LOW CARBON LIVING CRC

Pilot study on the development of synthetic lightweight aggregates

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CONTENTS

LIST OF FIGURES

INTRODUCTION

Utilisation of Coal Combustion Product (CCP) from coal-fired power stations is of great interest in Australia. According to ADAA (Ash Development Association of Australia), in 2012, 12.8 Mt (million tonnes) of coal ash was produced from coal fired utilities in Australia [1]. Due to the increase in energy demands, the amount of coal ash continues to increase each year. This increases the pressure on coal and utility industries and associated waste management, to find solutions to the environmental problems that are associated with coal ash production.

There are two types of coal ash produced from modern pulverised fuel furnaces. The fine ash, which is recovered from the flue gas, is called fly ash (FA) which makes up to 90% of the total ash produced. The reminder consists of similar particles that have been fused together into lumps, which falls to the bottom of the furnace as furnace bottom ash (FBA). The fly ash particle sizes range from less than 1 µm to 200 µm and are irregular to spherical in shape, while the particle sizes of bottom fly ash ranges from fine to coarse aggregate-sized lumps.

According to ADAA [1], some 5.4 Mt (42%) of the coal ash produced in Australia was effectively utilised. Some 2.34 Mt was used in low value-added applications such as onsite remediation and local haul roads. On the other hand, approximately 1.9 Mt was used in high value added applications such as concrete manufacture, cementitious binders and mineral fillers. In addition, about 0.52 Mt was used in non-cementitious applications such as structural fills, flowable fills, coarse/fine aggregates, mine site remediation and road bases.

One of the good approaches to utilise CCP is to convert fly ash into aggregates as a natural aggregate replacement. The main reasons to consider this approach are: (1) the continuous increasing demands for aggregates and (2) the depletion of the natural aggregate resource. Manufacturing of economical and good quality synthetic fly ash aggregate will reduce the impact of fly ash on the environment and provide a great benefit to economy.

Most fly ashes are physically and chemically suited for production of synthetic aggregates. By using different processing methods, it is possible to produce different qualities of synthetic aggregate in terms of strength, particle shape and density. Therefore, the synthetic aggregate can be more flexible than the natural aggregate as they can be used indifferent applications.

MANUFACTURING PROCESSES OF SYNTHETIC AGGREGATE FROM FLY ASH

Introduction

The basic method of manufacturing aggregates from fly ash is to convert the fine fly ash particles into larger particles, which have good physical and mechanical properties. There are many processes to produce fly ash synthetic aggregate, including many types of agglomeration. In addition, there are several methods to bond/harden the agglomerated fly ash particles together to obtain the required aggregate properties.

The manufacture process of synthetic fly ash aggregates involves the following steps:

- mixing of fly ash and other additives
- agglomeration
- aggregate formation (hardening or binding of the fly ash particles).
- further processing if needed (crushing and screening)

A detailed flow diagram for this process is shown in Figure 1.

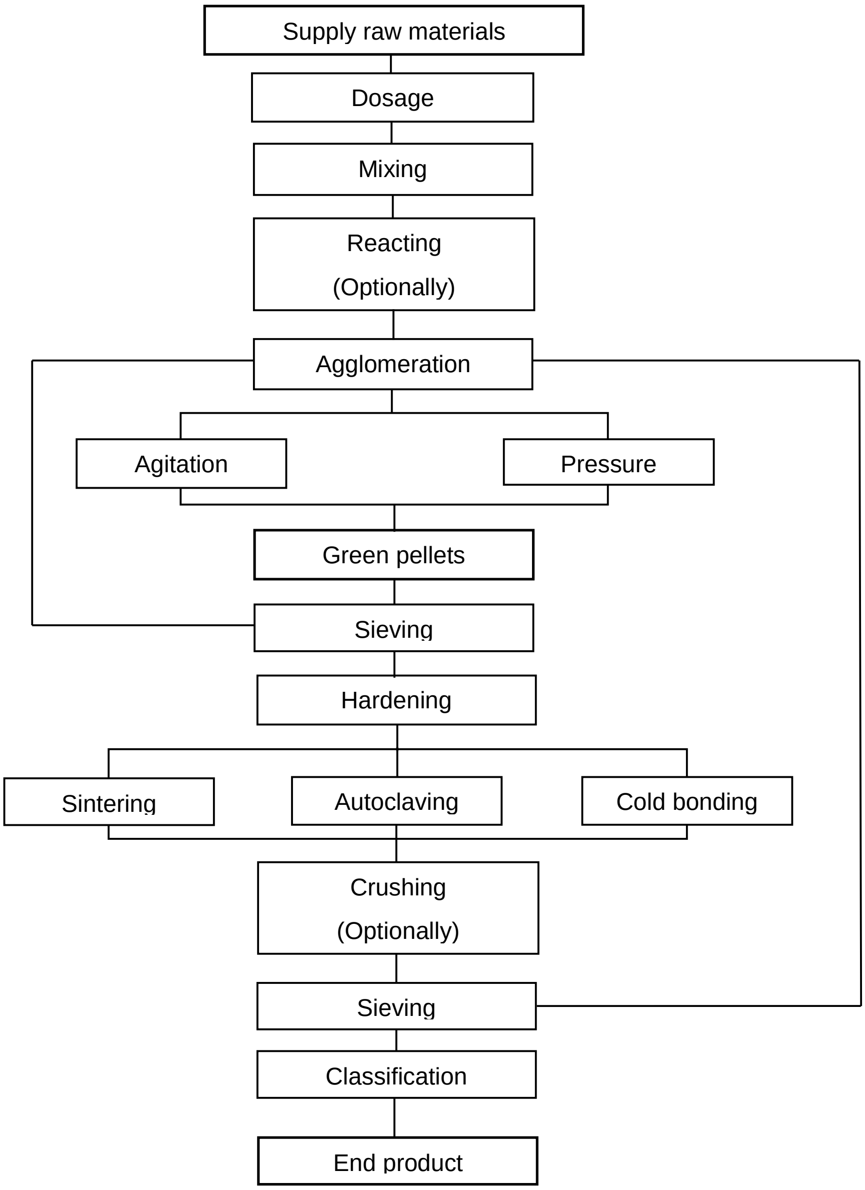


Figure 1: Process steps in synthetic fly ash aggregate manufacturing [2].

Types of Agglomeration

The main methods used to agglomerate fly ash particles can be divided into non-pressure and pressure agglomeration.

Non-pressure (tumble growth) agglomeration

The agglomeration occurs without external compacting forces except tumbling forces, and typically in the presence of a binder. The fly ash particles are balling together as a result of mechanical and capillary forces. The fly ash particles have to be wetted. Usually water is used as a wetting (bonding) agent, but also other materials like water glass, starch solution or waste water from paper mill are used. The dosage of the wetting agent is a critical factor. Too much or too little wetting agent will lead to muddy or looselypellets.

There are two phases in formation of pellets (usually balls), these are, formation of seeds, and ball growth. The seed begin to form when the fly ash particles are sprayed with a binding agent, and then the moisturized particles move closer together and become connected by water bridges. As more particles join in, and as additional moisture is fed, a seeds with capillary bonding originates [3]. The state of liquid saturation reached with increasing inter-particle forces is illustrated in Figure 2.

Ball growth is a stage in which the fly ash particles envelope the seeds; the simultaneous rotation and frequent impacts make the growing ball compact and the ball come to have a spherical shape[3].

The techniques used to granulate or pelletise fly ash can be divided into: mixer, drum, and disc granulation.

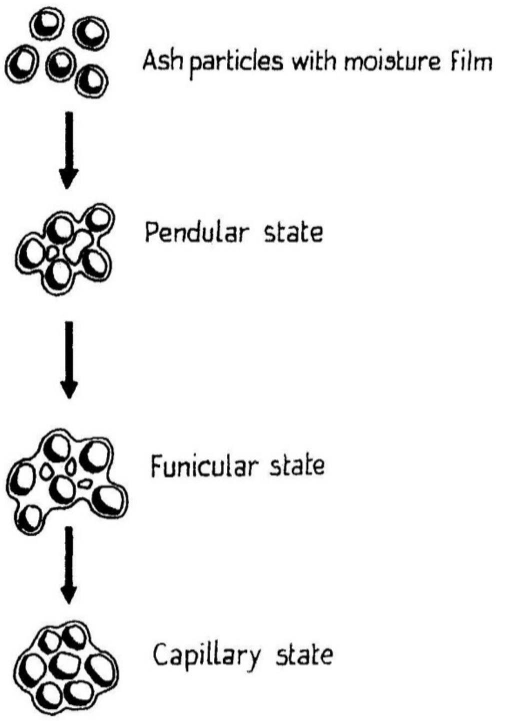


Figure 2: Mechanism of ball seed formation [4].

Pin mixer

The Pin mixer is a high-speed, conditioning and micro-pelletising device that transforms fine materials such as ashes, dusts or other fines into micro pellets using a high-speed central rotor shaft and radially extended pin assembly, with the addition of liquid binder.

The pin mixer (Figure 3) features a cylindrical shell with a replaceable inside liner and a shaft with radially extended pins. There is a small gap between the tips of the pins and the inside lining of the mixer shell. The shaft rotational speed is several hundred RPM. Pin arrangements are variable depending on processing needs.

The material enters at one end of the stationary cylindrical shell and a fine spray of liquid is added. The rotational spinning motion of the pins at high speeds provides agitation forces on the materials and liquid binder which eliminates air and reduces water volume between particles. This leads to fine mixing and densification of the materials as it move to the bottom outlet. The end product is a spherical to irregular shape wetted micro pellet.

The pin mixer is ideal for micro-pelletising, conditioning, or agglomerating fine materials, such as coal ashes, limestone fines, silica fume, pigments, or other fines. The pin mixer can be used as stand-alone agglomeration equipment, or as initial step processing equipment for material mixing and wetting (conditioning) prior to final agglomeration process using a disc or drum pelletiser [5,6].

