

*Wolfgang Pietsch*

**Agglomeration in Industry**

*Occurrence and Applications*

*Agglomeration in Industry.* Wolfgang Pietsch  
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*Wolfgang Pietsch*

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Occurrence and Applications



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WILEY-VCH Verlag GmbH & Co. KGaA

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Naples, Florida 34103-4409  
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**Library of Congress Card No. applied for.**

**British Library Cataloguing-in-Publication**

**Data:**

A catalogue record for this book is available from the British Library.

**Bibliographic information published**

**by Die Deutsche Bibliothek**

Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at <<http://dnb.ddb.de>>.

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KGaA, Weinheim

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Printed in the Federal Republic of Germany  
Printed on acid-free paper

**Typesetting** Mitterweger & Partner,  
Kommunikationsgesellschaft mbH, Plankstadt

**Printing** Strauss GmbH, Mörlenbach

**Bookbinding** Litges & Dopf Buchbinderei  
GmbH, Heppenheim

**ISBN** 3-527-30582-3

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 ISBN 3-527-30582-3

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## Preface

When this book was first planned, the idea was to combine in one volume concise descriptions of agglomeration phenomena, technologies, equipment, and systems as well as a compilation of the applications of agglomeration techniques in industry. The latter was intended to demonstrate the widespread natural, mostly undesired occurrences of the phenomena and possible ways of avoiding them as well as the old, conventional, and new, varied beneficial uses of the technologies.

However, it soon became obvious that, in its entirety, this project was too extensive and required much more time than anticipated. Therefore, it was decided to split the subject into two complementary books.

The first book, *Agglomeration Processes – Phenomena, Technologies, Equipment* (ISBN 3-527-30369-3) was published by Wiley-VCH, Weinheim, Germany, in 2002. It covers the fundamental phenomena that define agglomeration and industrial technologies and equipment for size enlargement by agglomeration. Applications are mentioned in a general way throughout this text but without going into details.

This second book is an up-to-date overview dealing with the occurrence and key applications of agglomeration, including size enlargement in pharmaceutical, food and animal feed, chemical, fertilizer and agrochemical, mineral, building material and ceramic, metal, solid fuel, and other industries. Furthermore, the book emphasizes recent developments at the level of single particles and applications of agglomeration phenomena in nanotechnologies.

Many people, institutions, and companies have contributed to the two books.

First and foremost, I wish to thank my wife Hannelore for her support and understanding, particularly during the years when I was compiling these books. They are both dedicated to her. Without my wife's active participation in preparing almost all my publications, including the first textbook entitled *Size Enlargement by Agglomeration*, which is a major reference for the current two books, and her acceptance that I was not available for many hours almost every day during much of two decades, these publications could not have been completed.

It is impossible to acknowledge all the help that was provided by a large number of individuals and companies. Chapter 15.1 is a list of vendors and other organizations, which mentions those who have, in one way or another, contributed as well as some others that might be of interest as potential contacts for the readers of these books. While I have decided not to clutter the text with references, sources have been acknowl-

edged if figures or tables were provided by or are based on input from particular companies. The Disclaimer at the beginning of this book should be referred to when using such information.

Chapter 13 lists literature references. The earlier textbook, *Size Enlargement by Agglomeration*, contains treatments and many references relating to the developing science of the unit operation and covers the sizing of agglomeration equipment in some detail. Since the emphasis of the new books is on industrial applications, rather than theory, the earlier book should be referred to for the theoretical background. Information on the availability of reprinted copies of *Size Enlargement by Agglomeration* (Wiley, 1991) is available in Chapter 13.1 as a footnote. I have also contributed major chapters on agglomeration to two other books, portions of which are used in this book. The other books are: *Handbook of Powder Science and Technology* (Eds: M. E. Fayed, L. Otten), 1st edn, Van Nostrand Reinhold, New York (1983) and 2nd edn, Chapman & Hall, New York (1997). Full references can be found in Chapter 13.1.

Since size enlargement by agglomeration is one of the four unit operations of Mechanical Process Technology (see Chapters 1 and 2) and, for the design and construction of agglomeration systems and plants of any kind, many or all of the other unit operations are required together with the associated transport and storage technologies, often even in multiplicity, and the analytical methods are applied for process evaluation and control, the reader who is interested in the topic of this book should also learn about or have access to information on the other fields of Mechanical Process Technology (references in Chapter 13).

Finally, I wish to thank the following individuals who, as professionals and experts in their own fields, are or have been colleagues and/or partners in several continuing education courses over many years in the USA and in Europe and have agreed that their presentations and course notes can be used directly, adopted, or modified for this book. They are, in alphabetical order: T. van Doorslaer, W. E. Engelleitner, B. J. Ennis, M. E. Fayed, M. Gursch, D. C. Hicks, S. Jagnow, R. H. Leaver, R. Löbe, K. Masters, S. Mortensen, H. B. Ries, F. V. Shaw, N. Stanley-Wood, J. Storm, R. Wicke, and the late R. Zisselmar. Other major contributors were M. Karel, Y. Kawashima, the late B. Kaye, and H. Schubert.

Wolfgang Pietsch,  
Naples, FL, USA,  
September 2004

## 1

**Introduction**

This book is complementary to the author's earlier books, *Roll Pressing* (1976/1987) [B.13b], *Size Enlargement by Agglomeration* (1991) [B.48], and *Agglomeration Processes – Phenomena, Technologies, Equipment* (2001) [B.97], as well as some major contributions to professional handbooks, such as *Size Enlargement by Agglomeration* (1997) [B.71].

While *Roll Pressing* [B.13b] dealt exclusively with aspects of pressure agglomeration in roller presses, *Size Enlargement by Agglomeration* [B.48] covered the entire operation and some related fields from a fundamental view point. It described in much detail the newly evolving science of the natural phenomenon “Agglomeration”, which has been used by living creatures, including humans and modern mankind, for thousands of years, and the technologies that were derived from it. In contrast, *Agglomeration Processes – Phenomena, Technologies, Equipment* [B.97] was trying to offer a complete, up-to-date compilation of the various agglomeration techniques and, in general terms only, their applications. To that end, in addition to introducing the properties of agglomerates and the specific characteristics of the different technologies, descriptions of equipment and their special features for particular uses as well as engineering know-how and information on specific peripheral equipment were the main topic of the book. Emphasis was on up-to-date practical knowledge, not theory.

The present book again does not claim to be a scientific publication. Agglomeration, both as a phenomenon and as the beneficial size enlargement of particulate solids, has become part of the newly defined interdisciplinary technical field of Mechanical Process Engineering and a science in its own right, as described earlier [B.97], (Chapter 2). Nevertheless, much of the research and development are phenomenological in nature and most of the designs for equipment and industrial plant still rely heavily on the experience and know-how of vendors as well as experts in the field. Therefore, after again reviewing the fundamentals of agglomeration in an even more abbreviated form, this book attempts to summarize and describe the occurrence of agglomeration in industry, the industrial applications of size enlargement by agglomeration, and other beneficial uses of particle adhesion. The latter, in particular, is found increasingly in new fields such as nanotechnology, life sciences, and even the communication industry (nanoelectronics).

Obviously, it is not possible to describe all the many occurrences of agglomeration and to cover every application of size enlargement by agglomeration in industry. Par-

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ISBN 3-527-30582-3

ticularly during the past 50 years, because of an increase in the production of fine and ultra-fine primary, intermediate, and final solid materials as well as the collection of ever finer particulate wastes, circumstances of undesired build-up, lumping, and other troublesome aggregations have increased tremendously. During that same period of time, a better understanding of the agglomeration phenomenon has led to many beneficial applications of desired and controlled size enlargement to obtain an increasing number of benefits (Chapter 6, Tab. 6.1).

Therefore, in planning the contents of this book, in spite of its growing importance, just one chapter was allocated to deal with the undesired occurrences of agglomeration and the most common methods to avoid or at least lessen its effect.

For the presentation of desirable size enlargement processes in industry, the entire field was sub-divided into a number of segments. In each, the most important application(s) is (are) being presented in considerable detail as examples, describing the history, development, and present state of the technique(s). From this, knowledge and guidance may be gleaned for interdisciplinary use during the evaluation of similar applications in other industries and/or for different materials.

In some areas, the author has decided to describe or indicate in varying detail some less well known, normally more partial methods for size enlargement by agglomeration. These were selected to broaden understanding of the possibilities for beneficially applying the phenomenon for obtaining specific product characteristics and may suggest the use of similar approaches for other cases.

## 2

## Agglomeration as a Generic, Independent, and Interdisciplinary Field of Science

Agglomeration, the sticking together of particulate matter, is a natural phenomenon and is as old as the existence of solids. Originally, it happened during the development of soil, stone, and rock formations. Later, unwanted agglomeration occurred during handling and storage of particulate matter by humans, especially when hygroscopic and/or soluble materials (such as salt) set into lumps or large more-or-less solidified masses. In the animal world agglomeration was and is used to develop protective coatings, to build nests, and to provide a nourishing and protective environment for the offspring (e.g., by the legendary *Scarabaeus Sacer*, the dung beetle, Fig. 2.1, the mascot of this agglomeration expert).

“Size enlargement by agglomeration” is the generic term for the operation in Mechanical Process Engineering that is characterized by the descriptions “combination with change in particle size” (Fig. 2.2). It is distinguished from the more general “size enlargement” such that particle growth occurring, for example, during crystallization

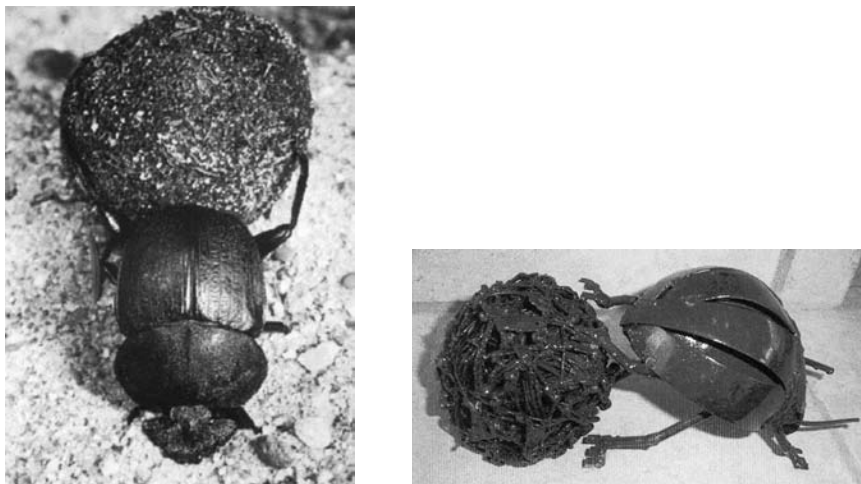


**Fig. 2.1** Beetle, *Scarabaeus Sacer*, “pelletizing” dung and an artist’s impression of this animal’s procedure

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|                                         | Separation                                                        | Combination                       |                                                                                                                                             |
|-----------------------------------------|-------------------------------------------------------------------|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Without Change in Particle Size         | Mechanical Separation<br>(Filters, Classifiers, Screens, Sifters) | Powder Mixing and Blending        | Particle and Bulk Material Characterization<br>(Size, Distribution Shape, Volume, Surface, Density, Mass, Porosity, Moisture Content, etc.) |
| With Change in Particle Size            | Size Reduction<br>(Crushing and Grinding)                         | Size Enlargement by Agglomeration |                                                                                                                                             |
| Transport and Storage of Bulk Materials |                                                                   |                                   |                                                                                                                                             |

**Fig. 2.2** Operations of Mechanical Process Technology and associated techniques

or the production of particulate solids by melt solidification are not part of this operation [B.97].

