CHAPTER 2

Theory

2.1 Refuse-derive fuel (RDF)

1. Definition

RDF is solid waste fuel which is derived from waste. RDF is counted as commercial fuel because it has the appropriate properties such as heating value, moisture, size, density, and chemical composition. European standard requires that RDF should have high calorific value (about 16.0-19.0 MJ/kg) and low concentration of toxic chemicals especially for heavy metals and chlorine (chlorine content about 0.02-0.03%). In Thailand, there is no RDF standard, however, it is being studied. Several scholars have been given for vary definition of RDF as Gendebien (2003), ASTM (2000), Velis (2010), Rotter (2004) are following discussion.

RDF is an alternative fuel which is derived from combustibles municipal solid waste such as waste plastic, textile, wood and soil. Technology for RDF are the process of presorting and standard units, such as mechanical shredding, magnetic separation, trommel screening and airclassification. It has a higher quality in heating value (Chang, & Chen, 1997). From Gendebien (2003) , RDF is the highest calorific fraction of derived Municipal Solid Waste (MSW). The other terms for MSW derived fuel is Recovered fuel (REF), Packaging derived fuel (PDF), Paper and plastic fraction (PPF) and Processed Engineered fuel (PEF). ASTM (2000) defined that RDF is energy recovery source from shredding MSW which is removed for non-combustible materials (for example, metal and glass). The majority components of RDF usually consists of plastics and biodegradable waste.

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Velis (2010) defined that RDF is a combustible waste, such as paper, card, wood and plastic, with high calorific value fraction which is produced by municipal mechanical treatment or similar commercial / industrial waste. Rotter (2004) also reported that RDF is produced from residue household waste which is passed the separation process by mechanical operation to achieve and assure quality targets for chemical characteristics of fuel.

2. RDF's classification

RDF classification can be defined into several categories. It is depend on method and process to change waste to RDF, condition of waste and fuel needs. Each type of RDF has different process and form. For example, RDF-1 or raw MSW is in discard form. RDF-2 or coarse RDF coarse particle size of MSW processed and has a 6-in. square size. RDF-3 or fluff RDF is shredded fuel and has small particle size than RDF-2. RDF-4 or powder RDF is crushed to powder form and has small particle size than RDF-3. RDF-5 or densified RDF is combustible waste compressed into pellets form. RDF-6 is in liquid form by liquidification process. RDF-7 is in gas form by gasification process. The American Society for Testing and Materials (ASTM) has classifies RDF into 7 categories as listed in table 2.1 (J. Bushnell, Haluzoke, & Nikoo Dadkhah, 1989).

Table 2.1 : Categories of RDF as guide by the ASTM.

Class	Form	Description	Mesh size	HHV/LHV	Density	Moisture	Ref.
RDF-1	Raw (MSW)	MSW fuel as discarded form.	N.A.	2329 kcal/kg (9.75 MJ/kg)	N.A.	55.93%	(*Ministry of Energy*, 2005)
RDF-2	Coarse (c-RDF)	Coarse particle size of MSW processed with or without ferrous metal separation such that 95% by weight	6 in. square	3215 kcal/kg (13.45 MJ/kg)	N.A.	17.45%	(Caputo & Pelagagge, 2002a)
RDF-3	Fluff (f-RDF)	Shredded fuel derived from MSW processed for the removal of metal glass and inorganic materials. The particle size of this shredded material is such that 95% by weight	2 in. square	3765 kcal/kg (15.75 MJ/kg)	N.A.	7.5%	(Caputo & Pelagagge, 2002a)

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Table 2.1 (continued)

Class	Form	Description	Mesh size	HHV/LHV	Density	Moisture	Ref.
RDF-4	Powder (p-RDF)	Combustible waste processed into powdered form, 95% by weight	0.035 in square	N.A.	N.A.	N.A.	-
RDF-5	Densified (d – RDF)	Combustible waste densified (compressed) into pellets, slugs, cubettes, briquettes, or similar forms.	N.A.	4227 kcal/kg (17.69 MJ/kg)	> 600 kg/m^3	6.6%	(Caputo & Pelagagge, 2002a, 2005)
RDF-6	Liquid	Combustible waste processed into liquid fuel.	N.A.	4438 kcal/kg (18.57 MJ/kg)	1,090 kg/m^3	11%	(Asadullah et al., 2007)
RDF-7	Gas	Combustible waste processed into gaseous fuel.	N.A.	2426 kcal/Nm^3 (10.15 MJ/kg)	N.A.	N.A.	(Kikuchi, Sato, Matsukura, & Yamamoto, 2005)

3. Characteristics and quality standards of RDF

Characteristics and quality standards of RDF production is separated to three participation groups: the RDF producers, potential RDF customers, and the respective authorities. They are defined in a term of quality standard values. The quality standards in Europe defined that RDF should have low concentration of the pollutants especially heavy metal and chlorine. A results of a survey of quality standards for RDF in Europe by (Rotter et al., 2004) are shown in Table 2.2. The quality properties of RDF that are designed for Eupean and other countries are shown in Table 2.3.

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Table 2.2 Survey of quality standards for RDF in Europe.

Content	Country (reference)		
	Switzerland (Buwal,1998) mg/MJ	Finland (SFS, 2000) mg/MJ	Italy(Ministerodell'ambient, 1998) mg/MJ
As	0.6	N.A.	0.5
Be	0.2	N.A.	N.A.
Cd	0.1	0.3	0.4
Co	0.8	N.A.	N.A.
Cr	4.0	N.A.	6.0
Cu	4.0	N.A.	17.0
Hg	0.02	0.03	N.A.
Ni	4.0	N.A.	2.0
Pb	8.0	N.A.	11.0
Sb	0.2	N.A.	N.A.
Se	0.2	N.A.	N.A.
Sn	0.4	N.A.	N.A.
Te	N.A.	N.A.	N.A.
Tl	0.12	N.A.	N.A.
V	4.0	N.A.	N.A.
Zn	16.0	N.A.	28.0
Cl	N.A.	1.5% by weight	0.9% by weight

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Table 2.3 Quality standard by Australia, Sweden, German and European country.

Property	RDF quality of each country					
	Australia	Sweden	German	European country		
				Class A1	Class A2	Class B
Calorific value (MJ/kg)	≥ 18.0	≥ 16.9	17.5 – 19.5	16.5 – 19.0	16.3 – 19.0	16.0 - 19.0
Moisture (%)	≤ 10	≤ 10	≤ 12	≤ 10	≤ 10	≤ 10
Ash (%)	≤ 0.5	≤ 0.7	≤ 1.5	≤ 0.7	≤ 1.5	≤ 3.5
Chlorine-Cl (%)	≤ 0.02	≤ 0.03	≤ 0.03	≤ 0.02	≤ 0.02	≤ 0.03
Sulfur-S (%)	≤ 0.04	≤ 0.08	≤ 0.08	≤ 0.03	≤ 0.03	≤ 0.04
Lead-Pb (mg/kg)	N.A.	N.A.	≤ 10	≤ 10	≤ 10	≤ 10
Chromium-Cr (mg/kg)	N.A.	N.A.	≤ 8	≤ 10	≤ 10	≤ 10
Copper-Cu (mg/kg)	N.A.	N.A.	≤ 5	≤ 10	≤ 10	≤ 10
Nikel-Ni (mg/kg)	N.A.	N.A.	N.A.	≤ 10	≤ 10	≤ 10
Arsenic-As (mg/kg)	N.A.	N.A.	≤ 0.8	≤ 1	≤ 1	≤ 1
Mercury-Hg (mg/kg)	N.A.	N.A.	≤ 0.05	≤ 0.1	≤ 0.1	≤ 0.1
Cadmium-Cd (mg/kg)	N.A.	N.A.	≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.5
Zinc-Zn (mg/kg)	N.A.	N.A.	≤ 100	≤ 100	≤ 100	≤ 100

Source: ObernbergerIngwald and ThekGerold, The Pellet Handbook, and The production and thermal utilization of biomass pellets 2010. (Thek, 2010)

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2.2 Factors affecting to RDF products

From many previous researches, many factors have influenced the RDF quality and properties. The most mentioned factors are type of binding agent, type of material, pressure of densification, moisture content, ratio of material and binding agent, type of densification equipment, particle size and preheating temperature. The properties of RDF are mechanical strength, calorific value, density, durability of briquette form and characteristic of combustion.

