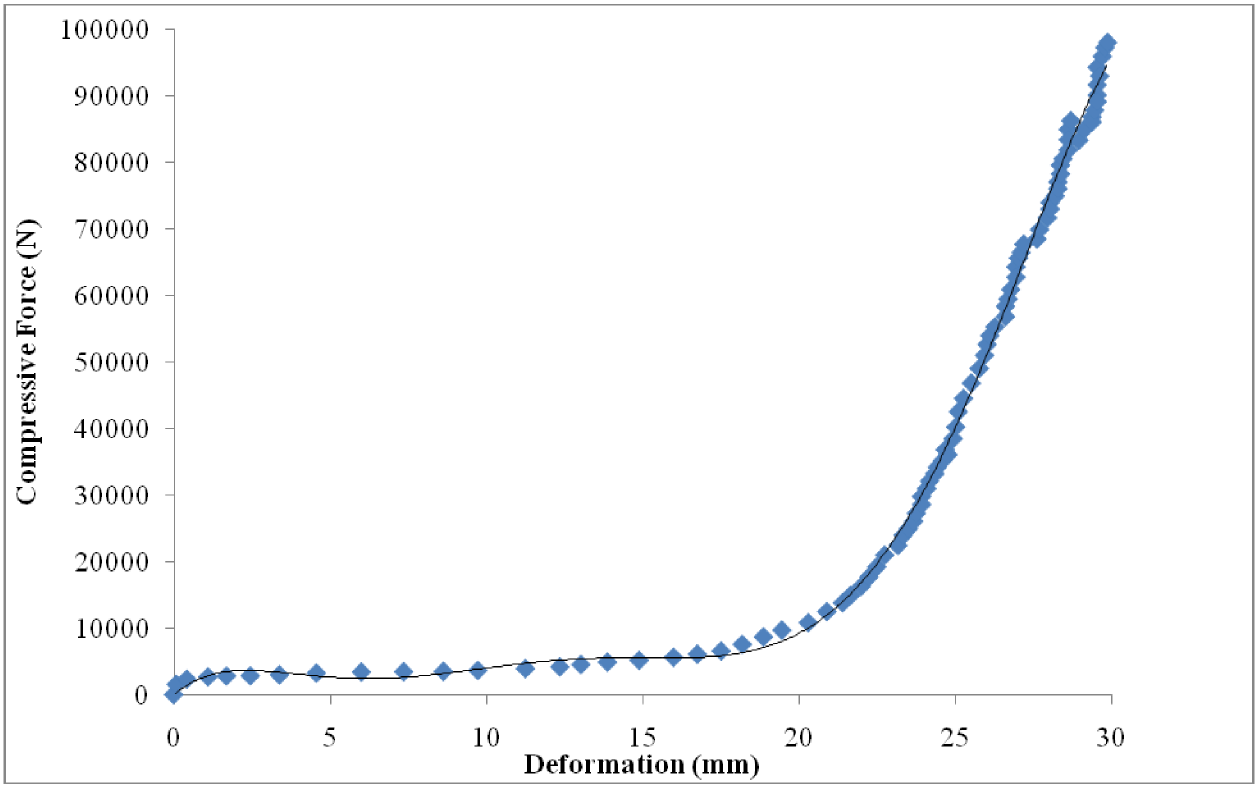

Fig 14. Force-deformation curve at the moisture content value of 45.12 % (w.b)

The equation representing the force deformation curve at the 3rd day moisture content was: $y(x) = 0.6533x^4-18.098x^3+127.96x^2+207.14x$, $[R^2=0.9941]$. The equation was integrated as follows.

$$\int_0^{27.29} \left(0.6533x^4 - 18.098x^3 + 127.96x^2 + 207.14x\right) dx = 4.122 \times 10^5$$

Therefore, the total energy E=412.2J. The total energy calculated from the equation (11) was, E= 413.91J. The total energy obtained from the equation was less than that obtained from the formula. However, the difference was still small.

Finally fig 14 presents force-deformation curve at the moisture content value of 47.83 % (w.b)

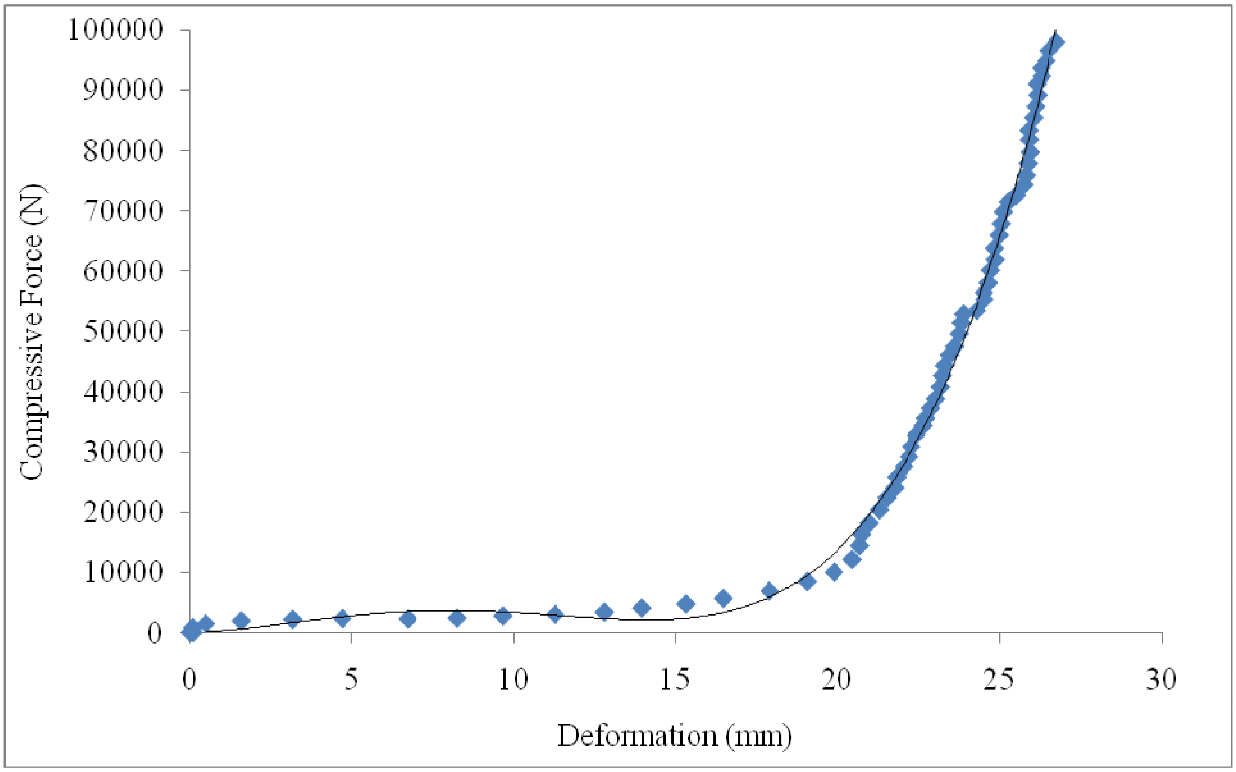

Fig 15. Force-deformation curve at the moisture content value of 47.83 %(w.b)