Paddle mixer

The paddle mixer (Figure 4), also referred to as a pug mill, consists of a horizontal barrel shape trough with dual counter rotating shafts and a series of paddles fixed at a pre-determined angle on these shafts along the length of the trough. There is a small gap between the tips of the paddles and the inside walls of the mixer. The action of the paddles moves the materials from the top of the trough down each side, and then forces the materials back up between the shafts. This creates a kneading and folding over effect, which gives a high mixing efficiency. A liquid or binder may also be used for conditioning (wetting) and agglomeration applications.

The paddle mixer can be used for the following typical applications:

- Mixing of FGD (Flue Gas Desulfurization) scrubber sludge, fly ash, Lime for SO_2 neutralization, municipal sludge, pigments and dyes.
- Conditioning of fly ash, cement or lime kiln dust, foundry dust, iron-oxide, lead fume and zinc oxide.
- Agglomeration of agricultural chemicals, fertilizers, pesticides, carbon powders and flue dust [7].

Figure 3: Pin Mixer [5,6]

Figure 4: Paddle Mixer

Rotary drum agglomerator

The rotary drum agglomerator (Figure 5), also referred to as balling drum, consists of open ended rotating inclined cylinder which provide a tumbling and growth action to form spherical pellets in the presence of a liquid or binder. The process necessarily consists of screening of the balls and continuous recirculation of undersizes. The undersize balls are returned two to three times tothe drum together with the raw fines. The motion pattern of the material inside the drum is controlled by the amount of material in the drum, the speed of the drum, and the structure of the inside surface of the drum.

The dimensions of the commercial rotary drums vary depending on the output required. The drum diameter can be between 1 to 3.5 meters; the length may be between 5 to 9.5 meters and the drum can be inclined through an angle of 2-10 degrees [3].

The rotary drum pelletiser is used frequently in the high capacity production applications such as iron ore pelletizing. Other typical applications of a rotary drum include:

- Agglomeration involving chemical reactions where the feed components consist of liquids or gases, such as in the production of inorganic fertilizers. The liquid and/or gas can be added into the bed of material to get a complete reaction and contain or reduce any emissions that may be generated.
- Heap leaching operations for the conversion of fine mineral ores (such as iron ore, copper ore, silver ore, uranium ore and gold ore) into easy to handle agglomerates or balls for further processing.
- Granulation where the only feed or the majority of the feed is a liquid or melt such as urea granulation.
- Coating of finished products by spraying a liquid onto the bed of the material.
- Mixing of multiple solids and/or liquids [8].

Figure 5: FEECO rotary drum agglomerator

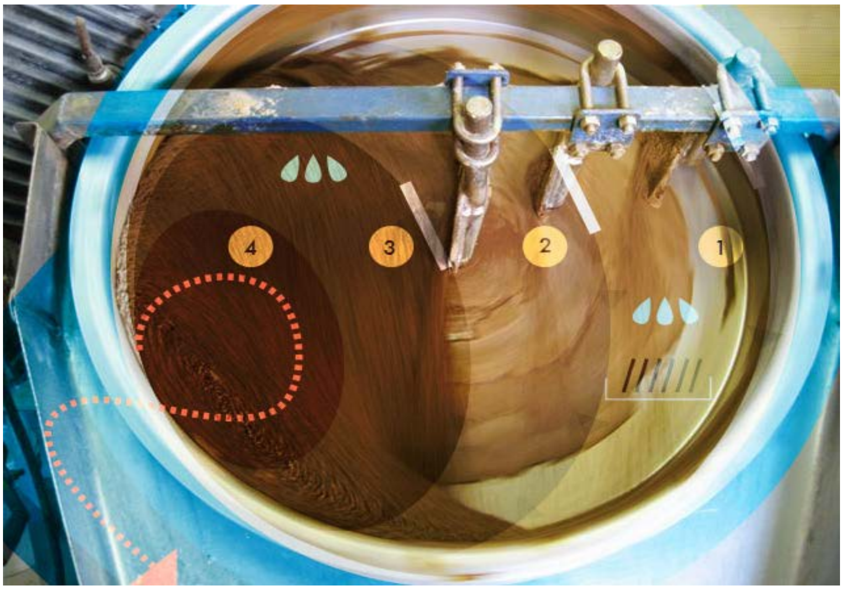
Disc pelletiser

The disc pelletiser (also known as pan pelletiser) consists of a rotating inclined disc driven by gear reducer, scraper frame with scrapers and binder spray system which are supported on a heavy structural frame and base. The discangle and rotational speed are adjustable to control pellet size and to suit various pelletising conditions and applications.

The disc pelletiser(Figure 6) provides a tumbling and growth action to form spherical or spheroidal pellets in the presence of a liquid or binder. The material is fed onto the disc, where it is taken up by the rotation of the disc. Droplets of moisture will collect several particles, and the rotation will impact and densify this loosely formed nuclei or seed. This densification forces water to the surface, where it can pick up more particles.

Centrifugal force causes the pellets to self-classify themselves based upon size. This can be seen in Figure 7, where the first stream of seed or nuclei is on the right, and as you move from right to left, the pellets grow. The pellets remain on the disc until they reach the absolute left side, where they have reached desired size, and are discharged from the disc. The scrapers remove any build-up that occur on the disc bottom and side wall and create a smooth surface. The scrapers also help direct the pellets into their separate streams [9].

Figure 6: FEECO disc pelletiser



1. **First Stream – Seed (or nuclei)**
2. **Second Stream –Growing pellets**
3. **Third Stream – Pellets**
4. **Pellets ready to exit disc**

Figure 7: A diagram overlayed on this actual running palletiser shows how the principles apply to the real-life operation of a palletiser.

Source: (FEECO International)

The disc pelletiser can be used as a stand-alone device for pelletising fly ash using binder and/or other materials. Disc pelletiser can agglomerate fine, dry feed materials such as chemical powders, limestone, fertilizer, coal fines, cement or lime kiln dust and fly ash.

Choice of non-pressure agglomeration techniques

When it comes to agglomerating a material, people are often faced with the decision of choosing the right agglomeration equipment for that material. There are many factors to take into account that will help you make the right decision for agglomeration of your material. Some of these factors are:

- Agglomeration equipment capabilities.
- Properties and the amount of the feed material.
- Properties of binder.
- Requirements for final product quality, moisture content, size and shape.
- Energy consumption.
- Production environment.
- Production rates requirements.

In this research, the main goal is to make synthetic aggregates from fly ash with sizes ranges from 1 to 5mm for fine aggregate and from 5 to 25 mm for coarse aggregate.

The pin mixer can be used as a stand-alone agglomeration equipment to produce fly ash spherical micro-pellets that offer improved, dust-free handling and transportation, but is not capable of producing the above required aggregate sizes. Instead, the pin mixer can be used as initial step processing equipment for conditioning fly ash prior to final agglomeration process using a disc or drum pelletiser.

As mentioned above, the paddle mixer can be used to agglomerate fertilizers, pesticides, manure and agricultural chemicals, but it cannot be used as a stand-alone device to agglomerate fly ash. It can be used as a stand-alone device for mixing fly ash with binder and/or other materials, or to de-dust the fly ash by conditioning. Similar to the pin mixer, paddle mixer can serve as the front end to fly ash agglomeration process. In this process, fly ash is conditioned then moved to the discor drum pelletiser for further processing.

In this research, trials to make a synthetic fly ash aggregates with a minimum cost will be considered. One of the steps to achieve cheaper fly ash aggregate is to use one type of agglomeration equipment. This step will reduce the energy consumption, simplify the production line design and reduce the footprint of the manufacturing plant. For this reason, both the pin mixer and the paddle mixer will notbe used in this research as it cannot be served as stand-alone agglomeration devices.

There are many differences between adisc pelletiser and a rotary drum agglomeration. Firstly, a disc pelletiser results in far lower recycle than a rotary drum does. This is ideal in situations where the material goes from a pelletiser to a dryer, because the less recycle that has to be dried, the more economical the manufacturing process will be. Secondly, in a disc pelletiser, it is easy to customise and fine-tune the product (size and quality of the pellet) by adjusting disc speed, disc angle, feed location and binder location, while it is hard to control pellet size in a rotary drum. Thirdly, in terms of maintenance, disc pelletiser requires less maintenance than a rotary drum. With disc pelletiser there are few parts to be replaced, usually only scrapers and spray nozzles, while there are many parts of a rotary drum that require regular maintenance and replacement.For these reasons, the choice of non-pressure agglomeration is the disc pelletiser.

Pressure or compacting agglomeration

In this type of agglomeration fly ash particles are formed into shapes. The density of the fly ash products will be higher than that of products produced with non-pressure agglomeration techniques.The dosage of the wetting agent has to be accurately adjusted to avoid squeezing of the pellets. The techniquesused in compaction agglomeration can be divided into: extrusion, pellet mills, roll pressing and Punch-and-Die presses (Unidirectional piston type compaction).

Extrusion press agglomeration

During extrusion process, a material or a mix of materials is forced through a customized metal tool called a die, which causes the material to take a specific shape needed for the product. The final product, which called the extrudate, is material that has a fixed profile and can be cut or processed to create a final product. There are different types of extrusion press, mainly the screw extruder and ram extrusion press.

Screw extruder:

In this machine, the movement of the material(s) is/are caused by the flights of the rotating screw(s) in tightly fitting barrel-shaped housing which produce the necessary pressure to overcome the friction in open-ended die plate that seals the end of the barrel (Figure 8) [10].

Ram extrusion press:

The principle of the ram extrusion press is shown in Figure 9. A common feature is the horizontal extrusion channel which first converges somewhat to allow the development of sufficient pressure in the mass for initial bonding. The reciprocating punch presses materials against briquettes which were formed during previous strokes and remain wedged in the channel. During each stroke, fresh materials as well as all the other briquettes in the channel are compressed until the axial force becomes high enough to overcome the wall friction and potential back pressure acting at the mouth of the channel. When this happens, shortly before the end of the each stroke, the entire column of briquetted material moves forward and a briquette emerges at the discharge end of the machine [10].