Most probably, humans first used agglomeration during the making of bread. The technology of bread making combines all components of a complex agglomeration process including preparation of solid feed particles by milling (adjustment of particle size and activation of the inherent binder, starch), mixing of particulate solids with additional binder(s), forming the mass into a green agglomerate, and a post-treatment (curing = baking = heating and cooling) to provide strength and texture. Very early it was also found that the porosity and, thus, the ease and enjoyment of consumption of the final product could be modified (increased) by making use of gases that are produced during fermentation (initiated by sourdough or yeast) and result in bubbles in the green mass. These voids are stabilized by strengthening the bread during post-treatment (baking).

For the construction of permanent shelter, humans may have observed the activities of animals that formed nests and protective “walls” from wet clay, which hardened during drying. By copying this behavior, wet clay, which was soon reinforced and made more water resistant by mixing-in straw or other fibrous material, was filled into a framework of wood branches and let harden during natural drying. To make building activities independent of the location of stone quarries, during prehistoric times bricks were already produced from clay and sand when rock was not easily available, thus allowing the development of villages and, during the 4th millennium BC in Mesopotamia, cities (e.g., Uruk) with large brick structures.

By experience, humans learned that certain natural materials helped cure specific illnesses. Minerals as well as dried animal and plant matter were ground to powder and formulated to yield medicines. Since powders cannot be easily consumed orally, natural binders, such as honey which, incidentally, also masked the unpleasant taste of some of the medicinal components, were mixed with the powder and the resulting plastic mass was rolled by hand into little balls (pills). The sticky binder(s) caused pills to adhere to each other; therefore, it was soon found that coating the pills by rolling them in flour or pollen solved this problem.

These three well-known ancient agglomeration techniques were used with little change through the ages of human history. Many other, lesser known or more recent processes could be added and some will be mentioned later in the appropriate sections of this book. At this point, the short review and the examples relating to three major modern industries (food, building materials, and health products) were selected to show that humans always lived with and used agglomeration. As a result, technologies for the mechanical processing of solids were considered normal activities, which, with the beginning of industrialization in the 18th and 19th centuries, were merely mechanized by simulating what was done manually before. During these early modernization efforts it was not considered necessary to question the fundamentals of the processes and improvements were based on empirical developments.

Until very recently, agglomeration technologies, as all the other unit operations and associated techniques of Mechanical Process Technology (Fig. 2.2), had been developed independently by the particular industries in which they were applied. Because the process requirements are very different in such unlike industries handling, for example, coal and ores on one hand or food and pharmaceuticals on the other, no interdisciplinary contact and exchange of information took place. In fact, although agglomeration techniques developed along similar lines, application related theories were defined, which were derived from investigations of specific requirements. Solutions of such work were not universally useable and the terminology was often incomprehensible to the agglomeration expert of another industry.

Agglomeration as a science began when an effort was made to interdisciplinarily combine the extensive knowledge that had been accumulated during sometimes hundreds of years in specific fields of human activities. It was found that, in all the different environments, agglomeration methods follow the same fundamentals, apply the same rules, and use essentially the same equipment and systems if looked at from a basic interdisciplinary point of view.

Although these facts become more and more known, there is still the understandable preconceived notion of, for example, somebody working in an ultra-clean environment, such as pharmaceutical, food, or electronic industries, that developments, expertise, and know-how gained in the dirty plants of, for example, minerals or metals production and processing, can not be considered as generally valid information and, therefore, may not be applied for the solution of a clean problem, and vice versa. In dirty industries, a typical concern is that the often much more deeply and completely investigated technologies that originate in clean industries can not be applied because the production capacities are too small, the process may be batch, the equipment too complex, the execution and the materials of construction too expensive and so on.

However, as has been shown among other topics in the author's previous book [B.97], methods for the selection of the most suitable agglomeration process for a specific application are the same for all projects. While some requirements, for example in regard to equipment or system capacity or on the shape, size, and special properties of the products, may already in the pre-selection phase result in the definition of cleaner or more heavy-duty, rugged processes, the normal approach is to determine the preferred method and/or technique by considering the fundamentals as well as an

interdisciplinary pool of expertise and know-how first. Special conditions of the particular application, such as, for example, hot and dusty large volume processing, or the opposite, clean, small capacity operation with cGMP (current good manufacturing practice) and CIP (cleaning in place) capabilities, are special design criteria that can be added to most of the systems later during the engineering phase.

Nevertheless, for manufacturing reasons and sometimes also because of special requirements on the company's test facilities (Chapter 9.1), some vendors specialize in equipment for one or the other industry. This is a decision of convenience by the individual supplier and does not indicate the existence of a fundamentally different technology. In fact, techniques or apparatus that were developed for a specific industry can be adopted for use in areas with different environment and requirements while still maintaining the fundamental underlying principle as well as the general machinery and process. Examples are crushing with high pressure roller presses, flaking, instantizing, spheronizing, and agglomeration with spray dryers.

#### Further Reading

For further reading the following books are recommended: B.3, **B.4**, B.6, B.7, B.8, **B.12**, **B.13a through e**, **B.15**, **B.16**, **B.17**, **B.19**, **B.21**, **B.22**, **B.24**, **B.26**, **B.35**, **B.36**, **B.40**, **B.41**, **B.48**, **B.49**, B.51, **B.52**, **B.55**, **B.56**, B.58, B.63, **B.66**, **B.67**, **B.68**, **B.70**, B.72, **B.73**, B.82, B.83, **B.89**, **B.93**, **B.94**, **B.97**, B.99, B.106 (Chapter 13.1). Books mainly devoted to the subject matter are printed bold.

## 8

## Applications in Environmental Control

Minimization of solid wastes, pollution control, and conservation of natural resources have become important and popular topics in all countries of the world. We live in an age of increasing government intervention, resulting in environmental laws, regulations, and enforceable penalties for offenders. Legal federal, state, and private citizen actions are taken increasingly often. They often result in considerable fines and sometimes even jail for those found responsible.

Every year billions are spent to capture, contain, and remedy solid wastes after their generation, and costs for “hazardous waste” treatment and disposal have multiplied during the past few years because of the limited availability of treatment and disposal sites and facilities.

**Tab. 8.1** Origins of particulate wastes and sources of pollution  
(presented in alphabetical order)

---

Primary wastes

- Agricultural wastes
- Excrements
- Mining wastes

Processing wastes

- Chemical processing wastes
- Metallurgical processing wastes
- Mineral processing wastes
- Vegetable and other food processing wastes
- Waste by-products
- Wood processing waste

Production wastes

- Energy production wastes
- Food production wastes
- Waste by-products
- Wastes from the forming, shaping, and finishing of solid products

Secondary wastes

- Wastes created during the disposal of wastes
  - Wastes created during the handling of wastes
  - Wastes created during the processing of wastes
- 

*Agglomeration in Industry.* Wolfgang Pietsch

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ISBN 3-527-30582-3

Most solid wastes are particulates with an increasing portion in the fine particle size range. As shown in Tab. 8.1, they are produced during primary activities, the processing of raw and advanced materials, and the handling, processing, and disposal of wastes from previous sources.

Agricultural wastes include, for example, straw. Formerly straw was burnt but this practice has been outlawed in many regions. Excrements used to be applied as a natural fertilizer. Today, concerns about public health forbid the direct application of raw feces, manure, and sewage on farmland or gardens in most developed countries.

People have mined the earth for thousands of years. Originally only high-grade ores and minerals were removed for further processing and use. Many of the oldest mine sites can be identified by the associated dumps of low-grade or undesirable material. Even today, tailings, below-grade slurries, and slimes that remain after high-efficiency upgrading and may now also be contaminated with chemicals, are still frequently disposed of in ponds or other deposits from which ground water is threatened by seepage.

During all processing steps, wastes develop featuring very diverse characteristics. In chemical processing, the solids are often very fine (dispersions), toxic, or hazardous. Metallurgical processing produces large amounts of fine (often metal-bearing) dusts. In mineral processing, size reduction is an important step that yields fines with particle sizes that are too small for direct further use and particulate, often contaminated, tailings are discarded from concentration plants. Vegetable, food, and wood-proces-

**Tab. 8.2** Origin, forms, and characteristics of particulate solid wastes

---

Origin

- Single-component or composite materials
- Primary or secondary (Tab. 8.1)

Forms (organized by size)

- Large and/or bulky parts
- Lumps and pieces
- Granular materials (0.1–10 mm)
- Fibrous materials (turnings, borings, organic fibers, etc.)
- Dusts (0.1–100  $\mu\text{m}$ )
- Ultrafine (nano) particles (0.1–100 nm)
- Cakes, sludges, slurries, and slimes
- Dispersions: suspensions (solids in liquid), smokes (solids in gas)
- Ultrafine particulate systems (colloids and aerosols)

Characteristics (arranged alphabetically)

- Hazardous (by composition, definition, nature, or size)
  - Inert
  - Obsolete
  - Organic
  - Radioactive
  - Reactive
  - Toxic
  - Useless
  - Valuable
-

sing facilities require the disposal of large amounts of organic matter, which is today summarily called “biomass”. By-products, such as molasses from sugar making, lignins from paper mills, oils and tars from the coking of hydrocarbons, or slags from metallurgical processing may be considered wastes because either their amounts are too large, contaminations prohibit their direct use, or, more recently, legislation requires mandatory processing, often to reduce secondary pollution and/or health hazards. In many of these by-products, the particulate solids are dissolved or suspended in a liquid phase.