1. Type of binding agent

Binding agents can be divided into 2 types which are natural binding agent and chemical binding agent.

a) Natural binding agent

Natural binding agents are biomass, organic substances and inorganic substances. Biomass binding agent consists of starch, protein, fiber, cellulose and hemicellulose, fat, lignin, and extractives (Kaliyan & Vance Morey, 2009; Pollution Control Department, 2009). Organic and inorganic substances are asphalt, sawdust, shell of sunflower seed, cassava starch, tar, clay, gum, molasses, starch solution, paraffin, glue, organic oil waste, limestone, etc. (Lope G.Tabil, 1996; Yaman, SahanŞahan, Haykiri-Açma, Şeşen, & Küçükbayrak, 2001). These binding agents can improve strength and durability of RDF. In addition to, the material particles of the RDF tighten together to form a briquette. RDF with high compressive strength are easily to pile up and transport without damage (W. S. Chen, F. C. Chang, Y. H. Shen, & M. S. Tsai, 2011; Sotannde, Oluyege, & Abah, 2010).

Chen (2011) studied for RDF-5 which use organic sludge and sawdust as a material. The binding agent of this study was asphalt. The result of this study found that RDF-5 which use asphalt as a binding agent was high calorific value and high strength. Beker (1998) studied for coal densification with many binding agents, i.e., sawdust, sunflower shell and molasses. The results found that these binding agents can improve coal briquette properties including higher strength, lower sulfur and ash. Sotannde (2010) studied saw dust densification. The binding agents are cassava and wood stick. These binding agents improves the combustion quality and strength of sawdust briquette.

Organic and inorganic binding agents are not usually used for densification process because they are expensive, and let increase the cost of production (O.Wilson, 2010). Many country in Europe are not allowed to use organic and inorganic binding agents. Instead, they are

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campaign to use natural binding agent, such as biomass which consists of starch, protein, fiber (cellulose and hemicellulose), fat, lignin and extractive.These components can act as binding agent for densification process (Kaliyan & Vance Morey, 2009).

Kaliyan (2010) found that monoculture including of sweet corn and switch grass have carbohydrate composition which can dissolve in water. Lignin, protein, starch, fiber and fat can build solid bridge which make particles of the RDF tighten together to form a briquette and high compressive strength. Chiemchaisri (2010) studied RDF production from plastic waste with cassava root as a binder. The result found that cassava root makes the particle of plastic to form a briquette after compaction. In addition, plastic briquette has high compressive strength and easy to pile up and transport without damage.

Each type of biomass has different composition as shown in Table 2.4. Major compositions are affected to binding mechanism including to protein, fat, starch, fiber, lignin and extractive.

Table 2.4 : Composition of each type of biomass. (agriculture waste)

Type of biomass	Composition						
	Protein	Fat	Starch	Fiber	Lignin	Extractive	Ash
Corn stover	5	N.A.	N.A.	64	19	4	6
Soy bean	5	N.A.	N.A.	47	-	14	6
straw	4	N.A.	N.A.	67	15	9	6
Barley straw	4	2	0.1	54	17	-	2
Canola straw	6.5	0.9	0.3	58.8	14.2	-	2.1
Oat straw	5.3	1.7	0.1	60	12.9	-	2.2
Wheat straw	2.3	1.6	2.6	57.8	13.9	-	2.4
Switchgrass	3	N.A.	N.A.	66	19	6	6
Sweet sorghum	-	N.A.	N.A.	37	11	-	5
Miscanthus	3	N.A.	N.A.	67	19	-	2
Forage sorghum	-	N.A.	N.A.	54	16	-	5

Source : D.Lee et.al. (2007) and P. Adapa et.al. (2009)

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Binding qualification of natural binding can be explain as follows:

1) Protein: It can change into plastic form and act as binder which supports the strength of densified product at high temperature. Factors which affect to protein reforming of densification process are heat, moisture and force (Kaliyan & Vance Morey, 2009). Other previous research found that higher protein content can increase more durable than higher only fiber content. For example, alfalfa grass can produce to densified product which has high strength (Tumuluru, Wright, Hess, & Kenney, 2011).

2) Fat or oil: It is the composition of biomass and acts as the lubricant between particle of material and between material and mold wall. It helps easily flow of material and reduces friction force during densification process (Lope G.Tabil, 1996; Stelte, Holm, et al., 2011; Tumuluru et al., 2011). Friction force reducing of densification process decreases the strength of densified fuel. In addition to, fat is insoluble in water and it can interrupt in binding mechanism of soluble substance between starch, protein, fiber and particle. The appropriate of fat or oil content is between 1.5-6. 5% (Briggs et.al., 1999; Kaliyan & Vance Morey, 2009; O.Wilson, 2010; Tumuluru et al., 2011).

3) Starch: At high temperature and moisture, it is in a glue form. It acts as binding agent during densification process. In addition, it acts as lubricating agent which helps material flowing easily in mold. Higher content of starch in form of glue make more strength of densified fuel (Kaliyan & Vance Morey, 2009).

4) Cellulose: cellulose content is effect to durability of densified fuel. Using too high cellulose content lead to easily breakable of densified fuel. Moreover, specific qualification of cellulose are strength and flexible which affect to poor bonding between particle and cellulose. Flexible of cellulose can reduce by adding

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Sodium hydroxide (NaOH), Calcium oxide (CaO) or Urea. Furthermore, these agents can increase durability of densified fuel (Kaliyan & Vance Morey, 2009).

5) Lignin and extractives: Lignin is acts as binding agent in densification process. Higher lignin content can make strong densified fuel because, it acts as glue which combine between particle (Tumuluru et al., 2011). At high temperature, lignin is soft and it holds the particle together which make strong densified fuel (Kaliyan & Vance Morey, 2009). Lignin is soft at glass transition temperature or T_g. T_g of lignin is different due to type of biomass, structure of molecule and moisture (Stelte, Holm, et al., 2011). The studied of lignin's T_g of biomass are shown in Table 2.5 and Figure 2.1.

Extractives are not the component of cell wall structure but they are the compound which make varieties plant such as color, flavor and strength. Higher extractives content can reduce durability and strength of densified fuel. This is because they reduce pressure during densification process which cause to less durability of a densified fuel (Kaliyan & Vance Morey, 2009; Stelte, Holm, et al., 2011).

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Table 2.5: The glass transition temperatures of each type of biomass.