Similarly, the force deformation equation at 4th day moisture content was: $y(x) =0.8803x^4-26.257x^3+189.07x^2+163.93x$, $[R^2=0.996]$. Integrating the equation over the moisture content range we get:

$$\int_0^{27.75}\left(0.8803x^4 - 26.257x^3 + 189.07x^2 + 163.9x\right)dx = 4.145 \times 10^5$$

Here again the total energy, E=414.5J. The result from equation (11) above was 415.66J. It seems polynomial equations approximate the data points nicely.

The most important mechanical properties of *jatropha curcas* seeds such as deformation at rupture point (maximum deformation), rupture force, hardness, total energy and unit energy at maximum deformation and seed height were determined and summarized in Table 4 below.

Table 4. Mechanical properties of jatropha curcas seeds at various moisture content

MC (%)	Deformation δ_{max} (mm)	Rupture Force F (N)	Hardness H (N/mm)	Total Energy E (J)	Volume V (m^3) (10^{-6})	Unit Energy U_E (J/m^3) (10^3)
7.14	25.98	98089.5	3775.56	328.54	424.89	773.26
33.33	26.77	97534.9	3643.44	405.54	437.79	926.32
38.05	27.19	97305.2	3578.71	410.11	444.66	922.29
45.12	27.29	96973.1	3553.43	413.91	446.30	927.43
47.83	27.75	96744.7	3486.29	415.66	453.82	915.91

4.2.2 Maximum Deformation

As it could be seen from Table 4 above, the maximum deformation has increased as the moisture content increased. This is because at lower moisture content the seed is fragile, and its rupture would be initiated at small deformations.

Similar trends have been observed by various researchers for different oil seeds. K. K. Singh & T. K. Goswam (1998) have reported that deformation at rupture point increased as the moisture content of cumin seed increased. Also Journal of Agricultural Science Vol.1 No.1 (2009) reported that deformation of fennel seed length section increased in the moisture range of 10.91

to 21.67%d.b. But there was not regular trend for deformation on the seed width section with increasing the moisture content.

4.2.3 Rupture Force

The rupture force required to rupture the seeds at different moisture contents are presented in Table 4 above. It can also be seen from Fig 16 below that rupture force decreased as the moisture content increased from 7.14% to 47.83 % w.b.

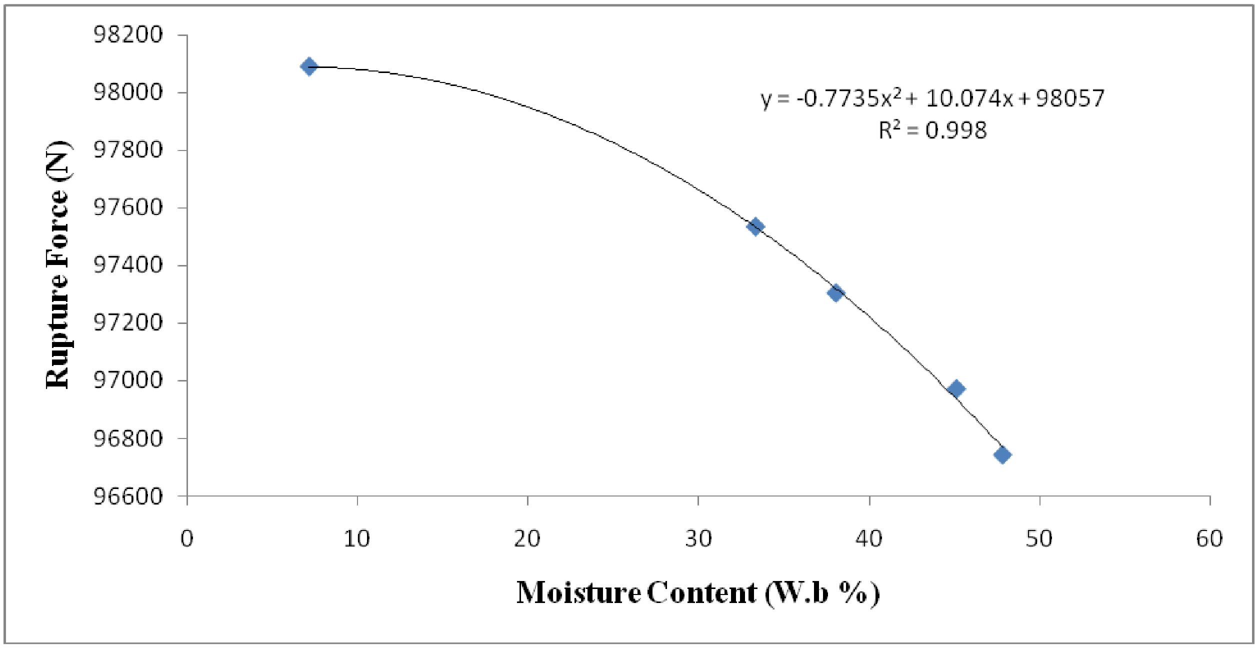

Fig 16. Rupture Force (N) versus Moisture Content (w.b %)

As seen in Fig. 16, the lower rupturing forces were required at higher moisture contents. This might have resulted from the fact that the *jatropha curcas* seeds are softened by higher moisture content. An experiment conducted on soybeans by Altuntaş and Yildiz (2007) showed similar trend. In fact their experiment was done in such a way that compressive load was applied to individual grains of soybean along different axes. Nevertheless, the reason for the decrease of rupture force over the moisture content range might be the same.

4.2.4 Energy Absorbed

The dependency of strain energy on moisture content was summarized on Table 4. And also the graph of deformation energy versus moisture content is presented in Fig. 17 below. The graph shows that the energy absorbed has increased as the moisture content increased.