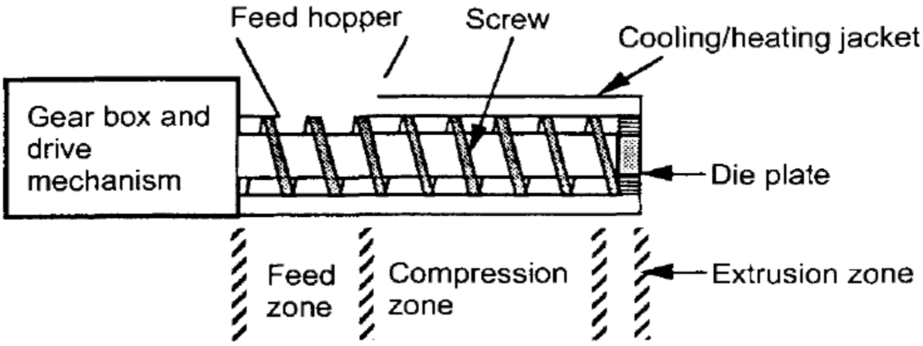


Figure 8: Schematic cross section through a screw extruder [10].

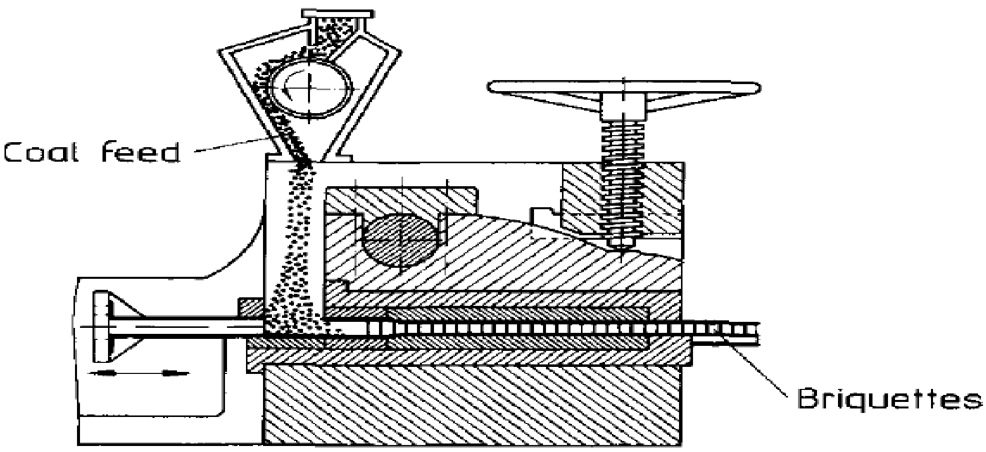


Figure 9: Schematic representation of ram extrusion press [10].

Pellet mills

Pellet mill is another device used for agglomeration of fly ash. In this process the materials are forced through open die to form pellets or briquettes of a cylindrical shape with fixed diameter and variable length. There are different types of pellet mill, mainly the ring die pelleting mill and flat die pellet mill. Generally, flat die pellet mills are used for small scale pellet production and ring die pellet mills are used for large scale pellet production.

Flat die pellet mill:

In this machine (Figure 10), the raw materials are fed to the press from above and it drop down by its own weight into the pelletising chamber and form a layer on the die. The pan grinder rollers run over this layer and compact it (Figure 11a& b).The pressure is continuously increasing whilst the material is being rolled towards the effective holes, thereby pushing the product in the holes slightly forward.

The rollers pass over each hole several times per second and the individual layers of material forced into the holes of the die forms an endless strand which is cut to the desired length from below using adjustable knives. Die diameter, free perforated surface, track width, diameter, width, and number of rollers can be varied according to the pelleting characteristics of the material to be pelletised [11].

Ring die pellet mill:

In ring die pellet mill (Figure 12), comprises of a rotating vertical ring die with stationary rollers on the inside. It is common that the feeding system includes a conditioner, in which material(s) is/are mixed with binderto the required moisture condition.The conditioned material(s) is/are fed into the door of the pellet mill, then a screw auger feed(s) the materials into the operating area of the mill (die area).In most ring die pellet mills, an adjustable plows are located between the press rollers, which divide the advancing feed into equal parts and direct it evenly in front of each press roller (Figure 13) [10]. Friction drive rolls compress the material through holes in the die as the die rotates to form pellets.

The pellets are cut as they extruded from the die using knives mounted on the swing cover. The pellet fall and discharged through an opening in the swing door.Figure 14 illustrates the design and operating principles of ring die pellet mill.

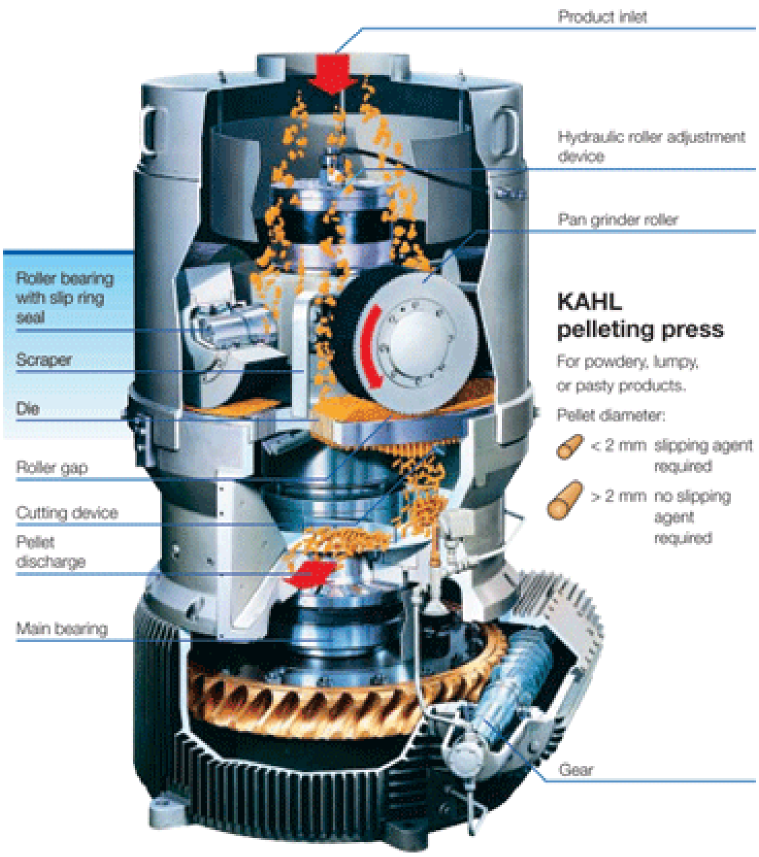


Figure 10: Main parts of the flat die pellet mill

Courtesy AmandusKahl, Germany

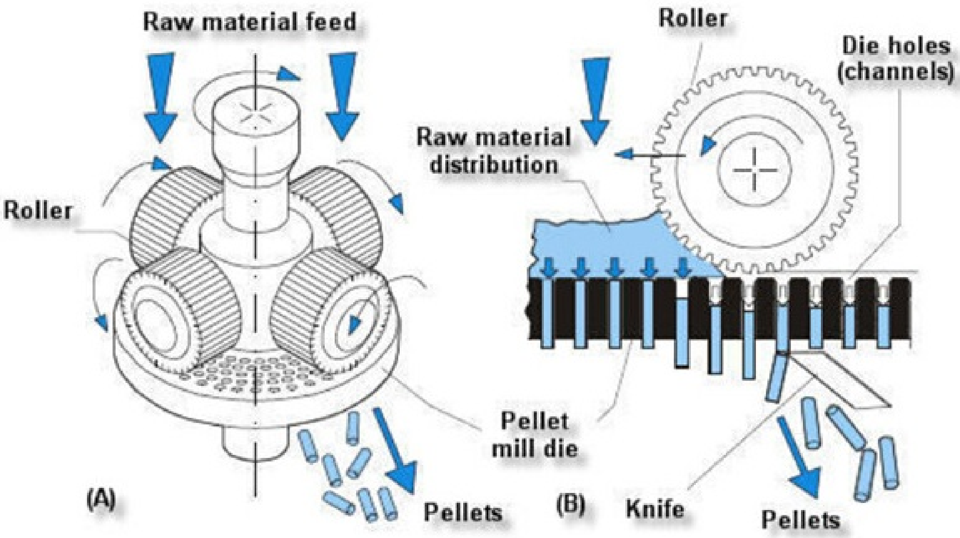


Figure 11: Design and operating principles of flat die pellet mill [12].