Biomass	Glass transition(T_g) (°C)	Reference
Straw Pine	53 91	(Stelte, Clemons, et al., 2011)
Soft wood Hard wood	119 93	(Mohanty, Misra, & Drzal, 2005)
Corn stover Switch grass	75 75	(Kaliyan & Morey, 2010)
Cornflour	60	(Z. & Sun, 2005)

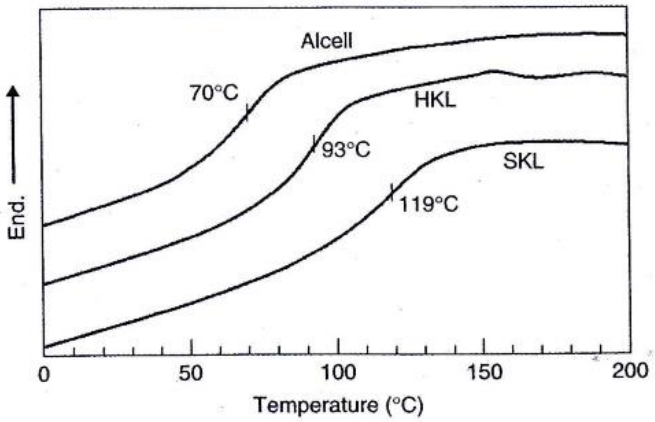

Figure 2.1 : Glass transition of lignin.

b) Chemical binding agent

There are calcium compounds which can be used as chemical binding agent (Piao et al., 1998). Most calcium compounds are calcium oxide or calcium limestone (CaO), calcium hydroxide ($Ca(OH)_2$), calcine dolomite ($CaO.MgO$) and calcium lingo sulfonate (co-product from paper and cellulose production). These binding agents can improve combustion property and durability of densified fuel by adding them in mixer before densification process or in a flue gas. Sometimes, CaO powder is added to the top, middle or bottom layer of sample (Tatemoto, Bando, Yasuda, & Nakamura, 1999). These agents can catch Chlorine (Cl) in ash form. The equations of combustion of HCl content reducing by calcium compound are in equations (1) and (2). $Ca(OH)_2$ supplies Ca^{2+} and reacts with Cl^- in flue gas of RDF combustion to form $CaCl_2$ which is in ash form and reduces the concentration of HCl in a flue gas (Chiang, Jih, & Lin, 2008).

$$Ca(OH)_2 \leftrightarrows CaO + H_2O \qquad (1)$$

$$CaO + 2HCl \leftrightarrows CaCl_2 + H_2O \qquad (2)$$

Corella J. (2008) found that calcined dolomite ($CaO.MgO$) is effective more than calcined limestone (CaO) because it can reduce more HCl content in form of $CaCl_2.MgCl_2$. However calcined limestone can also

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react with HCl inform of $CaCl_2$. Tabil (2008, 1997) studied alfalfa densified with lignosulfonate and calcium hydroxide as binding agent. The result found that alfalfa densified which mixed with lignosulfonate and calcium hydroxide has more than 80% strengthen. It can conclude that alfalfa densified only has less strength than alfalfa densified with binding agent.

2. Type of material

Type of material effects the densified properties including durability, strength, density, gross calorific value, pollutant emission, etc. Previous researchers found that RDF which consist of paper, soft plastic, fabric, or organic waste is low polluted fuel. RDF which consists of long-lived plastic products or long-lived material is high polluted fuel (Rotter et al., 2004). Material with fiber element can produce strong densified product. Densified product from coal powder and cardboard newspaper or used paper is durability, since paper consists of fiber which helps material particles of densified product are hold together (John Watson, 1988). Densified product which is produced from mixture of paper waste and wheat straw is durable without binding agent. This is because both paper and wheat straw have a component of natural binding agent which helps particles bonding together (Demirbaş & Şahin, 1998). Yaman (2001) studied physical properties of densified lignite coal with paper waste, saw dust, cotton rag, pine flowers and olive residue. The result found that paper waste and saw dust improves strength of densified lignite coal, while cotton rag and pine flower improve water resistance of densified lignite coal. Li (2001) studied the higher heating values (HHV) and proximate analysis from type of combustible materials use. They found that mixed paper briquette only has low HHV because high of ash content (Yaman, Şahan, Haykiri-açma, Şeşen, & Küçükbayrak, 2000). However, both of HHV and ash contents were improved when the paper briquette was mixed with plastic. Because plastic contains low ash content and presents high heating value which can improve combustion property. The example of combustion characteristics of combustible materials is shown in Table 2.6.

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3. Pressure of briquetting form

Pressure affects to durability and density of densified product. Higher pressure condition can produce the better quality of densified product and higher density which is close to or higher than 1 g/cm^3(Li & Liu, 2000). Previous research found that at compression with pressure equal of more than 70 MPa can compact the mixtures of paper and plastic into good briquette with density higher than 0.8 g /cm^3(Li et al., 2001).

The increasing of pressure which is effect to the density of densified fuel is shown in table 2.7. Natural binding such as starch, protein, lignin and pectin in the feed or biomass materials are squeezed out of particles and contribute to inter particle bonding under high pressure (Kaliyan & Vance Morey, 2009). In addition, distance between particles is decreased and gaps between the particles are filled under high pressure. So, the densified fuel has high mechanical strength. The effect of pressure to mechanical strength is shown in Table 2.8. Yaman (2000) found that increasing briquetting pressure can improve for shatter index and water resistance time of briquetting form. Demirbas (1998) showed that increasing pressure from 300 MPa to 800 MPa can increased density, bending and compressive strength of mixed waste paper and wheat straw briquette. Beker (1998) studied shatter index and compressive strength under the briquetting pressure at 566 MPa and 708 MPa. The result showed that shatter index and compressive strength under compressed at 708 MPa are higher than at 566 MPa. Demirbas (1998) studied the effects of the briquetting pressure to the density, moisture content, bending strength and compressive strength at pressure of 300-800 MPa. They found that briquetting pressure increasing can improve briquette properties.

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Table 2.6 example of combustion characteristics of combustible materials

Material	HHV (MJ/kg)	Fixed carbon (%)	Volatile matter (%)	Ash (%)	Reference
Mixed paper[a]	15.4	12.5	77.9	9.6	(Li et al., 2001)
LDPE film	46.2	0.05	99.8	0.1	
HDPE film	44.6	0.04	99.8	0.5	
Hard HDPE	46.4	0.0	100	0.0	
Hard PET	23.3	5.3	94.7	0.01	
Hard PS	36.7	4.7	94.9	0.5	
Foamed PS	40.9	0.2	99.4	0.4	
Hard PP	46.4	0.06	99.6	0.4	
Textiles	18.7	17.5	69.0	3.5	
Oak wood	19.9	18.0	80.9	1.2	
Olive husk	19.2	26.1	70.3	3.6	(Ayhan, 1997)
Hazelnut shell	19.7	28.3	69.3	1.4	
Hazelnut seedcoat	19.4	27.0	71.2	1.8	
Hardwood	19.6	28.1	70.0	1.7	
Wheat straw	19.0	25.0	72.3	2.7	
Wood bark	18.7	23.5	63.0	13.5	
Waste material	20.4	31.8	66.6	1.6	
Corncob	17.4	16.8	78.7	4.5	
Tea waste	16.6	12.5	86.5	1.0	
Corn stover	16.8	13.6	85.0	1.4	
Sqruce wood	17.6	17.6	78.7	3.7	
Beech wood	19.7	28.3	70.2	1.5	
Tobacco leaf	18.9	24.6	74.0	0.4	
Ailanthus wood	16.3	11.2	72.6	17.2	
Tobacco stalk	19.0	24.8	73.5	1.7	
	17.6	18.0	79.6	2.4	
Olive refuse	21.4	Not available	67.5	5.0	(Yaman et al., 2000)
Paper mill waste	13.0	Not available	65.5	15.5	

Table 2.7 The effect of increasing pressure to quality and density of briquettes

Material	Forming pressure (MPa)	Density (g / cm^3)	Reference
Newsprint	34	0.62	(Li & Liu, 2000)
	69	0.81	
	103	1.00	
	138	1.13	
Commercial printing	34	0.83	
	69	1.02	
	103	1.14	
	138	1.25	
Mixed paper and hard plastic	69	0.91	(Li et al., 2001)
	102	0.93	
	138	0.99	
Mixture of paper, plastics, textiles and wood	69	0.71	
	102	0.79	
	138	0.82	