Similarly, various particulate wastes develop during the production of industrial or consumer products. In particular, the shaping, forming, and finishing of articles from solid material yields turnings, borings, chips, grindings, and dust. By-products, for example gypsum or ammonium sulfate obtained during flue-gas desulfurization as required by “clean air acts”, are increasingly obtained in response to anti-pollution legislation. The production of food, such as canning and fish or meat packing, again results in large amounts of biomass, which must be dealt with in an environmentally safe manner. The broad category “energy production” comprises wastes from all fuel-powered motors and generators of any kind and size.

Secondary pollution is a cause for great concern during the handling, processing, and disposal of solid refuse. Since primary waste materials are often fine, they tend to

**Tab. 8.3** Possible effects and applications of size enlargement by agglomeration in environmental control

---

(A) Collection of contaminants

- Improvement of the collection efficiency after agglomeration by
  - Particle contacts in turbulent flow regimes
  - Sonic agitation
  - Coalescence in the presence of moisture
  - Flocculation by stirring with or without polymer addition.

(B) Handling of particulate solid wastes

- Elimination of dust by size enlargement
- Increased bulk density or decreased bulk volume
- Improved flow, including derived characteristics of bulk materials (metering)
- Optimized or modified product shape.
- Reduced reactivity

(C) Processing of particulate solid wastes

- Same as (B)
- Additionally
  - Modification of properties (strength, porosity, dispersibility, solubility, reactivity)
  - Adjustment or engineering of composition.

(D) Disposal of particulate solid wastes

- Same as (B)
  - Additionally:
    - Production of permanently strong and/or dense pieces
    - Encapsulation of toxic or radioactive materials
    - Achievement of leach-prove bonds
-

dust if they become dry, may be washed away with liquids, or seep into the ground where they may contaminate soil and aquifers.

Tab. 8.2 lists typical origins, forms, and characteristics of particulate solid wastes. They must be considered during handling, processing, and disposal. Solid wastes may consist of materials containing one single component or of composites comprising two or more substances. They may be primary discards, such as domestic refuse and solids contained in sewage, or secondary wastes such as ashes from refuse incinerators and digested filter cakes from municipal waste-water treatment plants. Secondary pollution can also arise from the emanation of dust or ultrafine particles from primary wastes.

The dimensions of solid wastes span the range from meters (for example automobile scrap and obsolete structures and equipment) to nanometers (in particulate residues from combustion and products of sublimation).

Originally, the removal of particulate pollutants from liquids and gases was accomplished by settling or with relatively simple filters and collectors. Ultrafine particles are so tiny that they can not be observed with the eye or by light microscopy [B.70]. Also, because of their small mass they remain suspended in gases (especially in air) and dispersed in liquids. Furthermore, they follow the streamlines of flowing fluids and so can not be captured by conventional means. Electron microscopy made such particles visible and relatively recent research revealed that very fine particles enter the respiratory tract during breathing or are resorbed from drinks, causing previously unrecognized health risks (for example silicosis and asbestosis or intestinal infections).

For these reasons, the characterization of hazardous solid materials has changed and, with it, the requirements for pollution control. In addition to its nature, described by certain properties (e.g., radioactive) and compositions (e.g., containing toxic components), legislation often defines the term “hazardous material” by “below a certain particle size”. With this definition, totally inert materials, consisting of or containing ultrafine particles, become hazardous by law and require processing.

Since in most cases the dimensions of particulate solid wastes, particularly those of contaminants, are small and, therefore, cause problems during collection and handling and with secondary pollution, size enlargement by agglomeration offers technologies that can assist in solid waste handling, processing, and disposal in many different ways. Tab. 8.3 summarizes the possibilities.

Increasingly, wastes are no longer just disposed of but processed for direct recycling or as secondary raw materials. With these technologies environmental protection laws are fulfilled, raw material sources are conserved, problem-causing waste deposits or extensive land fills are avoided, and, over all, energy is saved. This results in considerable reductions in costs and increases in profit potentials in all industries.

### Further Reading

For further reading the following books are recommended: B.3, B.7, B.8, B.15, B.16, B.18, B.19, B.20, B.21, B.22, B.24, **B.25**, B.26, **B.35**, B.36, **B.37**, B.40, **B.43**, **B.46**, B.48, B.49, B.51, **B.55**, B.56, B.69, B.70, **B.83**, B.87, B.89, B.93, B.94, B.97 (Chapter 13.1). Books mainly devoted to the subject matter are printed bold.

## 8.1

### Collection, Stabilization, and Deposition of Particulate Solids

#### 8.1.1

##### Size Enlargement by Agglomeration during the Collection of Particulate Solids

Most effluents from processing plants of any kind are contaminated in one way or another. Contaminants may be gaseous, liquid, or solid. Gaseous pollutants are often removed by chemical reaction, which may result in a solid by-product that needs to be processed, for example the removal of sulfur from the flue gas of power plants, or they are burned, which may produce particulates (soot) that become an increasing environmental concern. Liquid contaminants may be precipitated and then also form finely dispersed, suspended particles.

While for quite some time particles with sizes down to a few hundred micrometers have been successfully removed by conventional dust collection (mostly using gravitational and centrifugal or other field forces) and dry and wet filtration, air borne (Fig. 8.1) and suspended solid pollutants continued to be a great problem. Because of the small mass of fine and ultrafine particles they do not settle, even if high-field forces are produced, and they follow the flow lines in filter media so that impacts, which are necessary for collection (Fig. 8.2), do not take place.

For a long time, natural agglomeration has helped to improve the collection efficiency of, for example, filters and cyclones. Knees, bends, restrictions (e.g., valve seats), and even build-up in the pipes and channels of the cleaning device caused turbulence, particle collisions, and the formation of aggregates that, as a whole, have the combined mass of all the particles adhering to each other and a correspondingly larger cross section. Both effects allow the removal of particles that, individually, would be too small (Fig. 8.3).

Originally, the introduction of such turbulence was unintentional and led to sometimes surprising results: low efficiency if short straight connection lines are used between the source of particulate pollution and the collection device or unexpectedly high efficiency if, often for design purposes, tortuous, twisting lines had to be installed. More recently, process designers have applied this knowledge in the routing of effluent lines to assist dust collection.

Ultrafine particles that are suspended in a fluid exhibit Brownian motion, a random movement resulting from the impact with molecules of the fluid surrounding the particles. In spite of the randomness of the motion, it is very unlikely that particle-to-particle impacts will occur because the amplitudes of the movement and the par-



**Fig. 8.1** Example of an industrial plant (pyroprocessing of minerals) heavily polluted with airborne particulate solids

ticle sizes are very small. Therefore, other methods must be used to cause particle collisions that will result in coalescence and agglomerate growth. In addition to artificially induced turbulence, such techniques use uni- or bipolar charging in so-called electrostatic precipitators, magnetism, and ultrasound [B.48]. Although, from a process point of view, it is very advantageous that with these methods particle accretion occurs in the free-flowing fluid, a major drawback is that the collision probability changes with the square of the particle concentration. Therefore, as the number of particles becomes smaller, during the cleaning process itself by the incorporation of dust particles into the growing agglomerates, the collision probability decreases and the desired low concentrations of ultrafine particles in the off-gas may not be reached.

**Fig. 8.2** a) Enlarged view of the interior of a filter mat with particles sticking to the fiber surfaces. b) Detail of a dust laden fiber from (a) showing how particles extend into the gas stream [B.71]

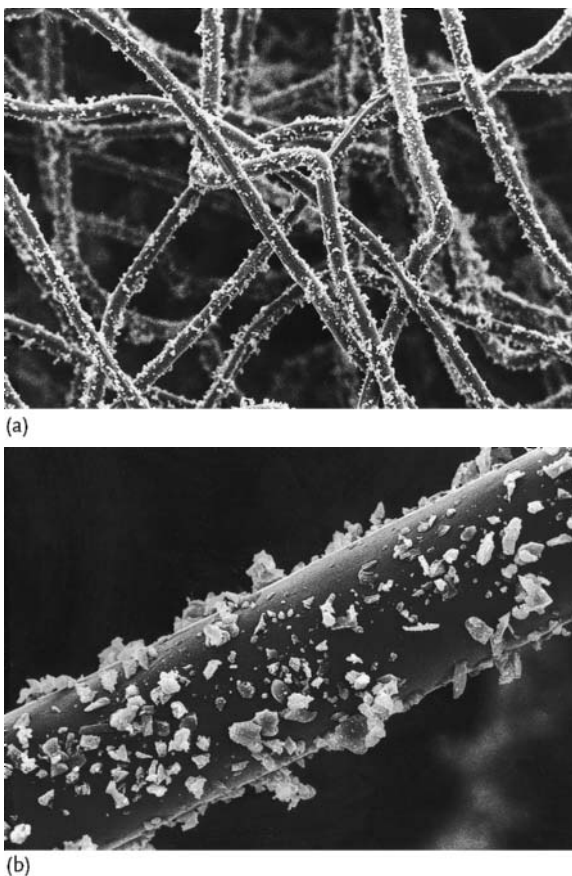
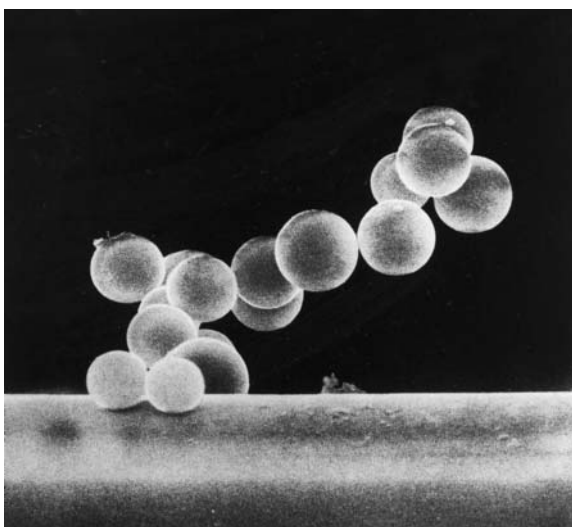


**Fig. 8.3** Naturally formed agglomerate of small ( $8\mu\text{m}$ ) glass spheres adhering to a filter fiber photographed during a laboratory experiment [B.48, B.97]



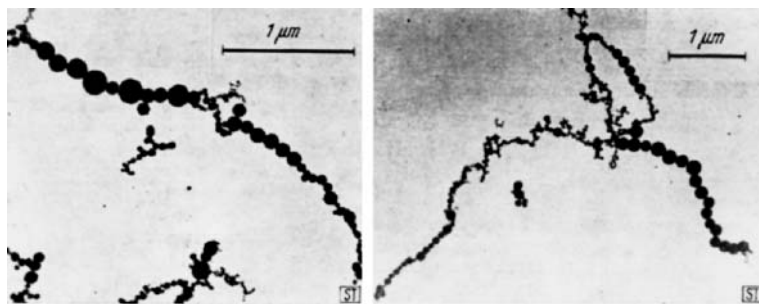


**Fig. 8.4** String-like agglomerates of “brown smoke” particles produced by natural magnetic coagulation [B.48]

For a long time, images similar to the one shown in Fig. 8.1 could have been seen at any steel-making complex in the world. The air was heavily polluted with “brown smoke”, consisting mostly of submicron  $\gamma\text{-Fe}_2\text{O}_3$  particles that are individually too small for collection by the early, rather basic gas-cleaning systems. After the invention of high-efficiency cyclones and multi-clones which, for physical reasons (low particle mass), can not collect submicron particles from contaminated gas, and their use in the steel and other metals or mineral-processing industries, it was found that, nevertheless, some of the brown smoke and similar airborne dust was removed anyway. In the meantime, it had become possible to observe ultrafine particles with the newly developed transmission electron microscope (TEM). It was determined that, because they are ferromagnetic dipoles,  $\gamma\text{-Fe}_2\text{O}_3$  particles naturally attach to each other, resulting in string-like agglomerates (Fig. 8.4). The larger of these aggregates were removed but an objectionable reddish plume was still discharged. The ultimate clean-up became possible after the naturally produced agglomerates (Fig. 8.4) were charged in an electrical field or by spray electrodes causing them to grow into larger dendritic structures (Fig. 8.5) that can be captured and collected [B.48].