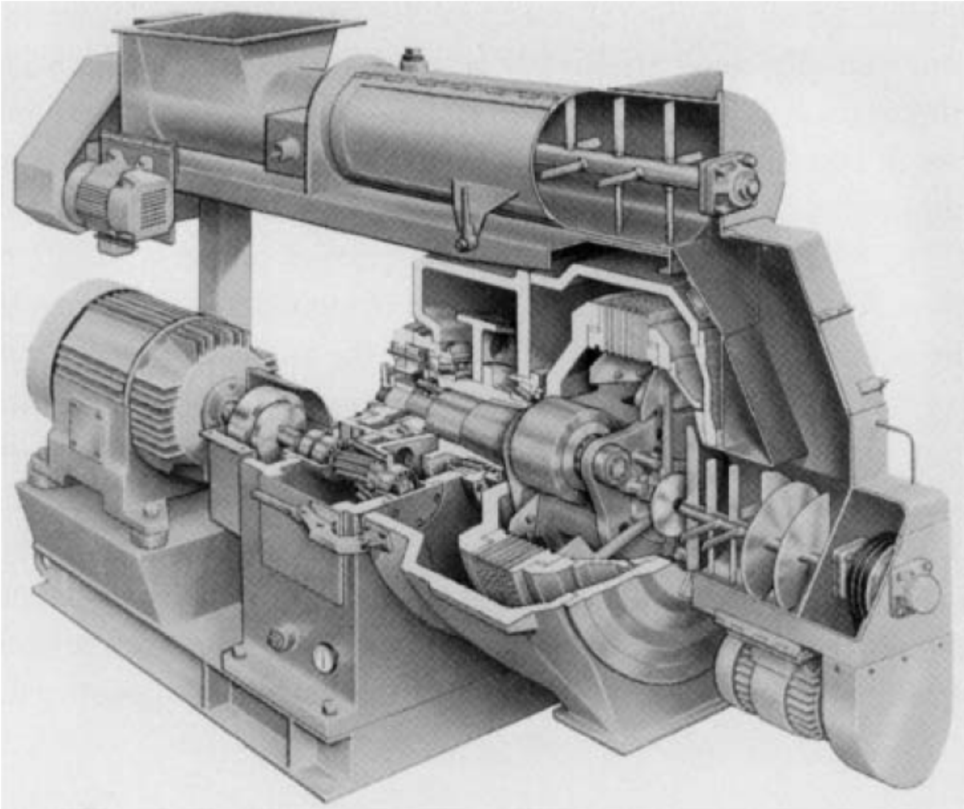


Figure 12: Partial cut through a directly gear driven ring die pellet mill

Courtesy Spout-Matador, USA [10]

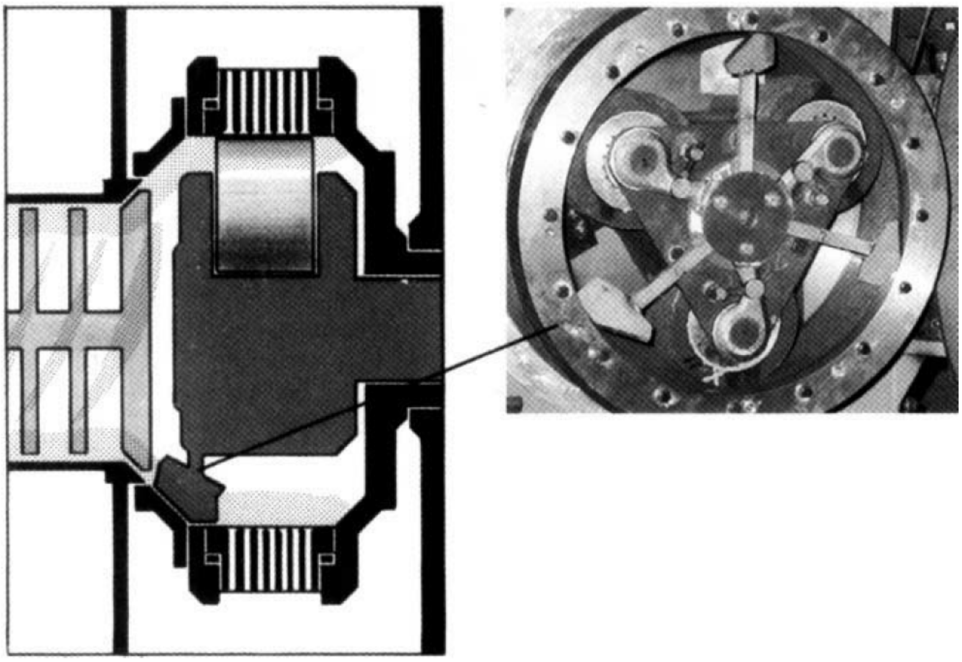


Figure 13: Schematic and photograph of a “Centri-Feeder” distributor

Courtesy Spout-Matador, USA [10]

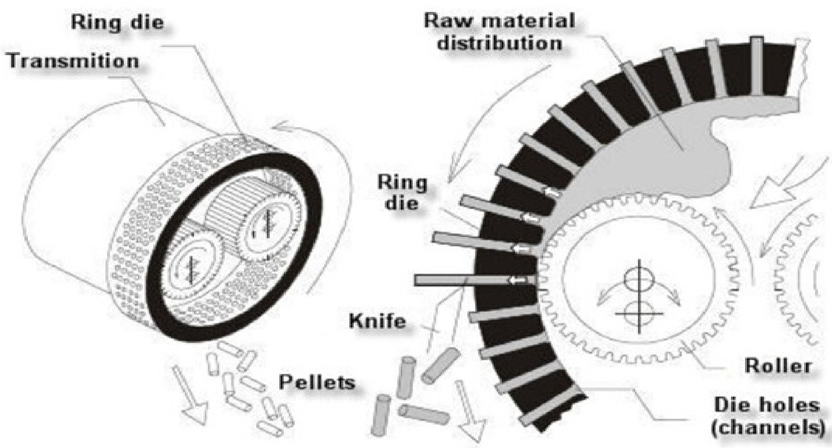


Figure 14: Design and operating principles of ring die pellet mill [12].

Roll presses

Roll pressing is of greatest interest for industries in which large amount of finely divided solids must be converted into larger agglomerated pieces. Roll presses feature two rolls of equal size which rotate countercurrently at equal speed and achieve compaction by squeezing the feed in the nip (gap) area.

If the rolls are smooth, fluted, waffled or corrugated the material is compacted into dense sheets (Figures 15, 17b). The compacted product can remain in sheet form or can be granulated into the desired particle size on size reduction machine.

If the two rollers carry rows of identical pockets and the rolls are timed such that the pockets match exactly, then briquettes are produced. Design of these pockets based on practical experience is important to ensure optimum briquette density, minimum fines production, and dependable briquettes release (Figures 16, 17a).

Most materials can be agglomerated by this technique with the aid of binders, heat and/or very high pressures if needed. The method generally requires less binder, and therefore there is little or no need for drying the agglomerates. This method of size enlargement is applied for a large number of materials in the chemical, pharmaceutical, food processing, mining, metallurgical and minerals industries [10, 13].

Figure 18 is photographs showing details of large briquetting machine for the briquetting of coal.

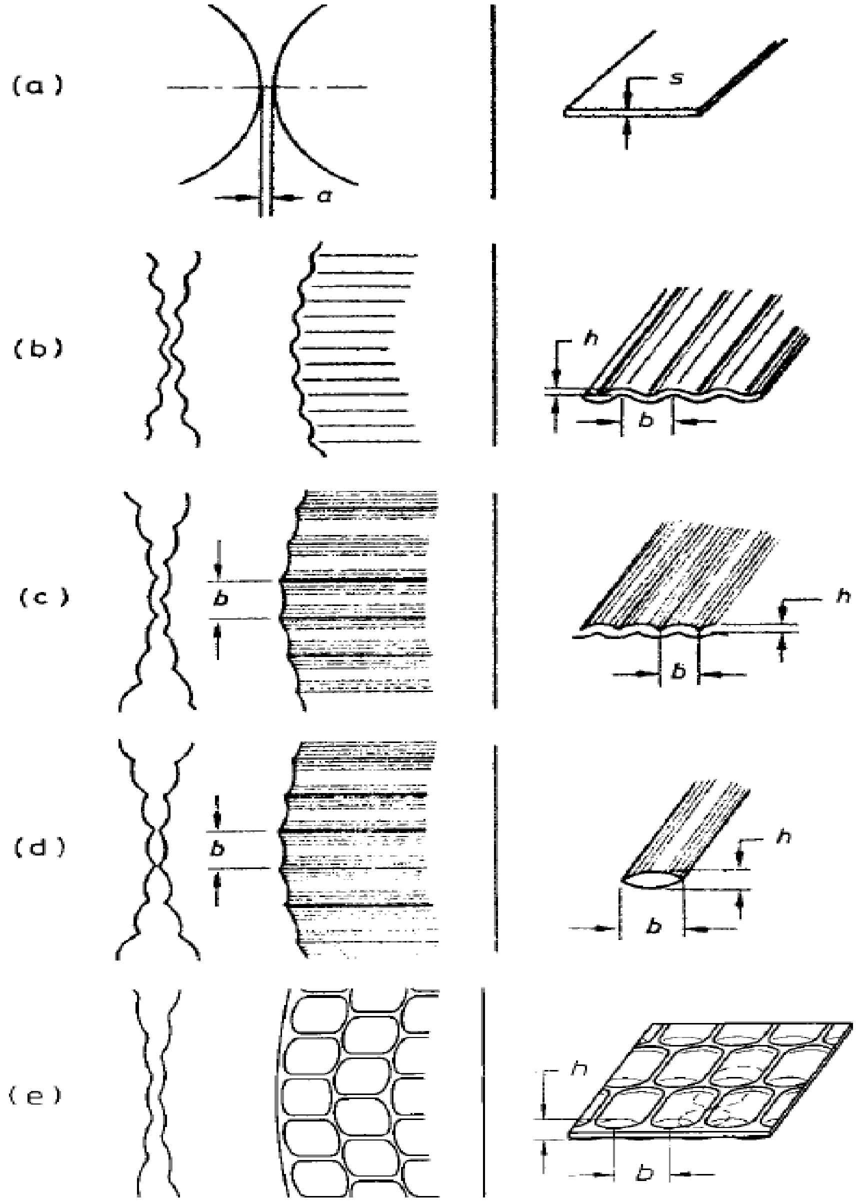


Figure 15: Sketches showing different roller surface configurations for compaction and corresponding products. (a) Smooth, (b) corrugated, (c) fluted offset, (d) fluted peak-to-peak, (e) waffled [10].

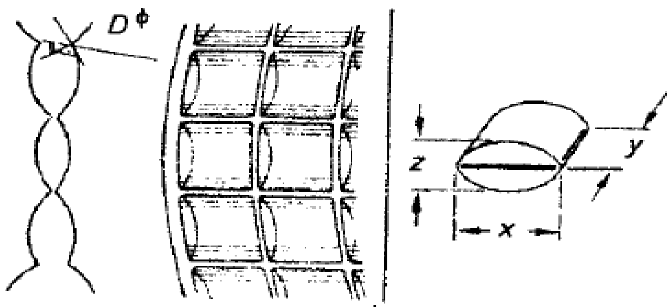


Figure 16: Sketch depicting a typical pillow pocket and briquette shape [10].