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Table 2.8 effect of briquetting pressure to mechanical strength

Material	Briquetting pressure (MPa)	Compressive strength	Reference
Paper mill waste	150	1249 kg/cm^2	(Yaman et al., 2000)
	200	1096 kg/cm^2	
	250	1299 kg/cm^2	
Oak sawdust	34	25 MPa	(Kaliyan & Vance Morey, 2009)
	69	28 MPa	
	103	45 MPa	
	138	49 MPa	
Pine sawdust	34	25 MPa	
	69	35 MPa	
	103	44 MPa	
	138	45 MPa	

4. effect of moisture

Moisture content is effect to quality of densified fuel including to density and strength. Proper moisture makes strong densified fuel. Demirbas (1998) studied the effect of moisture to properties of briquette form such as briquette density, bending strength and compressive strength. The result of this research found that higher moisture content can increase the properties of briquette. On the other hand, higher moisture content led to low calorific values of briquette sample. Ulker (1997) found that densified fuel with less moisture content showed high calorific value. For example, the calorific value of densified fuel is 4.61 MJ/kg at 46% of moisture content, but that of 9.21 MJ/kg is at 8% of moisture content. Li (2000) varied moisture contents from 5-20% and measured that how the contents effect the properties of densified from paper mixture. They reported that, higher than 17% of moisture content cannot produce the density of densified fuel near 1 g/cm^3. The optimum moisture content is 15% which gives high quality densified fuel including to high density and mechanical strength. Yaman (2000) reported that decreasing moisture content to 5% led to reduce in shatter index and compressive strength of olive refuse briquette and paper mill waste briquette. Maximum compressive strength and shatter index are occurred at 15% of moisture content.

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5. material and binding agent ratio

The strength of densified fuel is concerned with material and binding agent ratio. There are many researches that studied the effect of the ratio to densified fuel strength.

Chiemchaisri (2010) varied the weight ratio of plastic wastes and cassava root stem from 1:0.2 to 1:1.6 of weight ratio. He found that the optimum ratio is 1:0.8 which has maximum plastic content of 55.56% and high calorific value of 26.0 MJ/kg. The compressive strength of RDF briquette was good for storage and transportation without of damage at this ratio.

Yaman (2001) investigated for biomass and lignite blends at various ratio of 0 - 30% wt. They found that ratio of material and binding agent effects to compressive strength. For example, olive refuse decreases mechanical strength of the densified fuel. Paper mill waste, sawdust and pine cone are given the lowest of mechanical strength. Over 10% of binding agent gives more mechanical strength.

6. type of densification equipment

Density and mechanical strength are due to type of densification equipment which are divide into 4 types:

Type1) Piston press.

Piston press can be hydraulic, mechanic system or roller. Piston press can be used for large size particle of material or higher moisture content of material without binding agent. Densified fuel forms are in cubic, briquette or cylindrical pistons. The density of densified fuel from this equipment is between 900 – 1300 kg/m^3 (Sudhagar Mani, Tabil, Sokhansanj, Crerar, & Panigrahi, 2002; Tumuluru et al., 2011). High pressure and high temperature help to increase density. Because lignin in biomass is acts as binding agent, it holds the particle together and helps to increase the density of densified fuel.

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Type 2) Screw press.

Screw press is used to dense material which has the size of 2 – 6 mm. Material is continually squeezed and pressed with heating during densification process. Higher pressure makes more strong densified fuel (Tumuluru et al., 2011). Densified fuel product has a hole in the center. It occurred from the screw compression. This hole helps to discharge steam and improve the efficacy of combustion (Sudhagar Mani et al., 2002). The material becomes soft and loses of elastic nature at the temperature of 200-250ºC during the compression. The particle is closer and occurs interlocking. Meanwhile, it absorbs energy from friction which cause to high pressure and temperature of material. The temperature is high to 280 ºC at the final stage of compression. There are moisture that occurs and evaporates to steam. The removal of steam helps to form briquette (Tumuluru et al., 2011). The problem which can occur during compression is the ignition of material. Material can get heated to the ignition temperature which can cause to fire and pyrolysis to its surface (Nalladurai & R. Vance, 2008).

Type 3) Roll press.

Roll press has two rollers which are the same size and opposite way rolling. They are placed parallel to each other. Material size for roll press is the smallest than the other types. Material is compressed between the rollers. Factors which are effected to densified product are roller diameter, roller distance, roller power and mold shape. The typically of product density from roll press is 450-550 kg/m^3 (Tumuluru et al., 2011).

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Type 4) Pellet mill.

Pelletization is a famous technology for food or fuel production. There are two types of device: ring type and plate type. Material is pressed into mold. The pellets are extruded from the die and cut by knife blade. Typical shape of densified fuel is cylinder with 13-19 mm in length, 6.3-6.4 mm in diameter and 1125-1190 kg/m^3 in density (Jumuluru, Wright, Kenny, & Richard, 2010). There are friction between material and mold surface in the pellet process. This cause to high energy consumption for die extrusion.

7. Particle size of material

Density and durability of densified fuel are depending on particle size. Smaller particle size has higher density. The reason is that small particle size has higher contacting area than that of the large during densification (Adapa et al., 2009; Jumuluru et al., 2010; S. Mani, Tabil, & Sokhansanj, 2004; Sudhagar Mani, Tabil, & Sokhansanj, 2006a; Sudhagar Mani et al., 2002; Tumuluru et al., 2011). Kaliyan (Kaliyan & Morey, 2010; Nalladurai & R. Vance, 2008) concluded that the smaller particle size lets the higher durability and higher density of pellet.

8. Preheating temperature

Density and durability are represented the quality of densified fuel which is depending on preheating temperature (Grover & Mishra, 1996; Tumuluru et al., 2011).

Preheating of feed material can help easier compression and strong densified product. The reason is that it takes fewer loads and makes soften natural binder (such as oil, starch, lignin or protein) during compaction process (Chou, Lin, Peng, & Lu; Kaliyan & Vance Morey, 2009). Higher preheating temperature makes soften fiber, decreases energy consumption and resistance between particles. These reasons let too easy binding of particles. Grover (1996) studied for effect of preheating temperature (25 - 150°C) to densified strength. The result found that the strength of densified product is increase to the preheating temperature. Higher preheating temperature maybe caused of bad particle bonding. The reason is moisture migrates to the bottom of material during compression which effect to bad compressed particles. In addition, moisture could have block particle bonding during compression. Kaliyan (2008) found that the appropriate preheating temperature is in range of glass transition temperature (T_g) of lignin. At this temperature, lignin acts

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as plastic deformation. The densified product at T_g range is more durable than out of T_g range. Chou (2009) studied RDF-5 from rice straw hot plate compression. The heating from hot plate can improve density and strength of densified product. This is because moisture is evaporated and biomass oil is released, and therefore particle is bonded. At room temperature, the density of densified product is 0.56 g/cm^3 and the strength is 2.2 kg$_f$/cm^2. The temperature is increased to 150 °C, and then the density and strength are raised to 0.99 g/cm^3 and 65.7 kg$_f$/cm^2 in respectively.

All mentioned factors effecting to densified fuel are concluded and shown in Table 2.9.

Table 2.9: Factors which effect to densified product properties.