It must be a goal during the collection of particles in filters that they collide with the medium and adhere upon impact. As shown by the results of model calculations,



**Fig. 8.5** Dendritic growth of “brown smoke” agglomerates (Fig. 8.4) in an electrostatic field [B.48]

various particle sizes not only move differently but modified system conditions also influence the behavior of the particulate solids, for example if particles and/or fibers carry a natural or acquired electrical surface charge, which causes electrostatic forces [B.97]. Another new strategy for the removal of ultrafine contaminants from a gas uses a particulate collector medium that is fluidized in a suitable vessel by the gas to be cleaned. Aerosol particles adhere to the large surface area of the fluidized medium and form a coating that is densified when the collector particles collide with each other. As the coating becomes thicker, attrition results in the formation of secondary particles. These are agglomerates and substantially larger than the original aerosol so that they can be easily separated in conventional dust collectors [B.97].

Like many original methods of mechanical process technology, an old technique for the successful removal of airborne dust was first observed in nature. The capacity of rain to “clear the air” has been used since ancient times to remove suspended dust particles by passing the contaminated gas through a water spray (wet scrubbers). The liquid droplets capture the solid (and some of the gaseous) pollutants and collect them in a sump. While this reduces air pollution it transfers part of the separation problem to a secondary cleaning process: the removal of fine particulate solids from a liquid.

Although these pollution control devices are cheap and efficient, it becomes more and more difficult to satisfy the increasingly stringent legislation of environmental control that is introduced almost everywhere. Traditional sprinkler sprays that require pumps and high-pressure water systems with substantial water usage, tend to exacerbate the problem by producing contaminated water runoff, potential spillage, and more high-cost clean-up. This is of particular concern if the locations of the sources of pollution and, with it, the collection points are not stationary. For example, dockside mobile loaders (DML, Fig. 8.6) are used during the unloading and transfer of dusty materials [8.1.1]. To avoid the aforementioned disadvantages, a new development causes dust suppression by wet agglomeration and accomplishes collection of the enlarged particles with fabric filters in the same unit. For the wet agglomeration step, an almost dry fog is produced by an air or (inert) gas-driven oscillator. This device atomizes liquids by passing them through high-frequency sound waves. The air or gas expands in a convergent section (nozzle) into a resonator cap where it is reflected back to complement and amplify the primary shock wave. The result is an intense field of sonic energy focused between the nozzle body and the resonator cap. Any liquid that can be pumped into the shock wave is sheared and forms fine droplets. Gas bypassing the resonator carries the atomized droplets away and forms a soft plume. The droplets have low mass, a low velocity, and ensure uniform distribution of liquid with minimum overspray and waste. It was also found that large, relatively fast-moving droplets (from sprinklers) displace so much air that the flow around it prevents dust particles from contacting the droplets (Fig. 8.7, left) while the fine dust particles easily impact small droplets, triggering agglomeration (Fig. 8.7, right; see also Chapter 5, discussion of the importance of droplet size for wet agglomeration).

Sonic energy can be also used to initiate and/or accelerate dry agglomeration of ultrafine particles that are suspended, for example, in flue gases [B.43, B.48]. An acoustic field imposes sound pressure and energy. For a typical pressure of 160 dB the acoustic velocity is about 5 m/s and a typical frequency of 2000 Hz causes a fully en-



**Fig. 8.6** Loading of a truck by heavy duty clam shell grab via dockside mobile loader (DML) to avoid pollution of the environment [8.1.1]

trained particle to move back and forth 2000 times a second over a distance of about  $600\text{ }\mu\text{m}$ . Particle entrainment is explained by a factor that is a function of acoustic frequency, particle diameter and density, and the dynamic viscosity of the gas [B.48]. If the factor is 1, full entrainment is achieved, while with a value of 0, no entrainment occurs. The latter means that such particles are not affected by the acoustic field and remain still. For each acoustic frequency a particle size exists below which particles are so much entrained (factor  $> 0.5$ ) that they are sufficiently moved. For example, for a sound frequency of 2000 Hz, this “cut size” is about  $4.5\text{ }\mu\text{m}$ . The flight paths of larger particles remain essentially unchanged, while smaller particles move with large displacements, colliding with the large particles, and adhering because of high van-der-Waals forces.

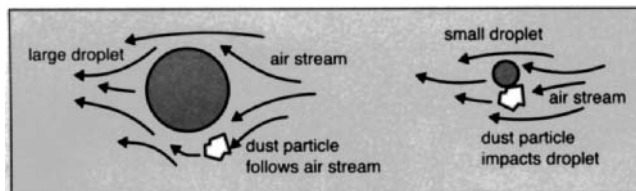


**Fig. 8.7** Demonstration of the importance of droplet size for particle agglomeration

In the hot gas cleaning system of a coal-burning power plant, acoustic agglomeration could be installed between the first cyclones, capturing coarser particles, and high-efficiency (multi) cyclones, removing the agglomerated fines. The power requirement to operate the acoustic agglomerator would be about 0.02–0.5% of the power plant output [B.48]. This means that for a 250 MW power plant several hundred kilowatts of acoustic power are needed, which is very high (compared with about 36 kW, the acoustic power output of a four-engine jet aircraft on take-off). To harness such large acoustic powers, considerable additional research and development are required.

Aggregation of fine particulate solids also takes place in liquids. In environmental control, the removal of particulate solids from liquid process effluents is of great importance. As for gas/solid separations, when the size of the solids diminishes and reaches the micron or submicron (nano) range, the mass of individual particles becomes so small that they remain in suspension and cannot be removed by settling. Because of the fineness, membranes would be required to retain particles on a diaphragm, which is uneconomical for the cleaning of large volumes of contaminated liquids from industrial plants or waste-water treatment facilities.

However, remembering the mechanisms of growth agglomeration (Chapter 5), if particles can be made to impact with each other, it is possible that they will adhere to one another in liquids, too. Therefore, when water that is contaminated with suspended fine solids is stirred, flocs may form naturally. If this happens, the size and shape of these aggregates depend on the circumferential speed of the stirrer and the processing time. Fig. 8.8 shows that flocs are larger if the shear forces are low and the

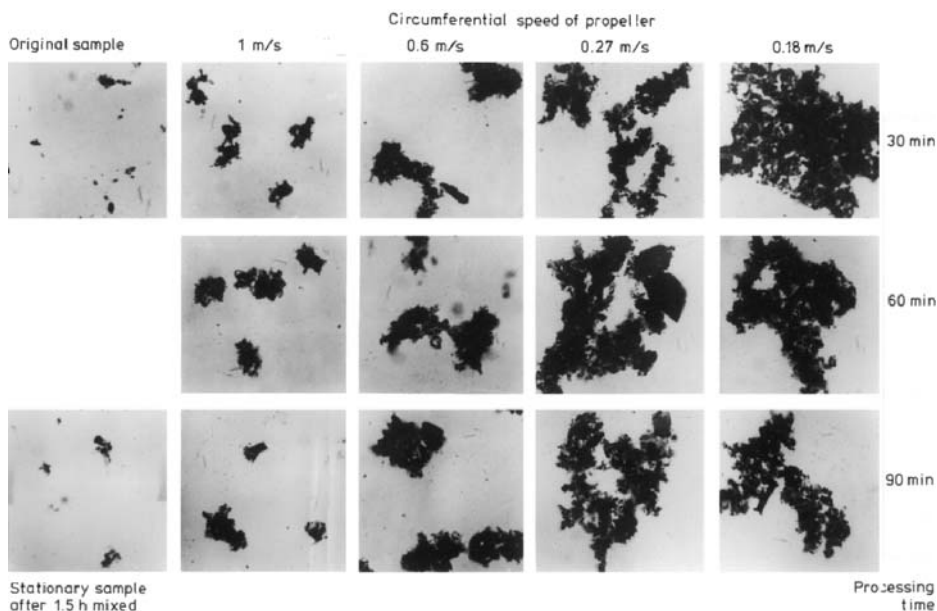


**Fig. 8.8** Natural flocculation of solid contaminants in river water [B.48].  
Parameters are the circumferential speed of the stirrer and the processing time

processing time is short. But further investigation revealed that higher speed of the stirrer and/or longer duration of mixing ultimately result in denser and more stable agglomerates. This is because of the previously discussed mechanism of growth agglomeration (Chapter 5) whereby loosely attached particles are removed under the influence of ambient forces (in this case, shear) and later have the chance to become re-attached in energetically more favorable positions thus yielding denser and stronger products.

It depends on the process that will be used for solids removal, which of the two agglomerate structures is required, the loose flocs resulting from relatively gentle movement or stronger agglomerates from a more vigorous stirring for a longer time. In the large diameter circular thickener/clarifier (Fig. 8.9) that is commonly used in municipal water-treatment plants and in many industrial applications, water, flowing slowly from the feedwell in the center to the overflow around the periphery of the circular tank, is gently moved by a slowly rotating arm. Loose flocs are formed, which settle by gravity to the slightly conical bottom. Differently shaped scrapers (rakes) are used to move the sludge to the discharge cone at the lowest point from where it is transported to conventional liquid filters. The more vigorous stirring that produces stronger agglomerates is used when the resulting agglomerates are moved with some of the water to an off-site filtering system and, therefore, must survive transport.