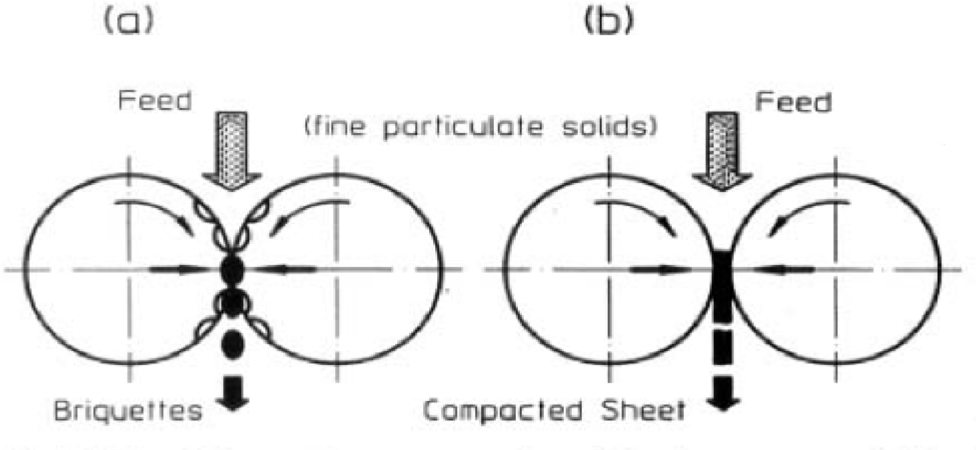


Figure 17: Schematic representation of roller presses. (a) Pressure agglomeration/briquetting, (b) pressure agglomeration/compacting [10].

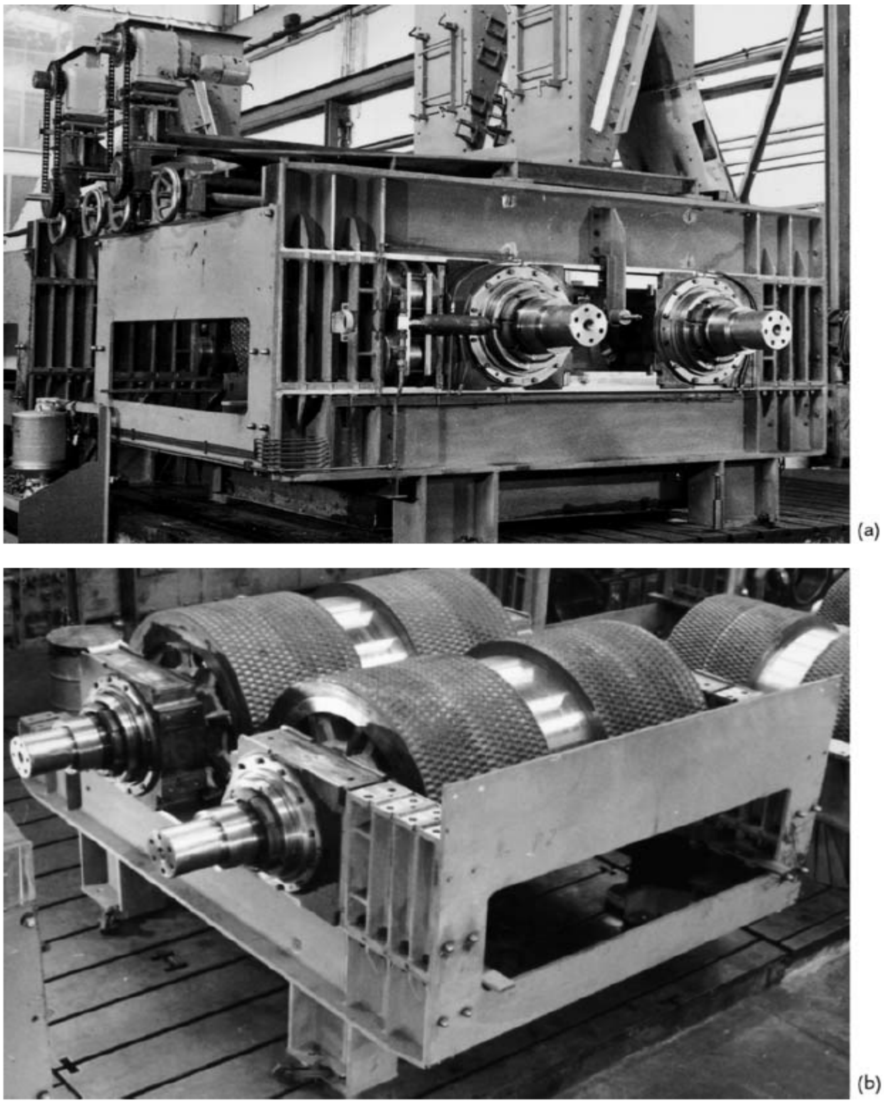


Figure 18: (a) Large briquetting machine for the briquetting of coal, (b) partially assembled roller press showing the two sets of rings (courtesy Koppern, Halting/Ruhr, Germany)[14].

Punch-and-Die presses (Unidirectional piston type compaction)

Punch-and-die presses for the compaction of materials are the oldest pressure agglomeration machines. The densification of powders in a totally confined volume is a well-defined process and the products resulting from such compaction feature excellent uniformity in size, shape, and density.

The techniques used in this type of agglomeration may be classified by references to the movement of the individual tool elements (lower punch, upper punch and die) relative to one another. Compaction within fixed dies can be divided into single action pressing and double action pressing. In single action pressing the lower punch and the die are both fixed. The compaction operation is carried out by the upper punch as it moves into the fixed die. In the double action pressing only the die is fixed in the press. Upper and lower punches move simultaneously from above and below into the die (Figure 19).

The agglomeration process in punch-and-die press can be sequenced as follows: Firstly, the die cavities fill with required amount of material to be compacted. Secondly, the upper punch with or without the lower punch (depending on the type of pressing required to achieve green density and thickness) moves to compress the material. Thirdly, the punches move back from the compact. Finally, the compact ejects form the die [15].

Some of the common shapes of the products from punch-and-die presses are solid and perforated cylinder, rectangular or cubic pieces, and structured shapes (Figure20).

Punch-and-die presses are of two types, mechanical and hydraulic, there are other partly hydraulic and partly mechanical called hybrid punch-and-die presses. Figure 21 shows a typical large punch-and-die hydraulic press for the manufacturing of refractory brick.

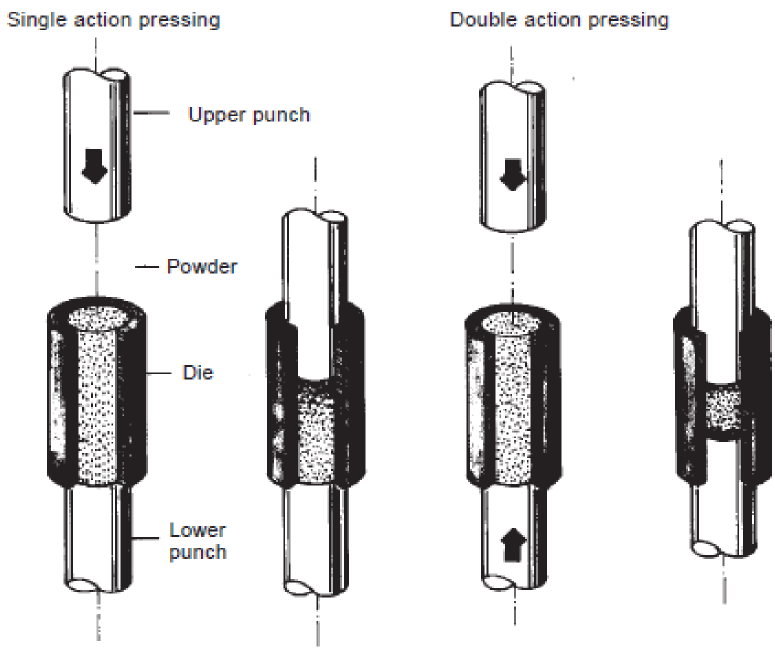


Figure 19: Single and double action pressing [15].

(a)

(b)

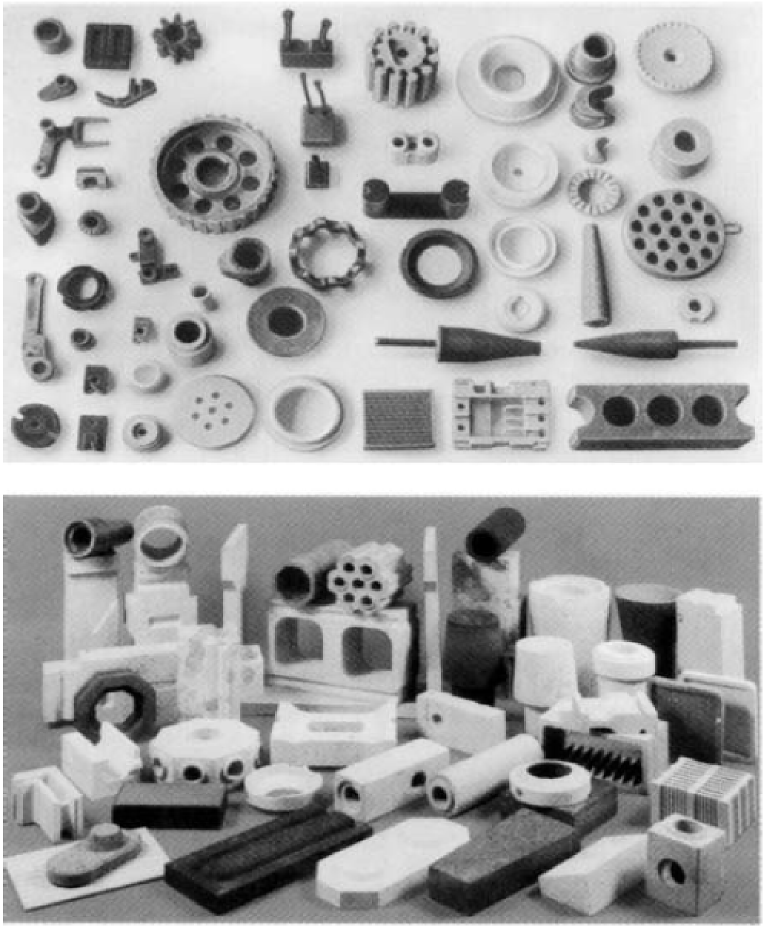


Figure 20: (a) Some parts made from metal powders, metal oxides, ferrites, ceramic materials abrasives, and other materials in punch-and-die presses; (b) A selection of different products made with punch-and-die hydraulic presses [10].