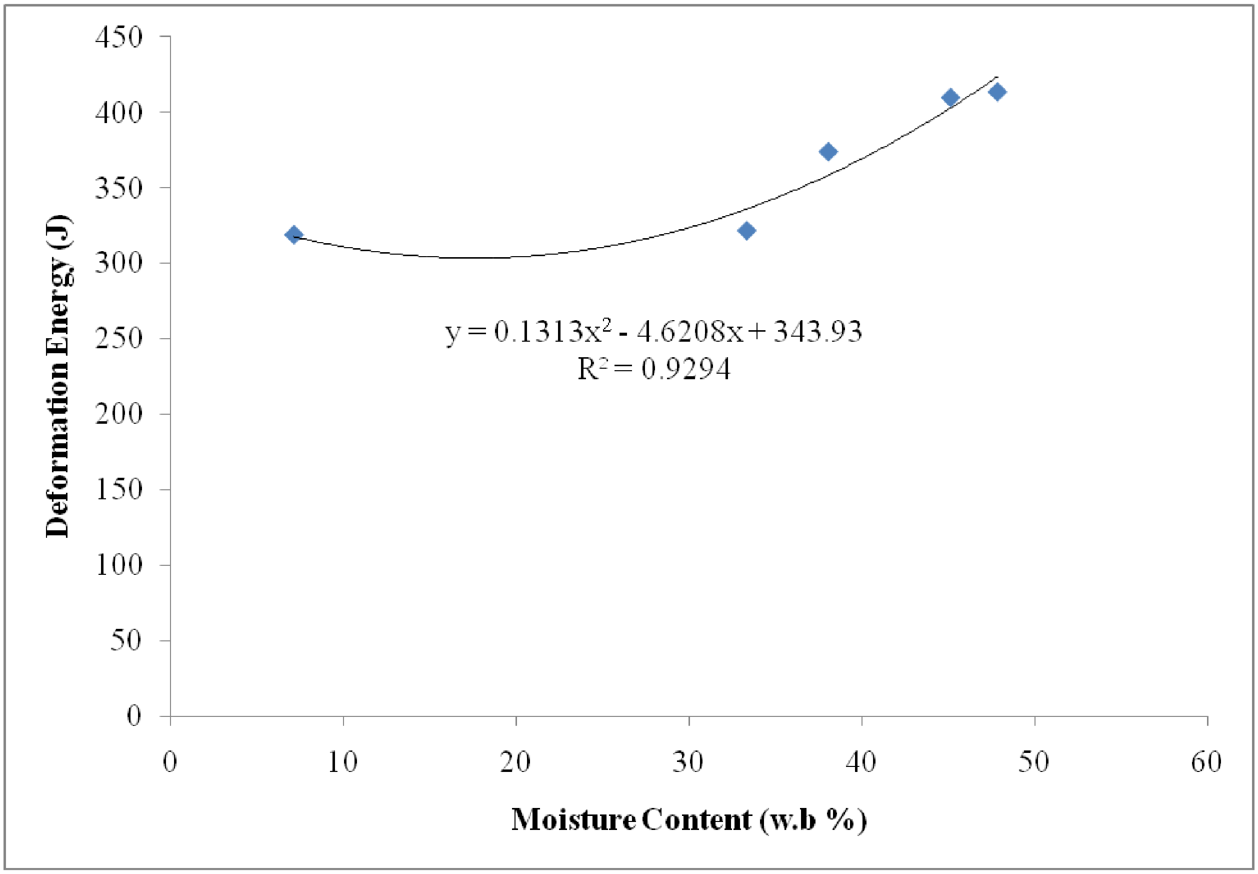

Fig. 17. Deformation Energy (J) versus Moisture Content (w.b %)

The optimum moisture content that minimizes the energy absorbed could be calculated from the equation shown on the graph. The energy is minimum at the point where the slope of the graph is zero or the tangent line is horizontal, at the lowest point. This is achieved by taking the first derivative of the equation and setting it into zero.

$$\frac{d}{dx}\left(0.1313x^2 - 4.6208x + 343.93\right) \rightarrow .2626 \cdot x - 4.6208$$

$$0.2626X - 4.6208 = 0$$

$$X = 17.60$$

Therefore, the optimum moisture content is 17.60% (w.b) and the corresponding minimum energy is 303.27J. However, the experiment has to be repeated several times to come up with such a conclusion.

Some of the previous works on other oil seeds reveal that energy absorbed increased as the moisture content increased. R.K. Gupta and S.K. Das (2000) reported that the energy absorbed at the rupture per volume of sunflower seeds as the moisture content increased. Similarly, Kaveh Mollazade et al, (2009) showed that the rupture energy of cumin seed degreased as the moisture content increased.

4.2.5 Hardness of seeds

Hardness has been calculated using eq. 10 and plotted against the moisture content in Fig. 18 below. The hardness of the seeds decreased as the moisture content increased. This is because of the rupture force decreased and deformation increased over the same moisture content range as discussed in section 4.2.3 and 4.2.2 respectively.