In many cases, even if collisions between particles do take place, the naturally available binding mechanisms, mostly molecular forces, which are considerably lower in a liquid environment than in a gas atmosphere, do not create bonds with sufficient strength to withstand the various separating effects and satisfactory flocculation does not occur. For quite some time it has been known that polymers, added to liquid-based particulate systems, have a dramatic influence on particle interaction. Molecules may attach themselves to solid surfaces and, depending on the characteristics of the exposed radicals, can cause particle attraction [B.29] or dispersion [B.63]. The second, dispersion, is applied to avoid agglomeration (Chapter 4) or enhance disintegration of aggregates.

There are two ways in which polymers can promote aggregation: either by making particles more susceptible to salts or by flocculating the system without the aid of electrolytes. These processes are known as sensitization and adsorption flocculation, respectively. The second is more common. To create aggregates or flocs, the polymer adsorbs on different particles simultaneously, which is best accomplished by using substances with high molecular weight and a strong affinity to the particles to be agglomerated. Fig. 8.10 explains the principle. In nearly all applications of polymeric flocculants, the polymer addition and the subsequent flocculation process are carried out under conditions in which the suspension is agitated in some way, for example by stirring. In this way, the polymer molecules are distributed uniformly throughout the system and adsorb onto the particles, which are then encouraged to collide and form aggregates. As described earlier in other contexts, bridging may be followed by break-up if the bond is not strong enough and, later, re-attachment during another impact. Fig. 8.11 is a sketch of a flocculate. Care must be taken not to oversaturate the suspension with polymer. If too much polymer is adsorbed, the par-

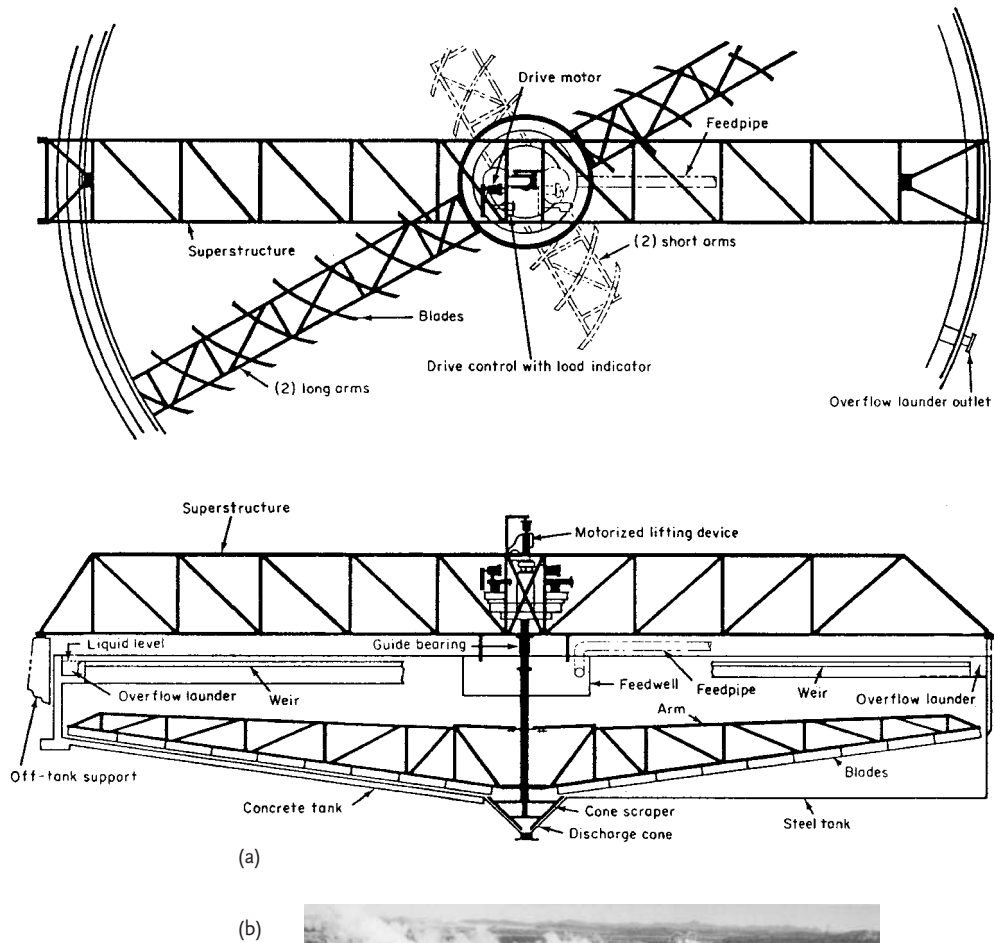


**Fig. 8.9** a) Diagram; b) photograph of a circular thickener/clarifier (according to EIMCO, Div. Baker Hughes, South Walpole, MA, USA)

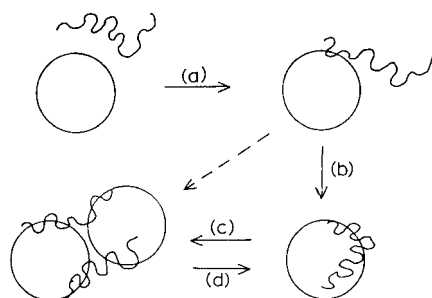


**Fig. 8.10** Principle of polymer adsorption and flocculation [B.29]:

a) adsorption of polymer molecule on the particle; b) rearrangement of adsorbed chain; c) collisions between destabilized particles and bridging to form aggregates (flocs); d) break-up of flocs

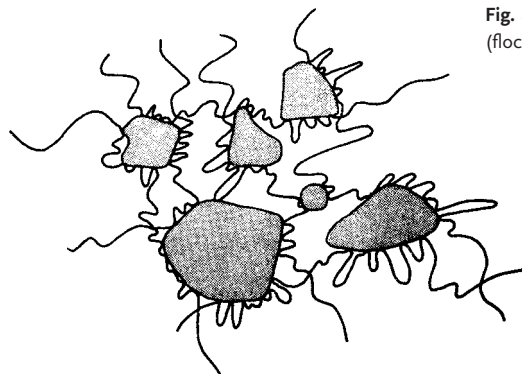


**Fig. 8.11** Structure of a flocculate (floc) bonded by a polymer [B.48]

ticles may become restabilized (deactivated) because of surface saturation or by steric stabilization [B.29]. Fig. 8.12 demonstrates diagrammatically bridging, which results in the desired flocculation, and restabilization.

Commercial flocculants are used extensively, for instance in water purification. By influencing the affinity of the polymer, it is also possible to obtain selective agglomeration.

Less well known is the fact that, more often than not, solids and immiscible droplets dispersed in aqueous solution are electrically charged because of preferential adsorption of certain ion species, charged organics, and/or dissociation of surface groups [B.48]. Depending on such variables as the nature of the material, its pretreatment, pH, and composition of the solution, these charges can be either positive or negative. Since the surface charges on particles are compensated by an equal but opposite

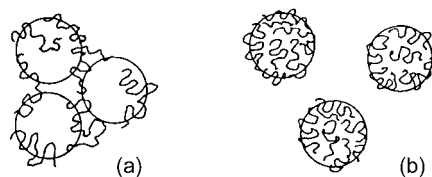


**Fig. 8.12** a) Diagram of polymer bridging between particles; b) restabilized particles [B.29]

**Fig. 8.13** Diagram representation of two particles with electrical double layers in a liquid [B.48]



countercharge surrounding them (Fig. 8.13) an electrical double layer develops (Chapter 5). Even though, as a whole, the system is electrically neutral, repulsion between the particles occurs. Upon addition of an indifferent (non-adsorbing) electrolyte (a salt), the double layers become less active and, as a consequence, the particles can now approach each other more closely before repulsion sets in. If enough salt is added, the particles may eventually come so close that van-der-Waals attraction binds them together. This is, in principle, the explanation of the sensitivity of colloids and suspensions to salts and why flocculation may be caused by the addition of salts.

For certain technical applications, electrocoagulators may be used to charge the solids in contaminated effluents [B.48]. Metal hydroxides are produced by a system of soluble electrodes (anodes) which, in suitable electrolytes, cause coagulation of suspended solid particles into larger flocs.

#### 8.1.2

##### **Size Enlargement by Agglomeration for the Stabilization and Disposal of Particulate Solid Wastes**

Current legislation in most developed countries classifies as hazardous most fine and all ultrafine particulate solids separated and collected from fluids with environmental control devices of any kind. In many cases, the mere fact that solids are micron or submicron sized, constitutes a reason for this classification. Owing to their fineness, dusts and slurries or moist residues from pollution abatement that are or become dry particulate matter easily become airborne causing a renewed threat to the environment and to human and animal or plant life (secondary pollution). Also, the large surface area of fine particulate solids results in high solubility so that toxic or otherwise undesirable substances may leach out and spill into surface water or end-up in aquifers if such fines are stored outside or deposited in unprotected landfills.

Therefore, a common task is to use agglomeration for the size enlargement of fine materials that result from pollution control measures. Emphasis in this case is on the production of large and heavy aggregates to avoid scattering by wind or water and of permanent bonds that are waterproof, survive freeze-thaw cycles, and, preferably, immobilize leachable compounds.

Because in this section recycling and the manufacturing of secondary raw materials are not a topic (for that, see Section 8.2), the only purpose of size enlargement is to render fine particulate solids suitable for safe handling, storage, and disposal. The cost

for carrying out the necessary processes is an extra burden and, consequently must be kept low. In Section 8.2, in connection with the size enlargement of low-grade ores or recovered fines for heap leaching, stockpile agglomeration is discussed as a cheap method. For the final disposal of terminal wastes, the same principle of agglomeration can be applied. Agglomeration is achieved at multiple transfer points from belts to belts (Fig. 8.14), on shaking or vibrating conveyor decks (Fig. 8.15), or on steeply inclined belt conveyors where material tumbles downward against the upward motion of the belt (Fig. 8.16) [B.48, B.97]. To obtain permanent, strong, and waterproof bonding, cement is often added as a low-cost, easily applicable binder. Agglomeration is initiated and bonding is activated by water sprays. Post-treatment for the production of final strength and long-term aggregate properties occurs in most cases naturally in curing piles prior to loading the material for transfer to the final disposal site, which does not need to be environmentally secured.