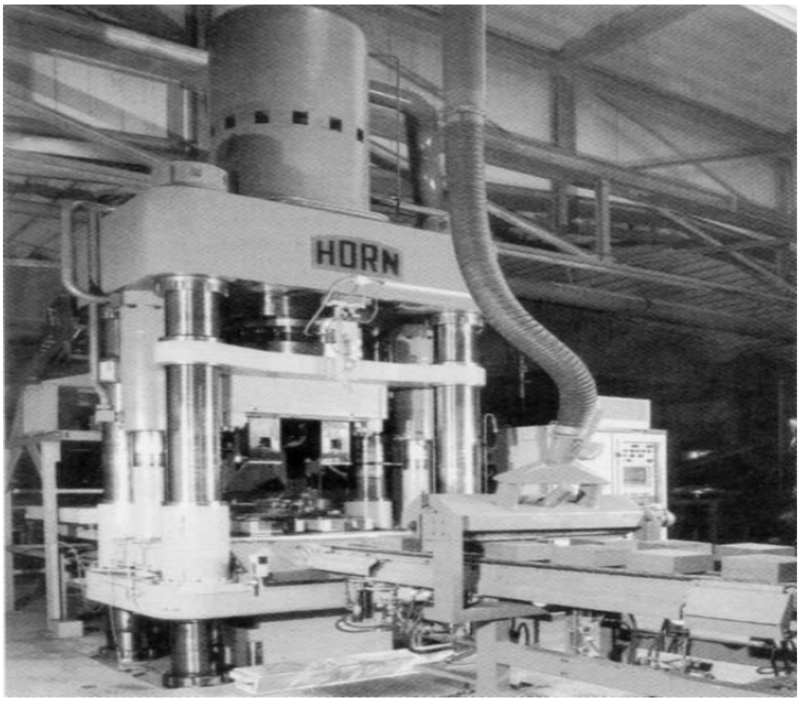


Figure 21: A typical hydraulic press for the manufacturing of refractory brick [10].

Types of Hardening or strengthening of fly ash agglomerates

In general the green pellets or briquettes formed by agglomeration process of fly ash particles are weak. Therefore the pellets have to go through a strengthening process in order to be considered for use as aggregates.

There are three main processes for the hardening of fly ash agglomerates. They are sintering (firing), cementitious binding (hydrothermal) and geopolymerisation (cold bonding).

Sintering process

Sintering is a heat treatment applied to fly ash pellets in order to provide strength and soundness. The temperature used for sintering should be below the melting point of the major component of the fly ash material.

After agglomeration, adjacent fly ash particles are held together by cold welds, which give the green pellet sufficient strength to be handled. At sintering temperature, the materials of the separate fly ash particles diffuse to the adjacent fly ash particles. Bonding that occurs during sintering greatly strengthens the pellets.

There are three steps in the sintering process, namely drying, preheating (pre-sintering), and sintering. The drying process has to be carried out very slowly in order to evaporate all moisture from the green pellets to avoid cracking. The second step is the preheating. This step is aimed to further evaporate volatile materials and oxidise all unburnt carbon and provide the burning of any additives. Preheating is also start to strengthen bonds between fly ash particles within the pellet, increasing its integrity for the next step. The final step in the process is sintering. In this step, fly ash particles within the pellet are fused on their mutual contacts and the pellet strength grows following the growth of the mutual contacts. The strength of the pellet will be higher when more contacts are fused.

Figure 22 illustrates particles bonding formation in sintering process. The initial stage of the particle bonding occurs as small necks form between the particles. Through diffusion and other mass transport mechanisms, material from the particles is carried to the necks, allowing them to grow as the particle bonding enters the intermediate stage when the pores between particles begin to round. As the mass transport continues, the pores will become even more rounded and some will appear to be isolated away from the grain boundaries of the particles. This is referred to as the final stage of bonding [16].

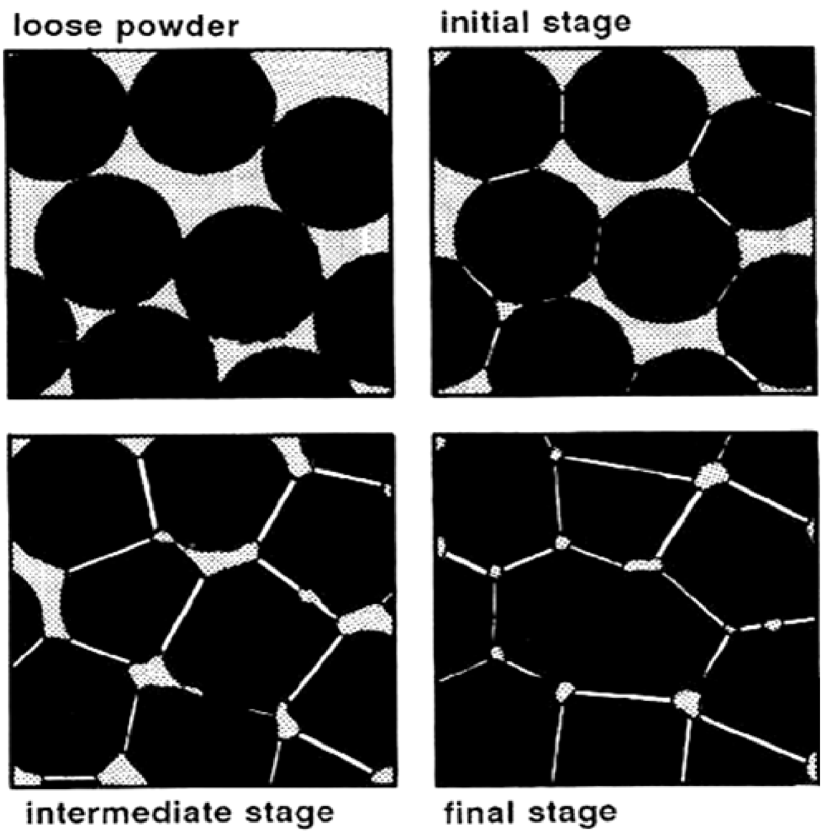


Figure 22: Particles bonding formation in sintering process [17].

Lytag aggregate

Lytag is a lightweight aggregate made from fly ash. It is manufactured within the European Union in accordance with EN 13055 (the standard for lightweight aggregates). Laytag Ltd has been supplying Laytag lightweight aggregate for around 50 years and has sold in excess of 16 million tonnes of material [18].

Fly ash used in the manufacture of Laytag contains some unburnt carbon (raw ash) which is generally less than the 8% fuel amount required for sintering process [19].The fuel amount is corrected by the addition of coal dust in the form of slurry. The fly ash and coal slurry are mixed in screw mixers then pelletised in large disc pelletisers.

The mixing of the raw materials is critical. Producing strong pellets with maximum strength, minimum density and minimum cost is only possible by careful control of the carbon contents of carbon mixture (raw ash and coal dust) and water [20].

The green pellets are then transported in the form of 200-300 mm thickness bed to the sinter strand. The pellet bed is ignited on its top surface when it forwarded slowly under the ignition hood which is maintained at a temperature of 1200-1300ºC. The pellets come out from under the ignition hood in a partially sintered state and the flame is then forces to advance down through the pellet bed by drawing air down through it. The carbon supplied by the fly ash and coal dust maintains the sintering process. The pellets become fully sintered by the time it reaches the end of the sinter strand. Figure 23 shows a schematic diagram for Lytag sinter strand process [2, 21].

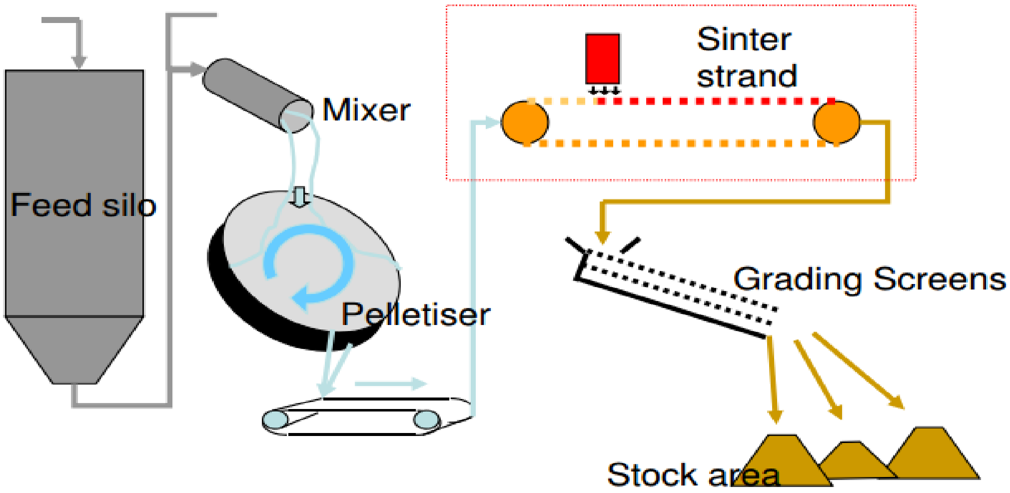


Figure 23: Lytag Process [22].