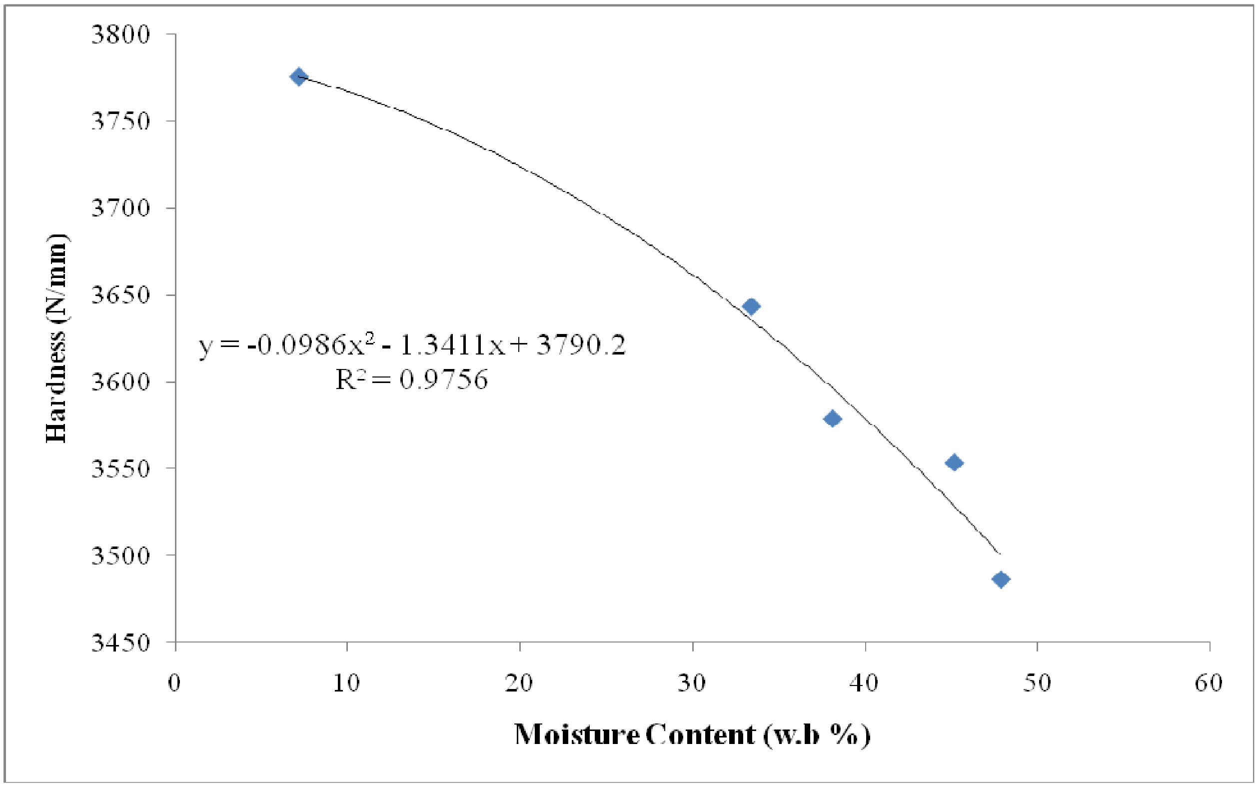

Fig. 18. Hardness (mm) versus moisture content (w.b %)

4.2.6 Energy per unit volume

The unit energy which is a measure of enery per unit volume was determined and plotted against moisture content in the Fig. 19 below. Again the relationship between unit energy and the moisure contenty was not strongly linear. The energy per unit volume has increased with increasing moisture content. But the obserbed relationship between the unit energy and moisture content was not linear.

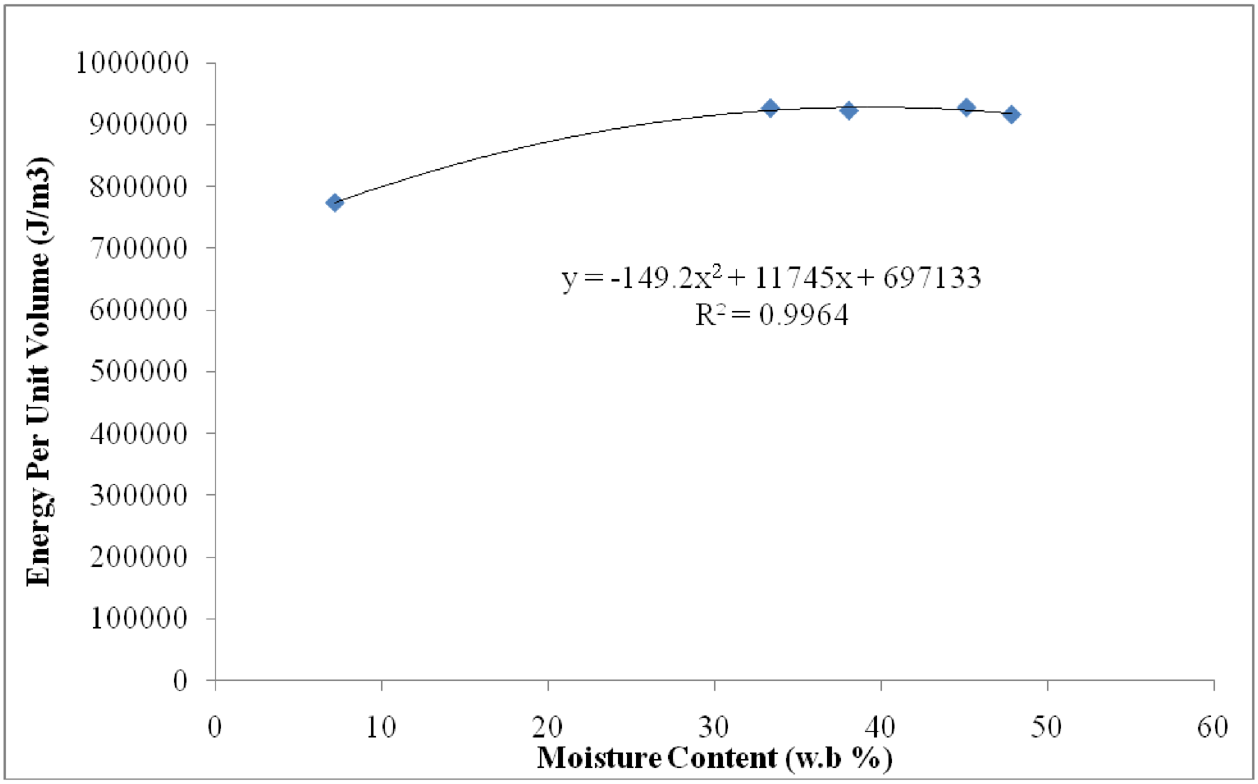

Fig 19. Unit energy (J/m^3) versus moisture content (w.b %)

5. CONCLUSION

The following conclusions can be drawn from the moisture dependant physical and mechanical properties of *jatropha curcas* seeds. The average linear dimensions such as the length, width, thickness, and arithmetic and geometric mean diameters of the *jatropha curcas* seeds increase as the moisture content increase in the moisture content range from 7.14% to 47.83% (w.b).

Physical properties such as length, width, breadth, arithmetic mean, geometrical mean, volume, sphericity, bulk and solid density, porosity, surface and specific surface follow a strict pattern with respect to moisture content variations. Therefore, these properties could be used for sorting *jatropha curcas* seeds into fractions that also reflect quality classes in terms of oil content.

Mechanical properties of *jatropha curcas* seeds such as rupture force, deformation at rupture point, hardness and energy needed for rupture were reported and can be used for designing deshelling equipment. The optimum moisture content could be used for compressing the seeds to obtain its oil.