Factors	Properties				
	Density	Durability	Heating value	Moisture	Pollution emission
-Type of binding agent	+	+	-	-	+
-Composition of material	+	+	+	+	+
-Pressure of briquetting form	+	+	+	+	-
-Moisture content	+	+	+	+	-
-Ratio of material and binding agent	+	+	+	-	+
-Type of densification equipment	+	+	+	+	-
-Particle size of material	+	+	+	-	-
-Preheating of temperature	+	+	-	+	-

Remark : + is mean "effect"

- is mean "no effect"

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2.3 RDF Production

RDF production generally consists of several processes which are combustible and non-combustible separation, gliding, shredding, size reduction, classification, drying and densification. The process sequences are due to type and composition of material (Caputo & Pelagagge, 2002b). Typically process can be divided into 3 categories according to type of material (Chou, Lin, Peng, et al.). Production process for saw dust material are gliding, drying, preheating, densification, cooling and drying process. The processes for ether agriculture wastes such as rice husk, coffee husks, peanut shells etc., or industrial wastes are gliding, size reduction, preheating, densification, cooling and packing process. The processes for sugarcane bagasse, mustard, rice straw and coconut husk are drying, size reduction, preheating, densification, cooling and packing. Caputo (2002a) found that production with difference process sequences makes changing to RDF heating value. For example, densified fuel with heating value of 3150 kcal/kg is produced from the process sequences of size reduction, gliding, 2nd size reduction, screening and densification. While, the process sequences of size reduction, gliding, separation, 2nd size reduction, drying and densification give heating value of 4000 kcal/kg.

2.3.1 Separation

Waste materials are separated for recycle parts which are metal, glass and can. Aluminium and organic wastes such as food waste and agriculture waste. Most of organic waste is made to a fertilizer (Velis et al., 2010).

2.3.2 Size reduction

Separated waste are shredded to size reduction. The important shredding machine are hammer mill shredded, rotary shredded etc. Type of materials, size of material, so on are the factors which are used to define type of shredding machine.

2.3.3 Gliding

The purpose of this process is remove other objects and size screening. Materials are separated into 2 groups. There are the large size which carry on the sieve and the small size which pass through the sieve (Nithikul, 2007). The principle of this process is depended on waste physical. This process is mainly used for metal or conductor separation.

2.3.4 Drying and densification

Drying process is used to improve RDF property, heating value and the storage ability (Nithikul, 2007). Drying method is depended on several factors including moisture content of material, size of material and type of densified equipment. The compression process of fuel waste in the form of pellet or

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briquette is called “Densification process”. This process helps to improve the density of material, and storage and handle ability (Kertsuwan & Pathumswat). All Factors which effect RDF product are mentioned on 2.1.

2.4. The economic analysis

The cost of RDF production depends on the process sequences. Caputo (2002a, 2002b) found that the minimum cost of RDF production is 6.65 Euro/ton. The process sequences are size reduction, gliding, waste separation by magnet using, 2nd size reduction, 2nd waste separation and densification. Waste can be separated by thrommel equipment, hand, magnet, 1st and 2nd size reductions and combined thrommel equipment and densification. The possibility consideration of RDF production is focus on heating value of RDF. RDF with LHV of 4050 kcal/kg is from maximum cost of RDF production. RDF with LHV of 4355 kcal/kg is from minimum cost. Factors which are considered for RDF production are economic feasibility, financial risks, waste composition, type of RDF (rough, soft or briquette), densification equipment, plant capacity, transportation distance and price of RDF product. Chiemchaisri (2010) compared the cost of energy production from RDF and other fuels in Thailand. The result found that the cost of energy production from RDF was 0.05 USD/kWh which is much lower than one produced from natural gas, fuel oil and diesel.

2.5. The application of RDF

RDF can be used as fuel like fossil fuel, either direct combustion or co-fuel with coal and other fossil fuel, for boiler in cement industry, electricity industry and other industries.

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2.5.1 Direct combustion

RDF can use directly for several industries which need heat for production. Piao (1998) tested RDF with fluidized bed combustion. The size of bed is 30 x 30 cm and the height is 4 m. Calcium was used as a binder in his work. Rate of fuel feed and combustion temperature was controlled in order to adjust the CO, HCl, SO_x and NO_x content. The result found that rate of RDF feed at 12 kg/h let CO volume over than 500 ppm. Feed rate at 10 kg/h let CO volume of 150 ppm. Volume of the other gas such as HCl and SO_x were the same as CO volume, but, a little of NO_x was released. At 10 kg/h feed rate, high NO_x volume was released. Furthermore, this research found that HCl volume in exhaust gas was high at the combustion temperature over than 900°C. Chang (1999) found that RDF can be directly used as fuel in the incinerator as same as coal. In addition to, ash of RDF can use as co-material for concrete production.

2.5.2 Gas production (Gasification process)

RDF can be used as fuel as coal for gasification process. However, heating value of RDF is much lower than that of coal. This can be improved by condition adjustment, such as, increasing rate of oxygen feeding and improving bed height.

Chiemchaisri (2010) used RDF, which is made from plastic waste and cassava root with updraft gasification. This research studied the effect of air feeding rate at 30 m^3/h and 50 m^3/h. The result found that more feeding rate let more combustion temperature to 604°C. And the content of CO and H_2 in emission gas was depended on air feeding rate and bed height. Pinto (2002) found that RDF, which was made from ethylene plastic waste and pine, can be used in gasification process instead of coal. The temperature in RDF combustion chamber was high to 900°C. This research also found that more poly ethylene plastic content let more of combustion rate and high energy to 98%.

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2.5.3 Using for cement kiln industry, boiler system and electricity production

RDF can be used as commercial fuel, because of its high heating value and low price comparing with coal. Nowadays, RDF is used in cement kiln industry, electricity industry and steam/heating production with boiler. In addition, using RDF can reduce the total cost of domestic fossil fuel and imported fuel.

Japan supports the usage of RDF, for electricity production, heating source for air conditioning system and warm water production for swimming pool, and so on. Tokyo Gas Engineering Co., Ltd. improved small fluidized bed boiler. The purpose is to produce heat for indoor swimming pool and exercise room usage. This boiler uses RDF at 190 kg/h (Nagashima, 1999). Ludwig (2010) use RDF as general fuel for incinerator of Park Hochst. Industry. It can produce 270 MW of heating. The heating value of RDF is 13,400 kJ/kg with 72.6 ton/hr feed rate. The maximum temperature of combustion is in range of 850 – 950^{o}C. This plant installed the several operation units in order to control RDF combustion, i.e., material and additive feeding unit, waste disposal unit (ash, dust, exhaust gas), and electricity and steam of production and distribution unit. Cyclone unit was also installed for separating dust from exhaust gas. The CO and C_xH_y contents can be reduced by increasing supplied air. Wagland (2011) studied RDF as co-fuel with coal at 10% mixture. It can produce 50 kW of energy for fluidized bed incinerator. The result found that RDF with 30% moisture let the combustion temperature less than 950^{o}C. The reason is that moisture content is high. The combustion was operated for 2.5 hours but the combustion temperature of RDF and coal was not reach 900^{o}C.

2.5.4 Environmental impact

Due to RDF is used for utility of several industries which need heating for their production, it should be friendly to the environment. Pollution gases including to NO_x, SO_x, HCl and chlorine compounds (PCDDs and PCDFs) is lower than the value regulated by environmental standard. RDF can be consisted of various components such as plastic, paper, fabric, wood, biomass and so on. Therefore, it can release pollution gases which effect the environment. Various work studied how to reduce pollution gas releasing from RDF combustion. These included binder addition during densification, type of material usage, and co-combustion with coal.

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Wan (2008) studied RDF which is made from paper and plastic waste in circulating fluidized bed co-generation boiler. It was used as co-combustion with the other fuels which were coal, waste tires and paper sludge. Ratios of RDF was varied to 0%, 10%, 20%, 25% and 30%. The result found that higher percent of RDF let more SO_x, but NO_x was reduced. In addition, SO_x and NO_x were increased slightly when using 30% of RDF. Pollution gas was increased since quantity of coal was decreased and a little coal was reacted with NO in the incinerator. Meanwhile, more RDF using let more CO emission because, there are more volatile from RDF. This research also found that using more RDF gave more dioxins emission due to there are a lot of Cl in fuel. Furthermore, the temperature should be control at 800^{o}C. Because, dioxins are more release at low temperature condition (250 – 400^{o}C).