The pellets falling off the sinter strand are dark brown in colour and are stuck together at their points of contacts, which are then separated and graded to the required grade, depending on the final use. The particles formed are rounded in shape and generally range in size from 14mm to fines (Figure 24) [18, 21].

The oven dry loose density of Lytag coarse aggregate is typically in the range of 700-800kg/m^3. Therefore, the weight of Lytag lightweight aggregate is approximately half that of normal weight aggregate, which typically 1,550kg/m^3. Lytag has a Class 1 fire resistance because of the sintering process and the cellular structure of the particles, which relieves any pressures from expanding gases. The high void ratio which is typically 40% gives Lytag aggregate excellent freeze and thaw properties. Lytag lightweight aggregate has a wide range of applications like structural lightweight concrete, structural fill, floor and roof screed, drainage and filter media, and refractory uses [18].

Figure 24: Lytag aggregate.

Flashag lightweight aggregate

Kayali et al [23] invented a new lightweight aggregate from fly ash named Flashag. The inventors believe that this product requires less energy, less workmanship and equipment than the commercial pelletised sintered fly ash aggregates [24].

The fly ash is mixed with about 70% of the required total amount of water in a suitable mixer for three minutes, and then a plasticiser is added (to facilitate the workability of the fly ash slurry or dough) and mixing is continued for another period of three minutes. The rest of the water is then added and the mixing is continued for three more minutes.

The fly ash dough is compacted and cut into briquettes, and then placed in a controlled curing chamber for 48 hours at 50ºC temperature and 37% relative humidity. After that, the cured briquettes are placed in a kiln and the temperature is raised gradually to reach 1300ºC within a period of nine hours. The temperature is kept at 1300ºC for more four hours to sinter the briquettes. The sintered briquettes then are crashed and screened to provide the required size of the lightweight fly ash aggregate [23].

Research work on sintered fly ash aggregate

Ramamurthy and Harikrishnan [25] studied the relative performance of three binders namely cement, lime and sodium bentonite on the properties of sintered fly ash aggregates. Binders were used in 10%, 20% and 30% by weight of the fly ash. The mixtures were pelletised using disc pelletiser then dried before sintering for 1 hour in a muffle furnace at a temperature of 1100ºC. They found that the properties of sintered fly ash depend on the type and dosage of the binder. Also, the binders did not modify the chemical composition, but they affected the microstructure of the aggregate, which results in improvement in the properties of aggregates. Moreover, sodium bentonite binder addition of 20% resulted in the optimal strength and minimum water absorption characteristics [25].

Kockal and Ozturan [26] investigated the properties of lightweight fly ash aggregates produced with the addition of bentonite and glass powder as binders using different heat treatments. A disc pelletiser was used for the manufacturing of the fly ash pellets. Binders were used at 0%, 5% and 10% individually, and in combination of 7.5% each, by the weight of fly ash. After pelletisation, the green pellets were dried in an oven at 110ºC. The pellets were then sintered in a kiln at 1100, 1150 and 1200ºC for 1 hour. The particles in fly ash aggregates without binder fused at 1150ºC, while melting and fusion occurred at 1100ºC with the addition of the binder. Addition of binders increased the specific gravity of the aggregates at 1100 and 1150ºC sintering temperatures; however the specific gravity of aggregates sintered at 1200ºC decreased due to expansion and bloating. Specific gravity of fly ash aggregates made without binder continuously increased with sintering temperatures. Water absorption of all fly ash aggregates declined with the increase in sintering temperature. Strength of fly ash aggregates with binders at 1100 and 1150ºC were much higher than the fly ash aggregate without binder and were increased when the binder content increased. Bentonite binder was more effective in increasing the strength of the fly ash aggregate than the glass powder. At 1200ºC the strength of the fly ash aggregates without binder was higher than the other fly ash aggregates [26].

Derun et al [27] studied the properties of fly ash aggregates using fly ashes provided from four different thermal power plants and two types of binders namely; calcium bentonite and sodium bentonite. A disc pelletiser was used for the manufacturing of the fly ash pellets. The bentonite binders were used at 0.5%, 0.7%, 0.9% and 1% by the weight of one type of the fly ashes to determine the more effective binder and its best dosage, which were later used for the remaining types of fly ash. After palletisation, the green pellets were dried at 105ºC for 1 day. The fly ash aggregates were then sintered at 1000ºC for 1 hour. Their results showed that sodium bentonite was more effective as a binder than calcium bentonite. Also, 0.7% content of sodium bentonite was the best binding dosage for manufacturing fly ash aggregates [27].

Manikandan and Ramamurthy [29] conducted a research to explore the influence of sintering temperatures on the properties of fly ash aggregate by using two types of clay binder; namely bentonite and kaolinite. A disc pelletiser was used for the manufacturing of the fly ash pellets. Based on their preliminary investigations [28], the bentonite and kaolinite were used at 12% and 30% by weight of the fly ash respectively. Sintering of fly ash pellets was accomplished using a muffle furnace with a heating rate of 15ºC per minute. The pellets were sintered at temperature ranging between 700 and 1400ºC at 100ºC intervals with sintering time between 15 and 120 minutes. They found that for aggregate with bentonite no improvement in fly ash aggregate properties was achieved when it sintered up to 900ºC, while for temperature between 1000 and 1300ºC, there was significant improvement in shrinkage, density and strength of fly ash aggregate. However, these properties were degraded at 1400ºC due to decomposition of the mineral phases. For aggregate with kaolinite, minor improvement in fly ash aggregate properties were observed at temperatures between 1100 and 1200ºC. However, for temperatures above 1200ºC theses properties were greatly enhanced and reached its best at 1400ºC.They also reported that the duration of the sintering has minor influence on the properties of fly ash aggregate up to 800ºC and 1000ºC with bentonite and kaolinite, respectively. Whereas, for sintering temperatures between 1000and 1400ºCthe properties of fly ash aggregate were improved for when duration increased up to 60 minutes. They concluded that fly ash aggregates with different strengths could be produced by varying the temperature and duration of sintering [29].

Adell et al [30] investigated the properties of sintered fly ash pellets using slow and rapid heating rates. Fly ash with 20% moisture content was formed into cylindrical pelletswith 20mm diameter by pressing at 32 MPa. The pellets were then dried at 105ºC then sintered at temperatures between 1050 and 1300ºC for duration ranging from 5 to 60 minutes using slow (conventional) and rapid heating process. In conventional sintering process the green fly ash pellets were heated at a constant rate of 20ºC per minute from ambient temperature up to the sintering temperature, then held for required sintering time and then cooled to the ambient temperature at a rate of 10ºC per minute. In rapid sintering process, the pellets were placed directly into a furnace set at the required sintering temperature and left in the furnace for the required sintering time, then were removed and allowed to cool rapidly to ambient temperature. They found that during rapid sintering the unburnt carbon in the fly ash is present in the pellets at the sintering temperature, while in slow sintering process the carbon was removed at lower temperatures before sintering was occurred. They also found that rapid sintering of fly ash produces pellets with different properties and microstructure from slow sintering of fly ash. They noted that the fly ash pellets that rapidly sintered at 1050ºC had microstructural characteristics similar to Lytag aggregate [30].

Hydrothermal process

In this type of hardening of fly ash products bonding is achieved by the chemical reaction of fly ash with cement or lime and water under pressurised steam conditions. During autoclaving the materials react to form calcium silicate hydrates (C-S-H). The temperature used for this type of process is higher than 100ºC and less than 250ºC.

This type of hardening process is similar to the production of autoclaved aerated concrete and fly ash/lime brick.

When fly ash pellets are hardened at pressurised saturated steam it achieved stronger bond, lower drying shrinkage and lower creep in comparison to pellets hardened at ordinary temperature [2].

Hydrothermal Aardelite aggregate

Hydrothermal Aardelite process is developed in Netherlands to produce pellets which can be used as a replacement to natural gravel in construction. Atypical composition of the pellets consists of 50% fly ash, 45% fine quartz sand and 5% lime together with water and some additives (like gypsum).

The quartz sand is added to achieve a better particle size distribution with lower pore number. After mixing the mixture moved into a reactor and stays for some hours to hydrate the lime. During this time the reaction between lime and fly ash starts. The mixture is then pelletised using a rotary drum. The partially hydrated pellets are then screened and those of the required size are introduced into an autoclave for about two hours at a temperature below 140ºC to harden under pressurised saturated steam conditions. Oversize and undersize pellets are recycled [2]. Figure 25 shows the Aardelite autoclave process.