Other low-cost processing of terminal waste may simply use mixing of the material with a suitable matrix binder (cement is again an option but hot mixing with bitumen

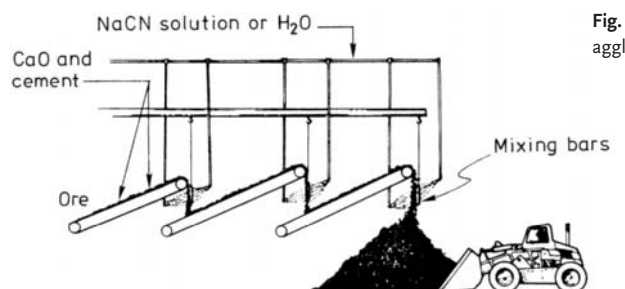


Fig. 8.14 Sketch of belt conveyor agglomeration [B.48, B.97]

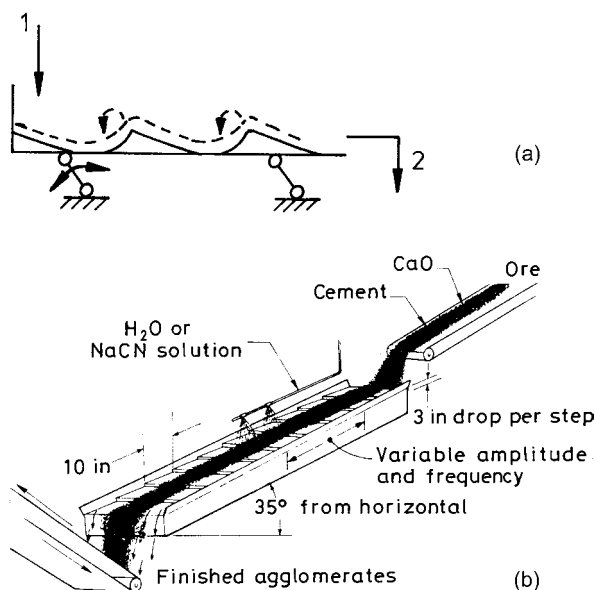


Fig. 8.15 a) Diagram of shaking trough; b) sketch of vibrating deck agglomeration [B.48, B.97]

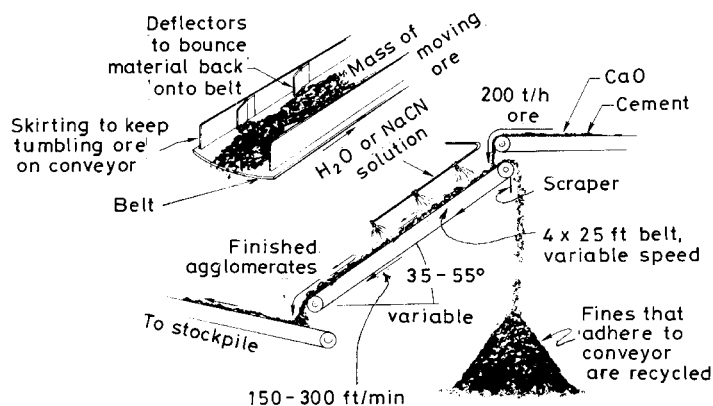


Fig. 8.16 Reversed belt agglomeration [B.48, B.97]

is a common alternative) and forming the blend into crude, brick-like bodies that harden into inert disposable pieces. Depending on the hazard level, more sophisticated (and expensive) methods may have to be chosen that can finally include some sort of additional sealing by surface coating or encapsulation. In this context, encapsulation could mean, for example, the pressing of the prepared mass into drums or barrels (Fig. 8.17) that are closed after hardening of the contents has been completed.



Fig. 8.17 Heavy-duty drum compactor  
(courtesy S&G Enterprises, Germantown, WI, USA)

In a growing number of cases, particularly if radioactive wastes are involved, glass is used as the matrix binder. Since, in this case, achieving safety requirements is more important than cost, rather elaborate processes are developed and used. They include the impregnation of evacuated porous agglomerates and, sometimes, also coating with liquid glass or the high-temperature post-treatment of agglomerates that contain ground waste glass.

Although recycling, the production of secondary raw materials, waste minimization, and resource conservation (Section 8.2) are the declared goals of all industrial societies, useless, terminal waste is also produced in growing amounts, which needs to be processed to avoid the costly disposal on secured sites or in managed landfills. Size enlargement by agglomeration is a new and quickly growing field of activities for this application. Knowledge of the fundamentals of this unit operation [B.48] and of the methods and equipment used to accomplish a multitude of tasks [B.97] and their interdisciplinary evaluation allows the development of suitable processes for safeguarding the environment, nature, enjoyment of life, and the future of the Earth.

## 8.2

### Recycling/Secondary Raw Materials

Since industrial wastes are commonly particulate solids, of which a large portion becomes increasingly finer, size enlargement is often required to render these materials suitable for beneficial use. Agglomeration, the sticking together of particles with the help of various binding mechanisms, results in products with controllable composition, strength, size, shape, density or porosity, and other desirable properties. The latter include lowered or increased reactivity, improved solubility or dispersibility, increased abrasion resistance, reduced dustiness, better flow and metering, or, generally, greatly enhanced handling characteristics.

#### 8.2.1

##### Historical Review of Waste Production

People have mined the earth for thousands of years. Initially these activities were limited to the gathering of metal, mostly gold nuggets and gem stones from the surface, but soon digging and tunneling into the earth began and materials other than the desired ones were also excavated. At the same time crushing was introduced to liberate valuable ingredients from unwanted solids. Fines, produced during crushing, and tailings (residue) were discarded in waste piles or dumped into holes. The location of many of the earliest mines is revealed by the waste heaps found nearby.

Between 4000 and 3000 BC the Bronze Age began: humans learned to extract copper and tin from ores by heat and produced the alloy bronze. Accordingly, mining activities increased and wastes were still simply discarded into heaps. Somewhat before 1000 BC, the Iron Age started in western Asia and Egypt as man learned to smelt

iron from its ores. Large amounts of smoke and fumes were emitted from the increasing number of small furnaces, but no one felt a need to capture or control it and slag was dumped.

Relatively early during the history of mankind carbonaceous materials, such as peat, lignite, and other coals, were collected and later mined to be burnt for various purposes. Like other mineral mine waste, coal fines were discarded, often in ponds after washing the coal lumps. There are indications that even in ancient times poor people retrieved the fines, mixed them with fat or oil, and manually formed them into bricks that hardened during open-air drying, a method that can still be observed today in coal mining districts of less-developed countries and in China. Such manually recovered agglomerated coal fines were used for home cooking and heating.

Nevertheless, and in spite of these isolated recycling efforts, until the early part of the 20th century and sometimes even today, wastes from mining, including fine coal, ores, and many other minerals, from the processing of organic materials, such as wood, plants of all kinds and types, and fruits, and from the production of industrial goods were mostly discarded.

During the past 100 years this situation has drastically changed. Industrial processing and production, yielding wastes of all kinds, skyrocketed. The desire and later the requirement to effectively clean gaseous and liquid plant effluents created large amounts of dusts and other fine or ultrafine particulate solids. Today, many of these materials are classified as hazardous because they may again pollute the environment and can be inhaled or ingested and resorbed, causing health risks. At the same time, industrial production and output are no longer concentrated in a few developed areas but distributed worldwide. Therefore, solid waste collection, treatment, processing, recycling, and disposal have become very important (often mandatory) industrial activities whereby handling of the finest materials poses the biggest challenge and costliest efforts.

In addition to the wastes produced during the collection, extraction, upgrading, and processing of natural raw materials, the quickly and still increasing production capacities in all industries result in large quantities of rejects and by-products, which inherently represent great value. Furthermore, the useful life of many industrial products is relatively limited and tends to become ever shorter. The obsolete items: equipment, such as machinery, cars, electronic components; packing materials, including paper, cardboard, foil, plastics, bottles, cans; wastes, for example newsprint, glass, wood, organic residue; and many more, contain a multitude of potentially valuable ingredients that must be separated and/or cleaned for further use.

Tab. 8.4 summarizes the most important advantages of agglomerated solid mineral and metallurgical wastes. Bullet points 1 to 3 are self-explanatory since the particle size of most solid wastes is too small for direct processing or is ultrafine after they were removed from gaseous or liquid plant effluents as solid pollutants (Section 8.1).

Because of their size-related large specific surface area, fine and ultrafine solid wastes, especially metallic fines or those containing metals or cellulosic dusts, are very reactive. Even at ambient conditions they combine easily with oxygen in an exothermic reaction that may cause accelerated, catastrophic heating or “dust explosions”. Size enlargement by agglomeration, accompanied by densification, sometimes

**Tab. 8.4** Advantages of agglomerated solid wastes

- 
- Agglomerated particulate solid wastes contain no or low amounts of dust; therefore, they provide increased safety during handling, even of hazardous materials, no secondary pollution, and, generally, fewer losses.
  - Agglomerated solids are freely flowing, featuring:
    - Improved storage and handling characteristics,
    - Better metering and dosing properties,
    - Increased bulk density and lower bulk volume.
  - Agglomerates have larger sizes and their size distribution can be controlled.
  - Within certain limits, depending on the process used, product porosity or density can be influenced; leachability and reactivity as well as other properties can be controlled.
  - Secondary raw materials can be crafted by:
    - Enlarging the size of wastes containing valuable ingredients,
    - Combining different solid waste components to obtain improved feed materials with controlled composition,
    - Including additives to bring about desirable processing characteristics.
- 

hot, renders such dusts sufficiently inactive for safe handling and use. Terminal solid wastes, destined for final storage, sometimes contain toxic or other hazardous components which, if untreated, may become airborne or leach into groundwater, requiring lined and/or covered disposal sites. Size enlargement by agglomeration using permanent binders, often in the form of a matrix, filling all interparticle voids, eliminates the need for special conditions for the deposition of such materials.

### 8.2.2

#### **Agglomeration Technologies for the Size Enlargement of Wastes**

A common classification of methods for the size enlargement of particulate solids distinguishes between two types of process (Chapter 5),

- natural and growth or tumble agglomeration (no external forces) and
- pressure agglomeration (low, medium, or high external forces)

and two techniques,

- binderless agglomeration and
- agglomeration with the addition of binders.

For fine metal ores and, more recently, for iron-bearing waste materials, agglomeration by heat (sintering), a less frequently used size-enlargement technology, is used. All agglomeration methods can be used to manufacture products for recycling and secondary raw materials.

Growth/tumble agglomeration happens in a similar fashion to natural agglomeration. Because the particles to be agglomerated are larger (surface equivalent diameter  $10 < x_o < 200 \mu\text{m}$  [B.97]), the particle-to-particle adhesion must be enhanced by binders and the collision probability must be increased by providing a high particle con-

centration. In most cases, growth/tumble agglomeration first yields “green” agglomerates, which are only held together temporarily by liquid binders. Final strength and potentially other product characteristics are obtained during post-treatment. Because of the growth mechanism, the agglomerated bodies are more or less spherical. If a narrowly sized product is desired, screening is used. Oversize (after milling) and undersize are recirculated to the agglomeration equipment.