2.6 Basic of densification (Grover & Mishra, 1996)

2.6.1 Pressure of compression

Biomass densification is the technology of biomass transform into briquette fuel which is well known in briquette densification. It is easy handle including transportation, storage, transportation cost reducing and the energy usage promotion from agriculture waste in rural area. Densification is the technique of agglomeration which is widely use like compression technology of waste such as, the compression of wood wastes, light biomass and other combustible wastes transform into briquette fuel which use as commercial fuel.

Compression technology can be divided into 3 types. (1) High Pressure Compaction, (2) Medium Pressure Compaction with a Heating Device and (3) Low Pressure Compaction with a Binder.The compression is briquette densification including particle compression in limit volume. Fine particle of material can deformed under high pressure without binder use. The strength of densified product is occurred from WanDer Waals force, Valence Force or Interlocking. Some of material has natural components which can transform into binder under high pressure condition. So, it does not need binder. Some of materials need binder during densification process because they do not have natural component to transform into binder. The mechanism of binding is shown in Figure 2.2.

2.6.2 Binding mechanism of densification process

It should be know the characteristics or physical and chemical properties of biomass densification which effect to properties of densified product. There

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are moisture content, bulk density, the space between particles and heating property. Biomass densification under high pressure let to interlocking and high bonding force between particles. The bonding force between molecules are divided into adhesion force, cohesion force, attraction force and interlocking. All of these force are occur under high pressure condition. Asphalt and the organic liquid are high molecule and high viscosity.

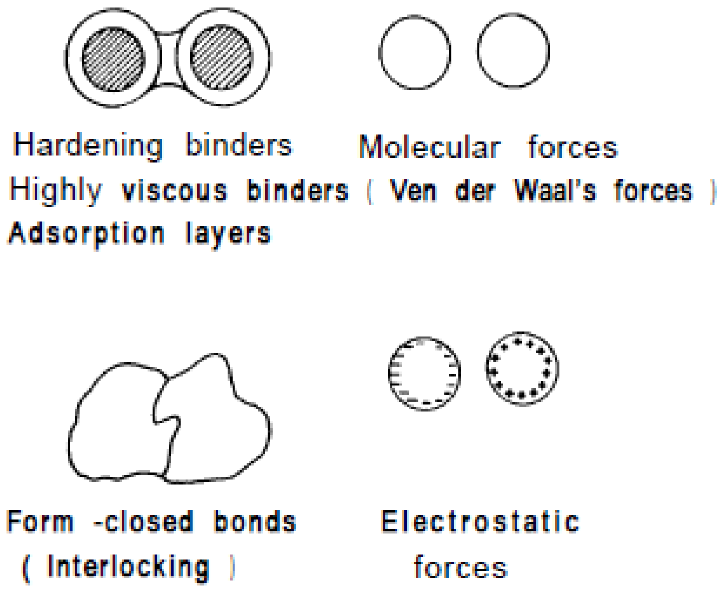

Figure 2.2 Binding mechanism (Grover & Mishra, 1996)

So, they are easy to bond and deform to solid bridge which generates either adhesion force between liquid and solid surfaces or cohesion force between solid surfaces. Lignin which is the component of biomass or wood can help to bond of particles. Lignin is soften at high temperature and pressure. Then it is hold the surface between particles. Furthermore, pressure increases the contact area and the strength of bonding.

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2.6.3 Compaction mechanism (Sudhagar Mani et al., 2002; ÇOMOĞLU, 2007)

Compaction mechanism is divided into 5 groups which are :

1) The attraction force between solid particles
2) Internal force and capillary force of moving liquid sufaces
3) Adhesion and cohesion force
4) Solid bridge

5) Interlocking mechanism

1) The attraction force between solid particles

The attraction force makes solid particles attract each other. This force is in the short range. It depends on size of particle and distance between particles.

2) Internal force and capillary force of moving liquid surfaces

The liquid which is occur during the agglomeration of particles makes cohesion force between particles. Therefore, number and type of liquid can define the strength of product. More volume of liquid means more compaction. Air spaces between particles consists of plenty of liquid and then agglomeration between particles which gives low ratio of liquid per air space. This condition call "Pendular state" as shown in Figure 2.3(a). The particles have the attractive force between its surfaces which are from liquid or liquid bridge.

Capillary state is occurred at high pressure. Particles bonding is from the attractive force between liquid and air surface as shown in Figure 2.3 (b). After capillary state, liquid is vaporize around particle surfaces that make strengthen in bonding. This state called "Funicular state" as shown in Figure 2.3 (c).

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3) Adhesion and cohesion force

Adhesion force is occurred between liquid surfaces and solid surfaces. Whereas, cohesion force is occurred between solid surfaces. Both adhesion and cohesion forces are hold between particle surfaces to make strengthen in bonding like solid bridge. For example, tar and organic material which is high molecule and high viscosity make bonding like solid bridge during densification process. Meanwhile, high pressure is increased the contacting area of material and the strength of particle bonding.

4) Solid bridge

Solid bridge is in form of the crystallization of soluble, the coagulation of binding, melting and adhesion and chemical reaction. It is occurred at high pressure and high temperature. It is the solution which is remained after the vaporization of the soluble or liquid.

5) Interlocking mechanism

The interlocking mechanism is occurred during densification process. It improves the strength of densified product which is against to the recovery resistance after densification process.

Figure 2.4 shows the diagram of densification process. At the initial stage, particles are heated and rearrange themselves to closely form. The energy is loss with the friction between particles and between particles and wall. At high pressure, particles are deformed into plastic. The particle are closely packing. Bonding forces are wan der waals force, electrostatic force and absorbing layer. Brittle particles let to the interlocking which makes strength to densified product. Higher pressure lets to smaller volume. The volume is increased continuously until density is nearly true density.

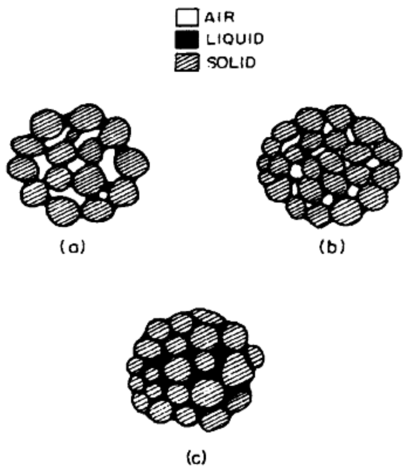

Figure 2.3 The adhesion between surface and capillary of moving liquid surface : (a) Pendular state; (b) Capillary state, (c) Funicular state

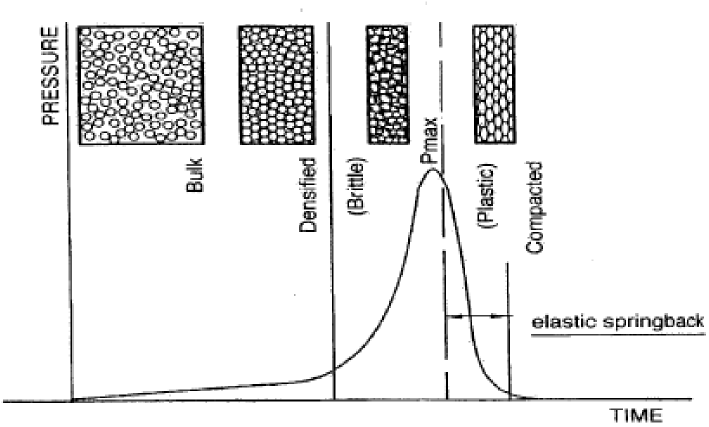

Figure 2.4 Diagram of densification process.