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APPENDIXES:

Force -deformation data at the Moisture Content value of 7.14% (w.b)

X (mm)	F (N)	X_{n+1}-X_n	[F_n+F_{n+1}]/2	Energy (N.m)
0	0			
0.253294	554.589	0.253294	277.2945	0.070237033
0.846516	999.767	0.593222	777.178	0.461039088
1.94949	1336.19	1.102974	1167.9785	1.288249918
3.05246	1672.61	1.10297	1504.4	1.659308068
4.49508	2010.34	1.44262	1841.475	2.656548665
5.85307	2237.03	1.35799	2123.685	2.883942993
7.04152	2352.33	1.18845	2294.68	2.727112446
8.0593	2799.15	1.01778	2575.74	2.621536657
9.41614	3468.72	1.35684	3133.935	4.252248365
10.8585	3917.17	1.44236	3692.945	5.32655615
12.3857	4365.95	1.5272	4141.56	6.324990432
13.5724	5145.59	1.1867	4755.77	5.643672259
14.5042	6034.96	0.9318	5590.275	5.209018245
15.6054	7035.71	1.1012	6535.335	7.196710902
16.3679	7702.99	0.7625	7369.35	5.619129375
17.4691	8703.74	1.1012	8203.365	9.033545538
18.4852	9814.88	1.0161	9259.31	9.408384891
19.2453	11367.9	0.7601	10591.39	8.050515539
19.6659	12919.7	0.4206	12143.8	5.10768228
20.0861	14582.1	0.4202	13750.9	5.77812818
20.5069	16023.1	0.4208	15302.6	6.43933408
20.8434	17242.4	0.3365	16632.75	5.596920375
21.1787	18904.5	0.3353	18073.45	6.060027785
21.4291	20566.3	0.2504	19735.4	4.94174416
21.5946	22227.8	0.1655	21397.05	3.541211775
21.9297	24000.6	0.3351	23114.2	7.74556842
22.0952	25662.1	0.1655	24831.35	4.109588425
22.2621	26770	0.1669	26216.05	4.375458745
22.4285	28099.3	0.1664	27434.65	4.56512576
22.5946	29539.3	0.1661	28819.3	4.78688573
22.7607	30979.3	0.1661	30259.3	5.02606973
22.9256	32862.3	0.1649	31920.8	5.26373992
23.0062	34523.4	0.0806	33692.85	2.71564371

23.1709	36517	0.1647	35520.2	5.85017694
23.3352	38621.4	0.1643	37569.2	6.17261956
23.4144	40836.2	0.0792	39728.8	3.14652096
23.6634	43051.6	0.249	41943.9	10.4440311
23.8237	46706	0.1603	44878.8	7.19407164
23.828	45045.2	0.0043	45875.6	0.19726508
24.1599	48036	0.3319	46540.6	15.44682514
24.4028	52576.5	0.2429	50306.25	12.21938812
24.4941	50141	0.0913	51358.75	4.689053875
24.5657	55234.5	0.0716	52687.75	3.7724429
24.6435	58002.9	0.0778	56618.7	4.40493486
24.8904	60993.3	0.2469	59498.1	14.69008089
24.9673	64093.8	0.0769	62543.55	4.809598995
25.1288	67305.4	0.1615	65699.6	10.6104854
25.3671	73617.5	0.2383	70461.45	16.79096354
25.3755	70406.6	0.0084	72012.05	0.60490122
25.4443	76607.3	0.0688	73506.95	5.05727816
25.6072	79265.3	0.1629	77936.3	12.69582327
25.6783	84580.2	0.0711	81922.75	5.824707525
25.6849	82033.6	0.0066	83306.9	0.54982554
25.7577	86684.2	0.0728	84358.9	6.14132792
25.8291	91888.5	0.0714	89286.35	6.37504539
25.8366	89009.7	0.0075	90449.1	0.67836825
25.9829	98089.5	0.1463	93549.6	13.68630648
Total Energy				**328.5379184**

Force-deformation data at the moisture content value of 33.33% (w.b)

X (mm)	F (N)	X_{n+1}-X_n	[F_n+F_{n+1}]/2	Energy (N.m)
0	0			
0.139463	1214.77	0.139463	607.385	0.084707734
0.289509	1990.02	0.150046	1602.395	0.24043296
0.866261	2560.66	0.576752	2275.34	1.312306896
1.87236	2816.83	1.006099	2688.745	2.705143656
3.21824	2975.25	1.34588	2896.04	3.897722315
4.81432	3252.65	1.59608	3113.95	4.970113316
6.41305	3420.17	1.59873	3336.41	5.334018759

7.67729	3465.68	1.26424	3442.925	4.352683502
8.93889	3621.06	1.2616	3543.37	4.470315592
10.8747	3800.72	1.93581	3710.89	7.183577971
12.4682	4188	1.5935	3994.36	6.36501266
13.5506	4776.85	1.0824	4482.425	4.85177682
14.8912	5155.03	1.3406	4965.94	6.657339164
16.2265	5752.98	1.3353	5454.005	7.282732877
17.3037	6561.59	1.0772	6157.285	6.632627402
17.9568	7464.92	0.6531	7013.255	4.580356841
18.4439	8252.3	0.4871	7858.61	3.827928931
19.0154	9042.71	0.5715	8647.505	4.942049108
19.4183	9827.06	0.4029	9434.885	3.801315166
19.8265	10391.6	0.4082	10109.33	4.126628506
20.3057	11508.7	0.4792	10950.15	5.24731188
20.7823	12735.6	0.4766	12122.15	5.77741669
21.0087	13843.5	0.2264	13289.55	3.00875412
21.401	15067.4	0.3923	14455.45	5.670873035
21.6195	16504.9	0.2185	15786.15	3.449273775
21.9196	18055.4	0.3001	17280.15	5.185773015
22.138	19493	0.2184	18774.2	4.10028528
22.2775	20707.8	0.1395	20100.4	2.8040058
22.6645	22151.4	0.387	21429.6	8.2932552
22.717	23473	0.0525	22812.2	1.1976405
22.8539	24797.7	0.1369	24135.35	3.304129415
22.9933	26012.5	0.1394	25405.1	3.54147094
23.2091	27559.9	0.2158	26786.2	5.78046196
23.2643	28771.6	0.0552	28165.75	1.5547494
23.3248	29763.6	0.0605	29267.6	1.7706898
23.459	31198.2	0.1342	30480.9	4.09053678
23.5931	32632.7	0.1341	31915.45	4.279861845
23.651	33734.6	0.0579	33183.65	1.921333335
23.7904	34949.3	0.1394	34341.95	4.78726783
23.9034	37262.9	0.113	36106.1	4.0799893
23.9325	36054.2	0.0291	36658.55	1.066763805
24.0455	38367.8	0.113	37211	4.204843
24.061	41227.8	0.0155	39797.8	0.6168659
24.1007	39579.6	0.0397	40403.7	1.60402689
24.1608	44090.8	0.0601	41835.2	2.51429552
24.1926	42772.2	0.0318	43431.5	1.3811217