Pressure agglomeration processes use external forces to enhance bonding by densification and to shape the product. As far as applicability is concerned, high-pressure agglomeration is the most versatile technology for the size enlargement of particulate wastes. If certain characteristics of the feed materials and conditions occurring during densification are considered and controlled during equipment selection, design, and operation, any kind and size (from nano- to millimeters) of particulate material can be successfully processed. Since high-pressure agglomeration is essentially a dry process, a limitation exists with regard to the highest tolerable moisture content of the feed. Filter cakes, for example, a common initial form of waste, can not be agglomerated by high pressure without first reducing the moisture to very low levels by additional drying.

### 8.2.3

#### **Applications in the Mineral, Metallurgical, and Energy Related Industries**

In the mineral and metallurgical industries, resource conservation by the recovery of valuable components from waste and the recycling of materials containing recoverable ingredients has already reached a high level of acceptance. New recovery technologies make the secondary processing of old mine waste deposits, particularly of ores and coal, economical and deposition of new wastes is minimized by the application of methods that convert a host of different, formerly obsolete materials into “secondary raw materials”, which are recycled, replacing primary raw feed sources. The latter also include iron and non-iron scrap, turnings, borings, grindings, dusts, etc.

Mixing different raw materials, additives, and binders, agglomerating the blend, and subjecting the product to different post-treatment methods to achieve special properties is known as material engineering. Industrial wastes can be included in such raw materials and additives can produce, for example, a fluxed feed for metallurgical operations, secondary raw materials with predetermined alloying ingredients, or smokeless fuels (Sections 6.8, 6.9, and 6.10).

Tab. 8.5 lists the areas in which size enlargement by agglomeration can benefit solid waste management in mineral and metal processing. *Waste minimization* is a preventive measure by which particulate solids are agglomerated to avoid pollution in the first place. Examples are in the bulk handling and transportation of naturally dusty minerals. In *pollution control* agglomeration has many applications. In most cases, collection of fine solids is improved or the removal of ultrafine particles is made possible (Section 8.1). Examples are the agglomeration of smoke particles or the flocculation of solid contaminants in effluent water. By agglomeration, *by-products* can be converted into materials that are suitable for beneficial use. Examples are fertilizers containing FGD

**Tab. 8.5** Areas in which size enlargement by agglomeration benefits solid waste management

- 
- Waste minimization
  - Pollution control
  - Beneficial use of waste by-products
  - Recycling/reprocessing
  - Production of secondary raw materials
  - Terminal wastes disposal
  - Prevention of secondary pollution
- 

(flue gas desulfurization) ammonium sulfate or pulverized Thomas slag, lump gypsum from FGD gypsum for use in cement production, and building materials from ashes. *Recycling* identifies the re-utilization of off-size solids after agglomeration in the same process in which this material was originally rejected. Examples are metal-bearing dusts from smelters, metal turnings, borings, grindings, etc., and coal, ore, and mineral fines from crushing and/or beneficiation. With modern processing technologies, many fine or low-grade raw materials which for decades and sometimes centuries were discarded at the mine or former processing sites can be used after recovery and agglomeration for *reprocessing*. Examples are fines deposits of rejected bauxite, coal, and ores (copper, gold, iron). With the exception of waste minimization all aforementioned applications are part of “resource conservation” by increased emphasis on *secondary raw materials*, process input obtained from wastes, rejects, and obsolete products, in most instances involving agglomeration. In some cases, the nature of terminal solid wastes, those which can no longer be processed for beneficial use, require agglomeration for *disposal* (Section 8.1). One reason for this can be to avoid leaching of toxic or radioactive components into the groundwater by the application of matrix binders such as cement or glass for stabilization. Another is to avoid *secondary pollution* because, after separation from plant effluents, many terminal wastes contain very fine particles in dusts, slurries, sludges, or slimes. Size enlargement by agglomeration is increasingly required to avoid costly disposal in scarce, small, specially designed hazardous waste deposition sites.

Some examples will be presented in more detail. They are selected such that, with the exception of natural agglomeration (used, for example, for the densification of silica fume, Section 6.7.3), at least one type of the available agglomeration processes is demonstrated.

Concerns regarding acid rain led to legislation in all industrialized countries aimed at limiting the sulfur content of flue gases, typically from power plants (Section 6.10.2, compliance fuel) and metallurgical processes. One of the most widely used desulfurization processes uses limestone as absorbent. The resulting calcium hydrogen sulfite is converted by oxidation into (synthetic) gypsum, called FGD gypsum (calcium sulfate dihydrate). Fig. 8.18 shows an absorber and associated processing facilities in a coal-fired power plant.

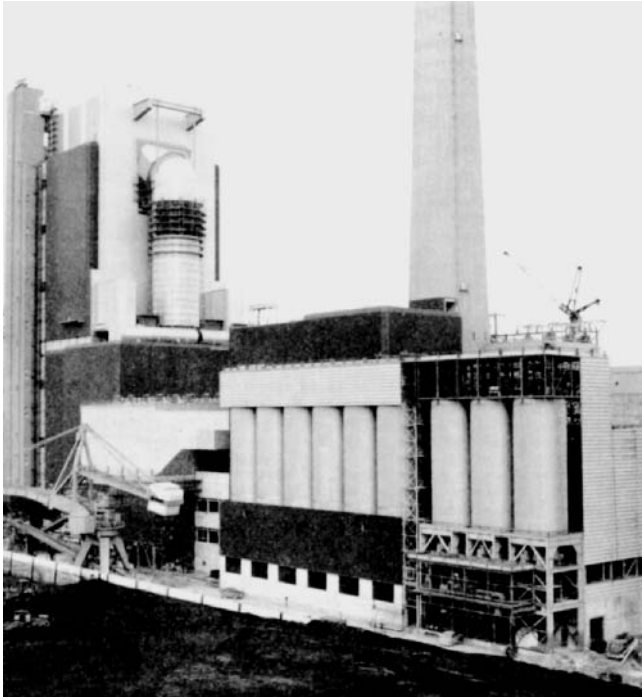


**Fig. 8.18** Sulfur absorption in the flue system of a coal-fired power plant (EVS, Heilbronn, Germany): left) absorber; right) limestone processing and gypsum recovery (briquetting) systems

The product from such a desulfurization system is a slurry and, after mechanical dewatering, a filter cake, containing finely divided solids. Disposal of the wet FGD gypsum is expensive and can result in secondary pollution if it becomes dry and is not stabilized. It has been found that, after agglomeration, the material can be used in cement kilns (replacing natural lump gypsum), economically transported to and used in plants producing gypsum board for the building industry, or safely discarded.

Principally three methods are used to convert the finely divided moist gypsum into the required lumpy form, all requiring no additional binder.

1. Tumble agglomeration of the moist gypsum in discs, drums, or mixers (Chapter 5, Fig. 5.2) and hardening the green, spherical pellets by thermal curing.
2. Densification of gypsum with reduced moisture content (8–10%) in pellet mills (Chapter 5, Fig. 5.10b1–b6) and hardening the green cylindrical pellets by thermal curing.
3. Drying the gypsum to < 1% moisture content and pressing and shaping it into finished, pillow-shaped briquettes with roller presses (Chapter 5, Fig. 5.11, lower right).

Fine particulate solids, dry or moist and from any source can be converted into larger products by growth/tumble agglomeration. The example shown in Fig. 8.19 depicts a simple system using an inclined disc for agglomeration, a rotary kiln for post-treatment, and screening and crushing for finishing.

Moist particulate solid wastes, such as predried FGD gypsum filter cake, can be extruded (Fig. 8.20) in, for example, flat die pellet presses (4 in Fig. 8.20) yielding cylindrical agglomerates, which are dried and screened prior to load-out.

Since in high-pressure agglomeration with roller presses densification is so high that the residual porosity can only hold very small amounts of moisture (Chapter 5),

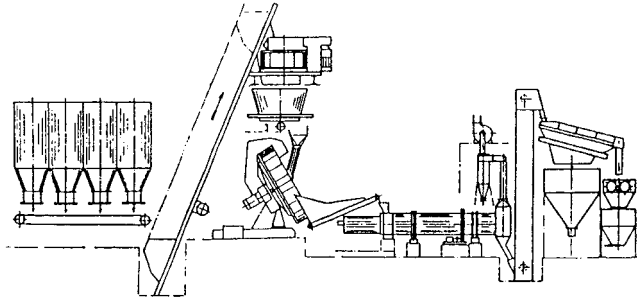


Fig. 8.19 Size enlargement of particulate solid waste by growth/tumble agglomeration (courtesy Eirich, Hardheim, Germany)

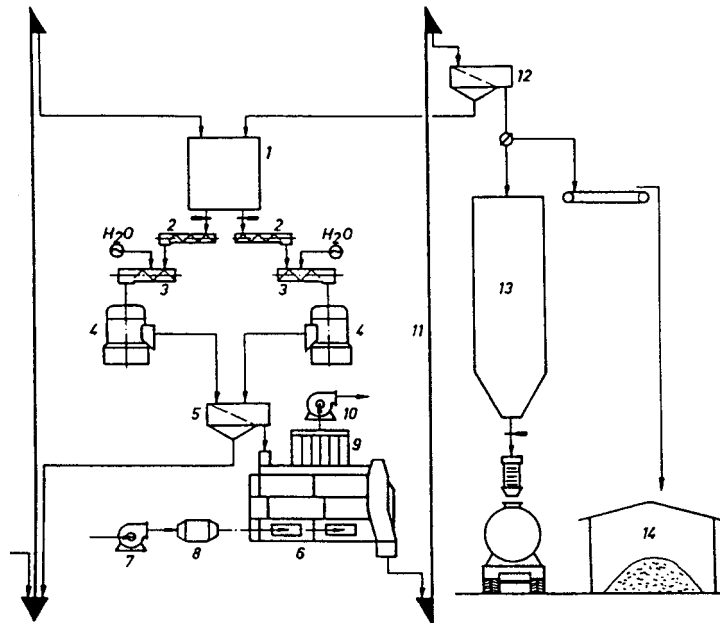


Fig. 8.20 Pelleting of wet FGD gypsum by medium-pressure agglomeration (flat die pelleting, courtesy Amandus Kahl, Reinbek, Germany)

if this technology is used, the FGD gypsum must be thermally dried to < 1 % moisture content prior to briquetting. The latter is very simple as shown in Fig. 8.21. To avoid starved feeding of the roller press and guarantee the production of high-quality briquettes, a small stream of excess material overflows at the end of the horizontal conveyor, is measured by a solids flow meter [B.97], and controls the discharge from the day bin, that is, the amount of press feed. Fig. 8.22 depicts photographs of a roller press in a FGD gypsum briquetting plant and of product samples.