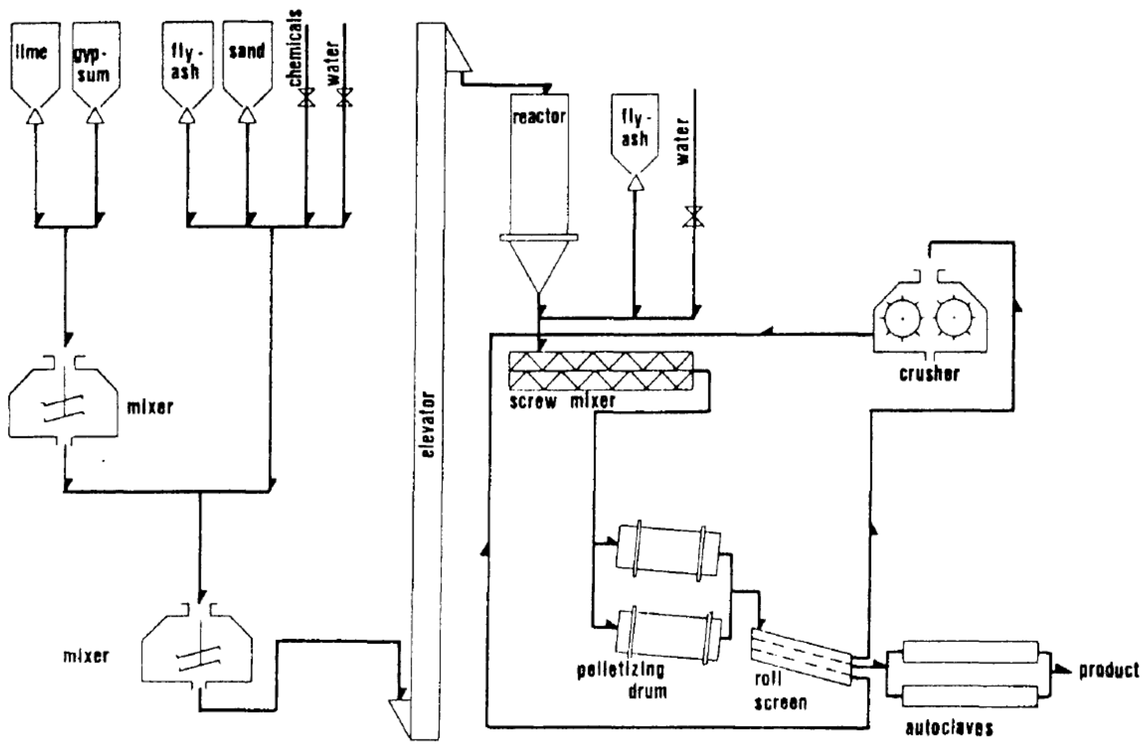


Figure 25: Aardelite Autoclave Process [2].

Cold bonding process

In this type of hardening of fly ash products bonding is achieved by the chemical reaction of fly ash with cement or lime and water at temperatures less than or equal to 100ºC.The fly ash as a pozzolanic material is able to react with calcium hydroxide found in lime and Portland cement at ordinary temperatures to form water-resistance bonding material.

The bonding developed by this type of hardening process is in general less rigid than that achieved by the other types of bonding discussed above. In addition, the drying shrinkage and the creep of the products are greater. These negative properties can be overcome by using compaction agglomeration processes to reduce the porosity which leads to lower shrinkage, lower creep and higher strength [2].

Aardelite cold bonding process

In this Aardelite technology [31], the fly ash and lime are mixed thoroughly using a mixer. The water is then added to the mix to form a mixture. The green mixture is then fed onto a disc pelletiser to form pellets.

The green pellets are then embedded in dry fly ash (to prevent them from sticking together) and are fed into a rotary pre-heater. Steam is then injected to preheat the embedded green pellets to 90ºC. The heated embedded pellets are then fed into a curing silo for about 20 hours.

The embedded cured fly ash pellets from the silo are then fed into a rotary screen to separate the pellets from the embedding material (fly ash). The oversize pellets are crushed and returned to the rotary screen. The fly ash which was used as an embedding material is recycled.

A typical composition of the pellets consists of 79.7% fly ash, 3.3% lime and 17% water. The bulk density of this Aardelite fly ash aggregate is 1050 kg/m^3. Figure 26 shows the Aardelite cold bonding process.

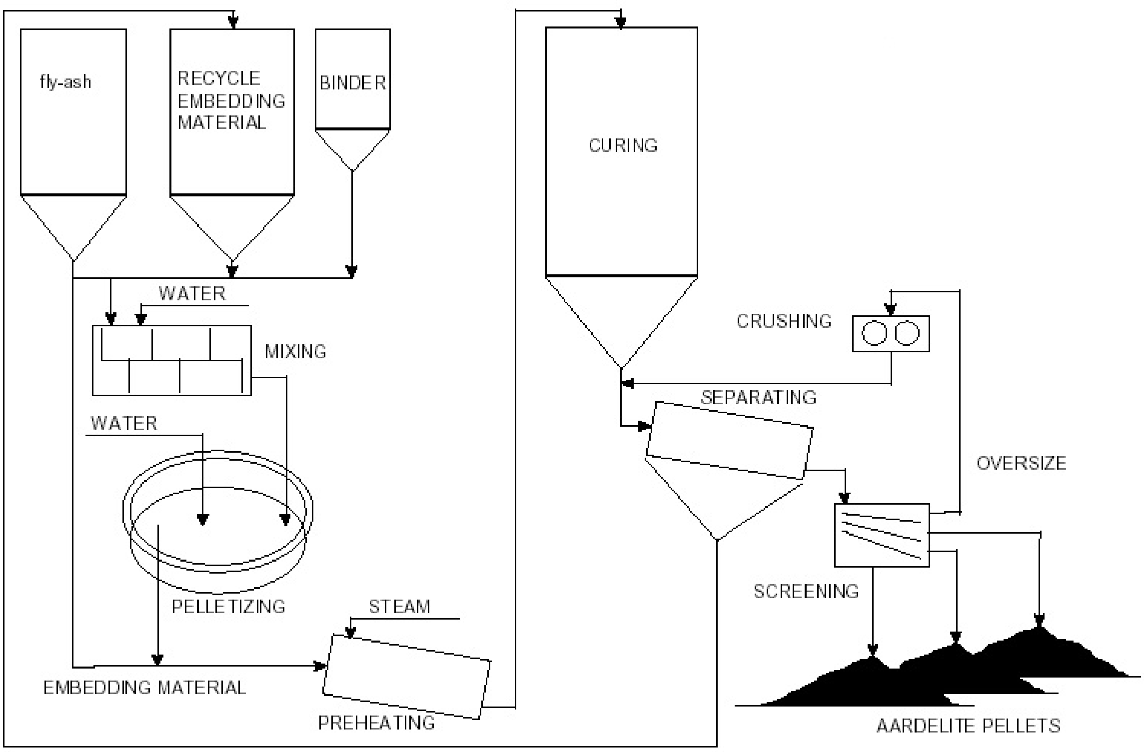


Figure 26: Aardelite cold bonding process [32].

Research work on cold bonding process

Gomathi and Sivakumar [33.34] investigated the production of fly ash aggregate using different types of binders namely; bentonite, metakaoline and ground granulated blast-furnace slag (GGBS). The binders were used at 10%, 20% and 30% by weight of the fly ash. Also, they used sodium hydroxide as alkali activator at a concentration of 8, 10 and 12M. A disc pelletiser was used to produce the fly ash aggregate with 25% moisture content. After pelletisation the fly ash aggregates were then air dried and later cured in an oven at 100ºC for a duration of 1, 3, 5 and 7 days. They concluded that the efficiency of pelletisation and strength of fly ash aggregates increases with the addition of binders and alkali activators. The maximum fly ash aggregate crushing strength was reported as 22.81, 17.62 and 14.51 MPa for 30% GGBS, 30% metakaoline and 20% bentonite binders at 7 days curing period, respectively [33,34].

Bui et al [35] studied the characteristics of cold bonded fly ash lightweight aggregate made with the addition of cement, granulated blast furnace slag (GGBS) and rice husk ash (RHA) as binders. The binders were used as 22% and 45% of GGBS or RHA with 10% cement, 20% and 40% of GGBS or RHA with 20% cement, and 15% and 30% of GGBS or RHA with 40% cement. A pelletising disc was used to produce the fly ash pellets which were then cured at room temperature (23ºC) for 28 days. They concluded that the addition of GGBS increased the crushing strength and reduced the water absorption of the fly ash aggregate, while the addition of RHA did not improve the crushing strength and increased the water absorption of the fly ash aggregate [35].

In another study, Bui et al [36] investigated the properties of pelletised lightweight aggregate produced form fly ash with or without the addition of GGBS and RHA as additives and using alkaline solution as a wetting agent and an activator. Additives were used at 25% and 50% individually, in combination of 25% each, and at 13% GGBS and 12% RHA by the weight of fly ash. An aggregate with only fly ash and activator is also manufactured. The activating solution was a combination of sodium silicate and 10M sodium hydroxide. After palletisation using a disc pelletiser, the green pellets were then cured at 23ºC and 60% relative humidity for 1, 3, 7, 14 and 28 days. The found that at early ages, the strength of the aggregate made with fly ash and GGBS was better than that of other aggregates. At later ages the strength of aggregate made with only fly ash was the lowest, while the aggregate made with fly ash and GGBS was the highest. On the other hand, they found that when GGBS content increased, the aggregate strength increased. In contrast, when RHA content increased the aggregate strength decreased. They also observed that the unit weight of the fly ash aggregate increased as the GGBS increased; on the other hand, it decreased as RHA increased. They stated that the water absorption of the aggregates containing GGBS recorded the lowest value of all aggregates [36].

Gesoğlu et al [37] studied the properties of lightweight aggregates made through pelletisation of different mixture combinations of cement, GGBS and/or Fly ash. Also, same fly ash with different blain fineness values were used to investigate the effect of fineness of fly ash on the palletisation process. Cement was used as a binder at 5% to 20% by weight of other material(s) (GGBS and/or fly ash). After palletisation using a disc pelletiser, the fresh pellets were kept in sealed plastic bags and cured at 21ºC and 70% relative humidity for 28 days. They found that palletisation efficiency was higher when fly ash with higher fineness value was used. Also, they found that the addition of cement increases the specific gravity of the pellets and decreases the water absorption. In addition, when the cement content increased, the strength of the lightweight aggregates increased, especially for GGBS aggregates [37].

CONCLUSIONS

As discussed in the report, there are varieties of methods that have been attempted to produce aggregates from fly ash. The critical factors are the energy use involved in many of the processes are very high and consequently the carbon emissions. This project aims to reduce the carbon emissions associated with the synthetic aggregate production method.

The geopolymer technology requires heating only up to 60 to 70ºC. This can greatly enhance the carbon reductions associated with synthetic aggregate production. The disc palletiser type is the one chosen for agglomeration of fly ash as this type is suitable for laboratory trials as well as full scale manufacturing methods. Early trials have already commenced with this type of palletiser with fly ashes supplied by Ash Development Association.

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