24.3766	45638.3	0.184	44205.25	8.133766
24.4212	47289.5	0.0446	46463.9	2.07228994
24.5501	48943.8	0.1289	48116.65	6.202236185
24.6816	50488.2	0.1315	49716	6.537654
24.8132	52032.7	0.1316	51260.45	6.74587522
24.863	53464.2	0.0498	52748.45	2.62687281
24.8997	55445.1	0.0367	54454.65	1.998485655
24.9182	54675.9	0.0185	55060.5	1.01861925
25.213	56446.2	0.2948	55561.05	16.37939754
25.2603	57987.5	0.0473	57216.85	2.706357005
25.3155	59199.3	0.0552	58593.4	3.23435568
25.4417	60963.5	0.1262	60081.4	7.58227268
25.4519	64043.2	0.0102	62503.35	0.63753417
25.4836	62724.6	0.0317	63383.9	2.00926963
25.4991	65584.6	0.0155	64154.6	0.9943963
25.5146	68444.6	0.0155	67014.6	1.0387263
25.5517	66906.2	0.0371	67675.4	2.51075734
25.9519	67800.4	0.4002	67353.3	26.95479066
26.0834	69344.9	0.1315	68572.65	9.017303475
26.136	70666.5	0.0526	70005.7	3.68229982
26.1912	71878.2	0.0552	71272.35	3.93423372
26.3253	73312.8	0.1341	72595.5	9.73505655
26.3779	74634.4	0.0526	73973.6	3.89101136
26.4304	75956	0.0525	75295.2	3.952998
26.4879	80577.1	0.0575	78266.55	4.500326625
26.5196	79258.5	0.0317	79917.8	2.53339426
26.5219	82667.9	0.0023	80963.2	0.18621536
26.5483	81569.1	0.0264	82118.5	2.1679284
26.5593	77610.3	0.011	79589.7	0.8754867
26.5638	84429.1	0.0045	81019.7	0.36458865
26.6031	86300.1	0.0393	85364.6	3.35482878
26.9301	83232.5	0.327	84766.3	27.7185801
27.1221	85768.9	0.192	84500.7	16.2241344
27.2872	92923.4	0.1651	89346.15	14.75104936
27.3458	86986.7	0.0586	89955.05	5.27136593
27.3613	89846.7	0.0155	88416.7	1.37045885
27.3949	95456.8	0.0336	92651.75	3.1130988
27.4059	91498	0.011	93477.4	1.0282514
27.424	94248.1	0.0181	92873.05	1.681002205

27.4448	96888.3	0.0208	95568.2	1.98781856
27.4879	88091.6	0.0431	92489.95	3.986316845
27.75053	97880.2	0.26263	92985.9	24.42088692
Total Energy				**405.541524**

Force-deformation data at the moisture content value of 38.05 % (w.b)

X (mm)	F (N)	X_{n+1}-X_n	[F_n+F_{n+1}]/2	Energy (N.m)
0	0			
0.187257	871.583	0.187257	435.7915	0.081605009
0.704196	1398.73	0.516939	1135.1565	0.586806666
1.22113	1925.88	0.516934	1662.305	0.859301973
1.97885	1892.54	0.75772	1909.21	1.446646601
2.9073	1961.68	0.92845	1927.11	1.78922528
3.83811	2140.69	0.93081	2051.185	1.90926351
5.10096	2085.13	1.26285	2112.91	2.668288394
6.36617	2139.45	1.26521	2112.29	2.672490431
7.54955	2307.35	1.18338	2223.4	2.631127092
8.14596	2611.05	0.59641	2459.2	1.466691472
8.91075	2907.33	0.76479	2759.19	2.11020092
9.92575	3082.64	1.015	2994.985	3.039909775
10.8542	3151.77	0.92845	3117.205	2.894168982
11.8692	3327.08	1.015	3239.425	3.288016375
12.7229	3839.41	0.8537	3583.245	3.059016257
13.6584	4238.16	0.9355	4038.785	3.778283368
14.4327	4973.95	0.7743	4606.055	3.566468387
15.0385	5717.14	0.6058	5345.545	3.238331161
16.0677	6551.69	1.0292	6134.415	6.313539918
16.9284	7393.64	0.8607	6972.665	6.001372766
17.6208	8243	0.6924	7818.32	5.413404768
18.2338	9315.81	0.613	8779.405	5.381775265
18.6783	10396	0.4445	9855.905	4.380949773
19.0434	11699.7	0.3651	11047.85	4.033570035
19.3266	13117	0.2832	12408.35	3.51404472
19.5257	14537.9	0.1991	13827.45	2.753045295
19.8113	16065	0.2856	15301.45	4.37009412
20.0945	17482.3	0.2832	16773.65	4.75029768
20.3007	19232.8	0.2062	18357.55	3.78532681

20.5092	21093.3	0.2085	20163.05	4.203995925
20.7177	22953.7	0.2085	22023.5	4.59189975
20.8443	24927.8	0.1266	23940.75	3.03089895
21.0387	26129	0.1944	25528.4	4.96272096
21.1913	29311.6	0.1526	27720.3	4.23011778
21.2448	27879.5	0.0535	28595.55	1.529861925
21.4021	31281.9	0.1573	29580.7	4.65304411
21.447	33369.5	0.0449	32325.7	1.45142393
21.5736	35343.6	0.1266	34356.55	4.34953923
21.6885	36768.2	0.1149	36055.9	4.14282291
21.8875	38189.2	0.199	37478.7	7.4582613
22.0842	39500.2	0.1967	38844.7	7.64075249
22.1944	40705.1	0.1102	40102.65	4.41931203
22.1975	44774.2	0.0031	42739.65	0.132492915
22.2581	43671.7	0.0606	44222.95	2.67991077
22.3045	41910.1	0.0464	42790.9	1.98549776
22.3281	43008.8	0.0236	42459.45	1.00204302
22.6043	44096.4	0.2762	43552.6	12.02922812
22.967	45290.2	0.3627	44693.3	16.21025991
23.0913	47154.4	0.1243	46222.3	5.74543189
23.1314	49022.2	0.0401	48088.3	1.92834083
23.2534	50776.5	0.122	49899.35	6.0877207
23.4689	52966.6	0.2155	51871.55	11.17831903
23.5138	55054.2	0.0449	54010.4	2.42506696
23.5468	56592.4	0.033	55823.3	1.8421689
23.5728	57801	0.026	57196.7	1.4871142
23.9843	57343	0.4115	57572	23.690878
24.1275	60086.1	0.1432	58714.55	8.40792356
24.2518	61950.3	0.1243	61018.2	7.58456226
24.3808	64034.2	0.129	62992.25	8.12600025
24.524	66777.3	0.1432	65405.75	9.3661034
24.6577	69081	0.1337	67929.15	9.082127355
24.7568	73695.7	0.0991	71388.35	7.074585485
24.8009	71824.1	0.0441	72759.9	3.20871159
24.8158	76442.5	0.0149	74133.3	1.10458617
25.2903	74991.9	0.4745	75717.2	35.9278114
25.3304	76859.8	0.0401	75925.85	3.044626585
25.3705	78727.6	0.0401	77793.7	3.11952737
25.4948	80591.8	0.1243	79659.7	9.90170071