2.7 Compression modeling

Compression model can be used for determining the optimal condition including pressure, moisture, density, so on. These condition affect to the properties of densified product. It can be used to explain the behavior of pellet or briquette compaction and to design the efficiency of compression equipment.

Adapa (2009) defined three-stage compaction mechanism: (1) particles are closely packing and rearranging under low pressure, (2) plastic deformation and elastic deformation, and (3) continuous pressing under high pressure until to melting point, the particles are bonded and deformed to solid bridge after cooling. This mechanism is shown in Figure 2.5.

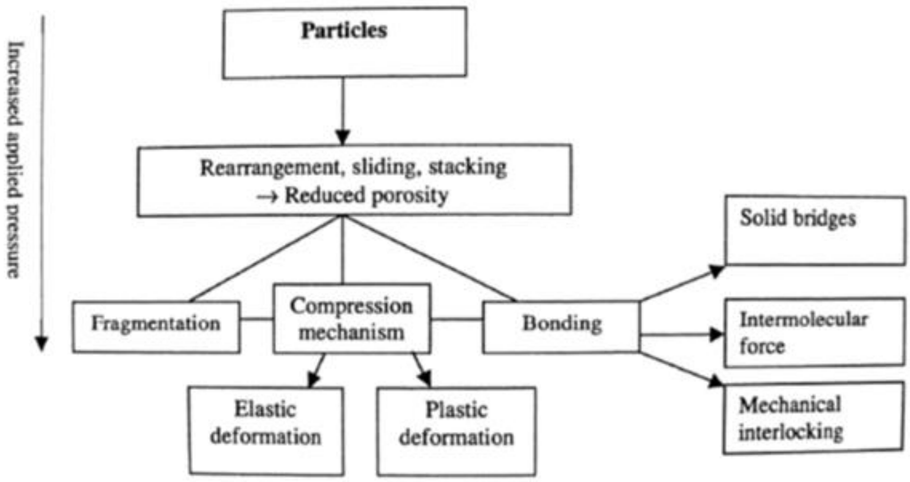

Figure 2.5 Compaction mechanism of powder particles

There are researchers that studied compaction behavior under various influence factors. Compression model is depended on nature of material. Most models are in form of empirical equation.

Empirical model is constructed from experimental result by statistical. It can be used for explaination of the relation of parameters in the experiment (Nalladurai & R. Vance, 2008). Various parameters due to experiments are concerned in the compression model. For example, model of Spencer - Heckel (Tumuluru, T. Wright, L.Kenney, & Hess, June, 2010; **ÇOMOĞLU**, 2007) was related with the density and pressure of compaction. Cooper - Eaton (Tumuluru et al., June, 2010; **ÇOMOĞLU**, 2007) and Kawakita – Ludde (Kawakita & Lüdde, 1971) studied compression model in term of volume and pressure. Model of Walker (2010) was the compression model for powder material.

The limits of empirical models are: (1) one equation cannot completely explain the compression behavior, (2) the effect of wall friction may not be included, (3) it cannot explain compression mechanism, (4) it cannot completely explain the material behaviors including elasticity or plasticity or visco-elastic, (5) it cannot predict the behavior (i.e. computer simulation) of stress and density of compaction.

2.7.1 Panelli model (2001)

Panelli used empirical model to find the relation of density (ρ) and compression pressure (P). This model consists of two constant A and B which are used to explain plastic deformation and relation of the briquette's density. The model is shown as equation (3)

$$\ln\left(\frac{1}{(1-\rho)}\right) = A\sqrt{P} + B \tag{3}$$

2.7.2 Spencer and Heckel model (**ÇOMOĞLU**, 2007), (Tumuluru et al., June, 2010)

Model of Spencer and Heckel is used for finding the density in term of compression ratio. The equation is shown as equation (4)

$$\ln\frac{1}{1-\rho_f} = mP + b \tag{4}$$

where $b = \ln\left(\frac{1}{1-\rho_f}\right)$ and $\rho_f = \frac{\rho}{\rho_1 x_1 + \rho_2 x_2}$

The constant b is related to relative density which is from the rearrangement of particles (ρ_f), and m is the average of pressure reverse which is used for elastic deformation.

2.7.3 Model Kawakita-Ludde (1971)

Model of Kawakita represents the relation of pressure as in equation (5).

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \qquad (5)$$

Where $C = \frac{V_0 - V}{V_0}$

C is the volume decreasing, V_0 is the initial volume, V is the net volume of power under pressure P, and a, b are the constant of powder characteristic which can be determined from the linear relation of $\frac{P}{C}$ and P.

The constant a is acted as the initial porosity of sample, and $\frac{1}{b}$ is relation of the stress of fracture in case of piston compression.

2.7.4 Model of Cooper-Eaton Model (**ÇOMOĞLU**, 2007),(Tumuluru et al., June, 2010)

Cooper-Eaton assumed 2 processes for completely compression, which are (1) gap filling which has the size as same as particle size and (2) gap filling which has the size less than particle size. The equation is shown as equation (6)

$$\frac{V_0 - V}{V_0 - V_s} = a_1 e^{-\frac{k_1}{P}} + a_2 e^{-\frac{k_2}{P}} \qquad (6)$$

Where, V_0= compression volume at P_0, m^3 ; a_1 , a_2 , k_1, and k_2 are model constant of Cooper-Eaton

2.7.5 Model of Sonnergaard (equation of Log-Exp) (ÇOMOĞLU, 2007),(Tumuluru et al., June, 2010)

Sonnergaard offered equation of log-exp which is use to consider the combination of two processes. These processes are: (1) volume decreasing due to fragmentation in term of logarithm equation, and (2) plastic

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deformation of powder in term of exponential equation. The equation is shown as equation (7).

$$V = V_1 - w \log P + V_0 \exp\left(-\frac{P}{P_m}\right) \tag{7}$$

Where , V_1 is volume at the pressure of 1 MPa (m^3)

P_m is average pressure (MPa), and

W is constant

Sonnergaard explained that this model gave the regression value better than model of Cooper-Eaton and Kawakita-Ludde. This model is suitable for medium pressure state (about 50 MPa).

2.7.6 Model of Walker (Tumuluru et al., June, 2010)

Walker developed model from experiment result of powder compression. Volume ratio calculation (V_R) is defined in term of pressure equation (P)

$$V_R = m \ln P + b \qquad \text{and} \qquad V_R = \frac{V}{V_s} \tag{8}$$

where P is pressure applied (MPa) ,V_R = volume ratio ,

V is volume at pressure P , m^3, and

V_s is gap between solid particle, m^3

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2.7.7 Model of Sharpiro (Adapa et al., 2009)

Model of Sharpiro can be used only for one and two state of compression process. It was not suitable for the studying of agriculture biomass compression behavior at high pressure. Model of Sharpiro is shown as equation (9).

$$\ln E = \ln E_0 - kP - bP^{0.5} \tag{9}$$

Which E_0 is the initial porosity, and

k and b are the constant of Sharpiro

2.7.8 Model of Jones (Adapa et al., 2009)

Jones represents the relation of density and pressure for metal powder as equation (10)

$$\ln \rho = m \ln P + b \qquad (10)$$

Where ρ is the specific volume of mixed powder briquette (kg/m^3), and m and b is constant

2.8. Constitutive Model

Constitutive model is the equation which explain the behavior of material deformation under reaction forces. It is shown in term of stress, strain, temperature and strain rate relation. Constitutive model is important for engineering because, it can estimate mechanic behavior of materials.