25.5443	82899.1	0.0495	81745.45	4.046399775
25.7717	85638.6	0.2274	84268.85	19.16273649
25.8819	86843.5	0.1102	86241.05	9.50376371
25.9944	88158.3	0.1125	87500.9	9.84385125
26.0463	90575.5	0.0519	89366.9	4.63814211
26.084	92333.5	0.0377	91454.5	3.44783465
26.1171	93871.7	0.0331	93102.6	3.08169606
26.143	95080.3	0.0259	94476	2.4469284
26.202	97827.2	0.059	96453.75	5.69077125
26.77013	96505	0.0559	97166.1	5.43158499
Total Energy				**410.1143619**

Force-deformation data at the moisture content value of 45.12% (w.b)

X (mm)	F (N)	X_{n+1}-X_n	[F_n+F_{n+1}]/2	Energy (N.m)
0	0			
0.594614	531.853	0.594614	265.9265	0.15812362
1.44124	1056.32	0.846626	794.0865	0.672294277
2.61993	1241.5	1.17869	1148.91	1.354208728
4.04932	1309.48	1.42939	1275.49	1.823172651
5.31201	1492.2	1.26269	1400.84	1.76882666
6.7414	1560.18	1.42939	1526.19	2.181520724
7.92009	1745.36	1.17869	1652.77	1.948103471
8.84809	2047.74	0.928	1896.55	1.7599984
10.2788	2225.54	1.43071	2136.64	3.056912214
11.2908	2525.46	1.012	2375.5	2.404006
12.2188	2827.83	0.928	2676.645	2.48392656
12.8935	3027.78	0.6747	2927.805	1.975390034
13.5708	3447.36	0.6773	3237.57	2.192806161
14.4974	3639.92	0.9266	3543.64	3.283536824
15.2601	4166.85	0.7627	3903.385	2.97711174
16.3587	4683.94	1.0986	4425.395	4.861738947
17.4586	5310.84	1.0999	4997.39	5.496629261
18.3066	5945.13	0.848	5627.985	4.77253128
19.1559	6689.23	0.8493	6317.18	5.365180974
19.9211	7435.79	0.7652	7062.51	5.404232652
20.4396	8629	0.5185	8032.395	4.164796808
20.8715	9605.04	0.4319	9117.02	3.937640938

21.3073	10910.5	0.4358	10257.77	4.470336166
21.7418	12106.2	0.4345	11508.35	5.000378075
22.0923	13304.3	0.3505	12705.25	4.453190125
22.3588	14504.9	0.2665	13904.6	3.7055759
22.544	15927.6	0.1852	15216.25	2.8180495
22.8091	17018.4	0.2651	16473	4.3669923
22.8223	18116.5	0.0132	17567.45	0.23189034
22.8368	19324.5	0.0145	18720.5	0.27144725
23.2713	20520.2	0.4345	19922.35	8.656261075
23.2845	21618.3	0.0132	21069.25	0.2781141
23.2937	22387.1	0.0092	22002.7	0.20242484
23.5681	24246.5	0.2744	23316.8	6.39812992
23.7611	26328.1	0.193	25287.3	4.8804489
23.7796	27865.5	0.0185	27096.8	0.5012908
24.054	29725	0.2744	28795.25	7.9014166
24.1577	31369.8	0.1037	30547.4	3.16776538
24.3481	33231.8	0.1904	32300.8	6.15007232
24.3692	34988.8	0.0211	34110.3	0.71972733
24.5596	36850.8	0.1904	35919.8	6.83912992
24.6673	38825	0.1077	37837.9	4.07514183
24.7697	40359.9	0.1024	39592.45	4.05426688
24.9549	41782.6	0.1852	41071.25	7.6063955
24.972	43210.2	0.0171	42496.4	0.72668844
25.0718	44525.6	0.0998	43867.9	4.37801642
25.169	45621.3	0.0972	45073.45	4.38113934
25.2648	46607.1	0.0958	46114.2	4.41774036
25.2767	47595.5	0.0119	47101.3	0.56050547
25.3712	48471.5	0.0945	48033.5	4.53916575
25.3778	49020.6	0.0066	48746.05	0.32172393
25.6875	46814.5	0.3097	47917.55	14.84006524
25.9592	48454.3	0.2717	47634.4	12.94226648
26.0617	49989.3	0.1025	49221.8	5.0452345
26.1589	51085	0.0972	50537.15	4.91221098
26.2613	52619.9	0.1024	51852.45	5.30969088
26.2811	54267.2	0.0198	53443.55	1.05818229
26.3901	56351.2	0.109	55309.2	6.0287028
26.4952	58105.8	0.1051	57228.5	6.01471535
26.5149	59753	0.0197	58929.4	1.16090918
26.7014	61285.5	0.1865	60519.25	11.28684012

26.897	63586.8	0.1956	62436.15	12.21251094
26.9194	65453.6	0.0224	64520.2	1.44525248
27.0232	67098.4	0.1038	66276	6.8794488
27.1243	68523.5	0.1011	67810.95	6.855687045
27.2202	69509.4	0.0959	69016.45	6.618677555
27.32	70824.8	0.0998	70167.1	7.00267658
27.3358	72142.5	0.0158	71483.65	1.12944167
27.3529	73570.2	0.0171	72856.35	1.245843585
27.4566	75214.9	0.1037	74392.55	7.714507435
27.5591	76749.9	0.1025	75982.4	7.788196
27.5723	77848.1	0.0132	77299	1.0203468
27.5894	79275.7	0.0171	78561.9	1.34340849
27.6249	82240.7	0.0355	80758.2	2.8669161
27.6513	84437	0.0264	83338.85	2.20014564
27.6892	80591	0.0379	82514	3.1272806
28.041	81898.9	0.3518	81244.95	28.58197341
28.1448	83543.7	0.1038	82721.3	8.58647094
28.2525	85517.9	0.1077	84530.8	9.10396716
28.4376	86940.6	0.1851	86229.25	15.96103417
28.4547	88368.2	0.0171	87654.4	1.49889024
28.456	88478	0.0013	88423.1	0.11495003
28.4758	90125.3	0.0198	89301.65	1.76817267
28.4916	91443.1	0.0158	90784.2	1.43439036
28.5888	92538.8	0.0972	91990.95	8.94152034
28.6859	93634.5	0.0971	93086.65	9.038713715
28.7017	94952.3	0.0158	94293.4	1.48983572
28.7123	95830.8	0.0106	95391.55	1.01115043
28.7228	96709.3	0.0105	96270.05	1.010835525
28.9	97473.1	0.1772	97091.2	17.20456064
Total Energy				**413.9117366**

Force-deformation data at the moisture content value of 47.83% (w.b)

X (mm)	F (N)	$X_{n+1}-X_n$	$[F_n+F_{n+1}]/2$	Energy (N.m)
0	0			
0.139463	1214.77	0.139463	607.385	0.084707734
0.289509	1990.02	0.150046	1602.395	0.24043296
0.866261	2560.66	0.576752	2275.34	1.312306896

1.87236	2816.83	1.006099	2688.745	2.705143656
3.21824	2975.25	1.34588	2896.04	3.897722315
4.81432	3252.65	1.59608	3113.95	4.970113316
6.41305	3420.17	1.59873	3336.41	5.334018759
7.67729	3465.68	1.26424	3442.925	4.352683502
8.93889	3621.06	1.2616	3543.37	4.470315592
10.8747	3800.72	1.93581	3710.89	7.183577971
12.4682	4188	1.5935	3994.36	6.36501266
13.5506	4776.85	1.0824	4482.425	4.85177682
14.8912	5155.03	1.3406	4965.94	6.657339164
16.2265	5752.98	1.3353	5454.005	7.282732877
17.3037	6561.59	1.0772	6157.285	6.632627402
17.9568	7464.92	0.6531	7013.255	4.580356841
18.4439	8252.3	0.4871	7858.61	3.827928931
19.0154	9042.71	0.5715	8647.505	4.942049108
19.4183	9827.06	0.4029	9434.885	3.801315166
19.8265	10391.6	0.4082	10109.33	4.126628506
20.3057	11508.7	0.4792	10950.15	5.24731188
20.7823	12735.6	0.4766	12122.15	5.77741669
21.0087	13843.5	0.2264	13289.55	3.00875412
21.401	15067.4	0.3923	14455.45	5.670873035
21.6195	16504.9	0.2185	15786.15	3.449273775
21.9196	18055.4	0.3001	17280.15	5.185773015
22.138	19493	0.2184	18774.2	4.10028528
22.2775	20707.8	0.1395	20100.4	2.8040058
22.6645	22151.4	0.387	21429.6	8.2932552
22.717	23473	0.0525	22812.2	1.1976405
22.8539	24797.7	0.1369	24135.35	3.304129415
22.9933	26012.5	0.1394	25405.1	3.54147094
23.2091	27559.9	0.2158	26786.2	5.78046196
23.2643	28771.6	0.0552	28165.75	1.5547494
23.3248	29763.6	0.0605	29267.6	1.7706898
23.459	31198.2	0.1342	30480.9	4.09053678
23.5931	32632.7	0.1341	31915.45	4.279861845
23.651	33734.6	0.0579	33183.65	1.921333335
23.7904	34949.3	0.1394	34341.95	4.78726783
23.9034	37262.9	0.113	36106.1	4.0799893
23.9325	36054.2	0.0291	36658.55	1.066763805
24.0455	38367.8	0.113	37211	4.204843

24.061	41227.8	0.0155	39797.8	0.6168659
24.1007	39579.6	0.0397	40403.7	1.60402689
24.1608	44090.8	0.0601	41835.2	2.51429552
24.1926	42772.2	0.0318	43431.5	1.3811217
24.3766	45638.3	0.184	44205.25	8.133766
24.4212	47289.5	0.0446	46463.9	2.07228994
24.5501	48943.8	0.1289	48116.65	6.202236185
24.6816	50488.2	0.1315	49716	6.537654
24.8132	52032.7	0.1316	51260.45	6.74587522
24.863	53464.2	0.0498	52748.45	2.62687281
24.8997	55445.1	0.0367	54454.65	1.998485655
24.9182	54675.9	0.0185	55060.5	1.01861925
25.213	56446.2	0.2948	55561.05	16.37939754
25.2603	57987.5	0.0473	57216.85	2.706357005
25.3155	59199.3	0.0552	58593.4	3.23435568
25.4417	60963.5	0.1262	60081.4	7.58227268
25.4519	64043.2	0.0102	62503.35	0.63753417
25.4836	62724.6	0.0317	63383.9	2.00926963
25.4991	65584.6	0.0155	64154.6	0.9943963
25.5146	68444.6	0.0155	67014.6	1.0387263
25.5517	66906.2	0.0371	67675.4	2.51075734
25.9519	67800.4	0.4002	67353.3	26.95479066
26.0834	69344.9	0.1315	68572.65	9.017303475
26.136	70666.5	0.0526	70005.7	3.68229982
26.1912	71878.2	0.0552	71272.35	3.93423372
26.3253	73312.8	0.1341	72595.5	9.73505655
26.3779	74634.4	0.0526	73973.6	3.89101136
26.4304	75956	0.0525	75295.2	3.952998
26.4879	80577.1	0.0575	78266.55	4.500326625
26.5196	79258.5	0.0317	79917.8	2.53339426
26.5219	82667.9	0.0023	80963.2	0.18621536
26.5483	81569.1	0.0264	82118.5	2.1679284
26.5593	77610.3	0.011	79589.7	0.8754867
26.5638	84429.1	0.0045	81019.7	0.36458865
26.6031	86300.1	0.0393	85364.6	3.35482878
26.9301	83232.5	0.327	84766.3	27.7185801
27.1221	85768.9	0.192	84500.7	16.2241344
27.2872	92923.4	0.1651	89346.15	14.75104936
27.3458	86986.7	0.0586	89955.05	5.27136593

27.3613	89846.7	0.0155	88416.7	1.37045885
27.3949	95456.8	0.0336	92651.75	3.1130988
27.4059	91498	0.011	93477.4	1.0282514
27.424	94248.1	0.0181	92873.05	1.681002205
27.4448	96888.3	0.0208	95568.2	1.98781856
27.4979	88091.6	0.0431	92489.95	3.986316845
27.75153	97880.2	0.26263	92985.9	24.42088692
Total Energy				**415.661524**