Finite Element Method (FEM) is widely used for compression model simulation. It can be used to explain the material behavior in form of stress and strain, stress and density of powder material, finite element simulation of powder material compressive which involve to equilibrium equation, compact equation, and constitutive equation and so on. Constitutive equation of the compression model must be integrated into finite element software in order to simulates the compression behavior compare with experiment.

Constitutive model for densified material should be based on fluid principle and rheological model. Behavior of material is the combination of elastic, plastic or viscous. Fluid model and rheological model can be used to predict the behavior of materials in term of stress, strain and time of compaction. The three type behaviors of material can be defined in term of spring (elastic solid) as shown as Figure 2.6, dashpot element (viscous fluid) and friction element. Typical models are Maxwell viscoelastic fluid (the series of spring element and dashpot element model) as shown Figure 2.6, and Kelvin-Voigt viscoelastic solid (the parallel of spring element and dashpot element) as shown Figure 2.6. These model can be described creep behavior which is shape deforming during the constant force applied. It is the function of time.

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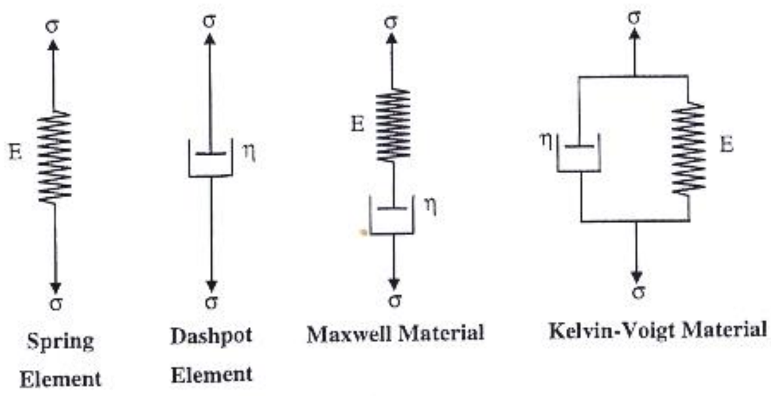

Fig. 2.6 mechanical elements which used to describe stress-strain of material. There are spring element, dashpot element, Maxwell model and Kelvin-Voigt model.

Kaliyan (2008) studied for constitutive model of corn stover and switchgrass grinds compaction in the relation of elasto-visco-plastic. There are five parameters which are elastic modulus, strength coefficient, strain hardening exponent, viscous coefficient and friction loss factor. This constitutive model is in term of total stress which are divided in three parts: (1) the elastic deformation and plastic deformation (spring element) $\sigma = E\varepsilon + R\varepsilon^n$, (2) the viscous dissipation (dashpot element) $\sigma = \eta\frac{d\varepsilon}{dt}$ and (3) the friction loss (Coulomb friction element) $\sigma = \sigma_f$. The constitutive model (total stress term) is: $\sigma = E\varepsilon + R\varepsilon^n + \eta\frac{d\varepsilon}{dt} + \sigma_f$. Where σ is stress, ε is strain, E is elastic modulus, R is strength coefficient, n is exponential of strain (strain hardening exponent), η is viscous coefficient, $\frac{d\varepsilon}{dt}$ is natural strain rate, and σ_f is Coulomb friction.

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Peleg (1983) studied the mechanical compaction behavior, creep, stress relaxation and material expansion of vegetables, fruits, cardboard and plastic foam. The constitutive model is divided into three parts (1) The model of elastic and plastic deformation (spring element), $s = Ee + Re^n$; (2) the model viscous flow (dashpot element), $s = h\frac{de}{dt}$ and (3) the model of friction loss (Coulomb friction element), $s = s_f$. The total stress is $s = Ee + Re^n + h\frac{de}{dt} + s_f$. Where, s is stress, e is strain, E is elastic modulus, R is strength coefficient, n is exponential of strain (strain hardening exponent), h is viscous coefficient, $\frac{de}{dt}$ is natural strain rate, and s_f is Coulomb friction.

Suched (2008) studied the constitutive model of stress and strain behavior prediction for asphaltic concrete under the response rate, stress and temperature changes. The model is base on the principle of visco-elastic behavior as follow.

$$\varepsilon^R = \frac{R}{E_R}\left\{E_\alpha t + E\rho\left[\frac{\left(1+\frac{t}{\rho}\right)^{1-m}-1}{1-m}\right]\right\}$$

It is the relation in term of stress and strain. Where, E_R is long term modulus, E is elastic modulus, E_R is initial modulus, ρ is relaxation time, m is constant, and t is time. The research found that, the model can predict compression result under high stress level.

2.9. Energy consumption for compaction

Energy consumption is depended on pressure, heating, moisture content, physical characteristic, compaction method, size of densified product, compaction device, and chemical composition of material including starch, protein, fat and fiber (Jumuluru et al., 2010; Tumuluru et al., 2011). Several research studied for energy consumption of production or all process of densified product.

Worapan M. (2011) determined the energy consumption of pellet fuel (RDF-5) production. Material of RDF-5 is mixed of plastic, paper and wood with binding agent as lime and starch. The energy consumption is started from waste collection, cutting/grinding/milling, mixing and compaction. The research found that con1 ton of RDF-5 use for 418.4 Wh of energy consumption and diesel oil 2.12 litres.

Lobe G.T. (1996) studied the energy consumption of alfalfa grass pelletization. The result found that size of pellet and compressive velocity affect to energy consumption. Durability also depends on energy consumption. Model of energy consumption is in form of a polynomial equation which is as $D = -1469 + 94.85E - 1.45E^2$. Where, D is a percentage of pellet durability and E is energy consumption of compaction

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(kWh/t). The research also found the increasing of mold velocity can reduce energy consumption. Small size of material also reduce energy consumption.

Mani S. (Sudhagar Mani, 2005; Sudhagar Mani, Tabil, & Sokhansanj, 2006b) studied the energy using of corn stover densification. Corn stover is chopped into small piece before densification process at the pressure of 5-15 MPa and moisture content of 5-15%. More pressure of densification led to more energy consumption at 12-30 MJ/t. High of moisture content give less energy consumption. The model of energy is as $E = 4.76 + 1.48P - 0.19M + 0.032PM$. Where, E is the energy using of the densification process (MJ/t), P is the pressure of densification (MPa) and M is moisture content of material. All of these variable has the relation in form of linear equation.

Stahl M. (2011) studied the energy consumption of sawdust and rapeseed pellet production. The research found that energy consumption is depended on type of material and temperature of mold. This paper found that high moisture content of material led to high of mold temperature and high of energy consumption. The model of energy consumption is $Q = P/\dot{m}_{DS}$. Where, Q is average energy (kJ/kg), P is average power (kW) and $\dot{m}_{DS}$ is mass flow rate of material (kg/s).

2.10 Situation of RDF in Thailand

In Thailand, RDF technology is on-going research. There are cement kiln industries such as Thai Cement Company, Siam City Cement Public Company Limited and TPI Polene Public Company Limited using this technology for their production. They use fluff RDF or RDF3 in combustion process for thermal production to produce electricity and cement production. While dust RDF or RDF4 is in powder form which is added in the cement kiln to mixed with cement dust (Chanasongkram, 2010). Pisanulok has the project of power production from RDF5 for 200 homes, 100-200 KW on 2553 with Wongpanit Limited and Kao Kaew Green Energy Limited. The technology of RDF5 production is from Australia. The wastes usages include bag plastics, foam shoes, bags, clothes, biomass and other plastic. The establishment power plant will be modeled to other communities.(Chaowaraj, Posted :26/10/2010; Wongpanit)

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