Unless only fine dusts must be treated, the more versatile processes for size enlargement in recycling and particularly the secondary raw materials industry use pressure agglomeration technologies. Especially with the high-pressure machines (ram extrusion, hydraulic punch-and-die, and roller presses, Chapter 5, Fig. 5.11) a wide variety of feed materials and particle sizes can be processed. The sometimes very large energy input results in extensive densification, yielding high molecular forces for bonding, disintegration of brittle particles followed by recombination bonding, momentary melting of roughness peaks at the contact points, resulting in solid bridges, and plastic deformation of malleable components. The latter can be enhanced if hot feed materials are used (Sections 6.6.2 and 6.9.2).

As early as 1885, briquetting of iron-bearing fine residues from cupriferrous pyrites after roasting and the extraction of copper was carried out commercially for recycling in the UK [Section 13.3, ref.103]. The processes used punch-and-die presses and a binder, producing relatively large, brick-like pieces that were subsequently fired to obtain final strength. Around the same time, great success was reported in the bri-

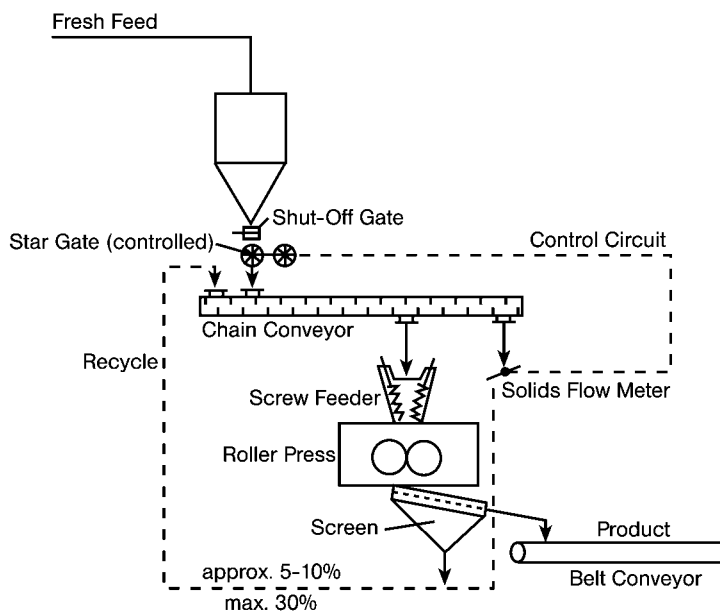


**Fig. 8.21** Flow diagram of a FGD gypsum roller press briquetting plant. Thermal drying of the feed is not shown

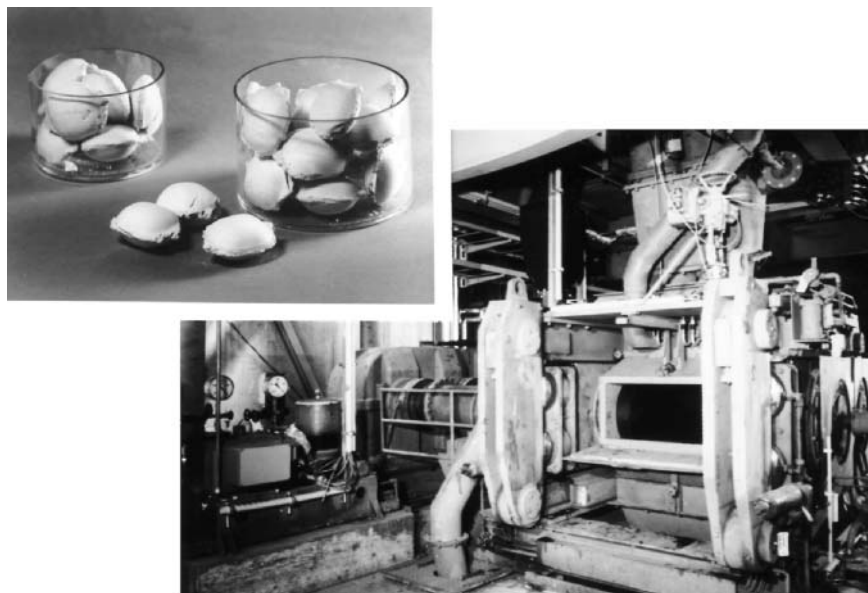


**Fig. 8.22** Roller press for the briquetting of (synthetic, FGD) gypsum in a flue gas desulfurization plant: inset, synthetic gypsum briquettes (courtesy Köppern, Hattingen/Ruhr, Germany)

quetting of blast furnace dust since this by-product contains lime, alumina, and soluble silica and, therefore, like cement, already possesses hydraulic binding properties. However, although they had been considered as quite important at the time, these early technologies were soon abandoned because, due to increasing costs of labor, energy, and, where applicable, binder, it became more economical to simply dump waste materials into industrial landfills.

The desire for environmental protection and the growing need to conserve raw materials, such as, fuels, ores, or strategic alloying components, and natural resources, such as land and water, have revitalized these efforts, leading to new processes utilizing modern equipment and technologies. Therefore, today's briquetting systems have little in common with early brick-making procedures. Fig. 8.23 is the flow diagram of a briquetting plant for metallized, metal-bearing, or other recyclable fines. The possibility of adding solid or liquid binders, either alone or in combination, render this simple system very versatile. As shown, the feed material(s) is (are) dry and cold and the binders are self-curing, that is, they gain final strength at ambient temperatures in a ventilated (to remove heat, moisture, and gaseous reaction products) briquette storage bin. Incorporation of certain materials, such as oxide fines or certain mill scales, and/or restrictions on binder amount or composition may require the installation of a curing oven. Typically the briquetted product is pillow shaped, strong, free of dust, and can be easily stored, handled, and metered during recycling (Fig. 8.24).

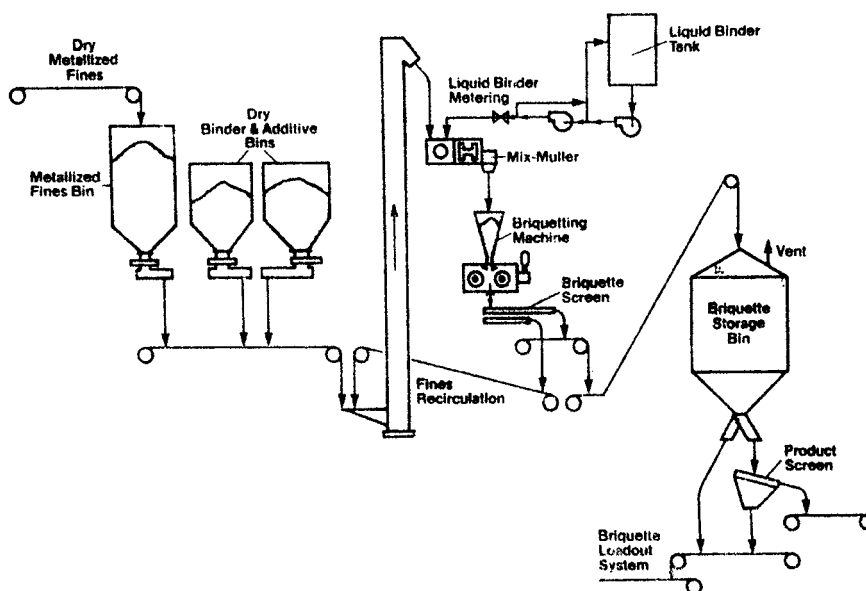


Fig. 8.23 Flow diagram of a generic briquetting plant for metallized, metal-bearing, or other recyclable fines

For recycling and the manufacture of secondary raw materials, successful size enlargement by agglomeration often hinges on finding a binder that is chemically (no contamination) and economically (low cost) acceptable and physically effective (adequate strength, high abrasion resistance, good flow and metering characteristics). The addition of fibers or other elongated particles is an innovative method for reinforcing agglomerates [B.97].



Fig. 8.24 Close-up view of a pile of typical briquettes produced by roller presses for recycling

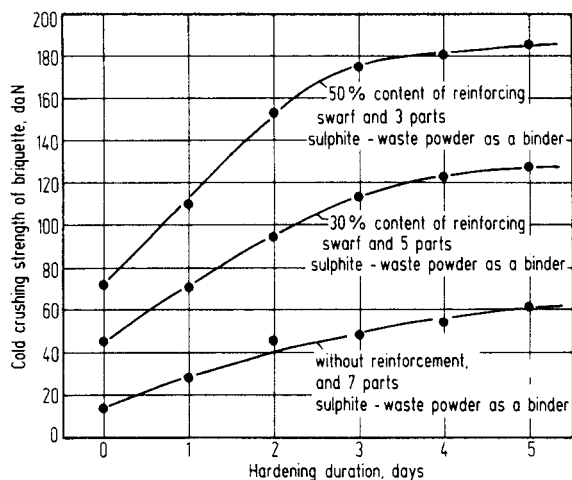


Another application of “fibers” as a reinforcing binder component is the addition of grinding swarf during the briquetting of metal-bearing filter dust [B.48, B.97]. Up to 50% of high-grade steel grinding swarf < 30 mm and a small amount of the conventional binder lignosulfonate powder (sulfite waste from paper making) were added to residue (filter dust and sludge) from specialty (alloyed) steel production. Since the product is destined for recirculation into the metal-making process, it is important to produce high strength of which at least a certain part is retained at high temperature, until the surface of the liquid metal bath is penetrated and melting occurs. Thereby, secondary contamination because of premature release of dust is avoided. This is achieved by the presence of reinforcing fibers in the structure. Fig. 8.27 indicates that the briquette strength increases with addition of swarf while the necessary amount of chemical binder, constituting contamination and non-temperature resistant bonding, decreases. During simple atmospheric curing a considerable increase in strength occurs because of hardening of the chemical binder component, which improves the product’s handling and storage properties.

Fig. 8.28 shows a broken cylindrical compact that was manufactured during process development with a laboratory punch-and-die press and actual briquettes obtained in an industrial plant. Concerns that, when produced with a roller press, the addition of “fibers” would prohibit separation into mostly single, handleable pieces (see also Section 6.9.2) were unfounded.

Most dusts from pyroprocessing plants in the minerals and metals industries contain calcium and/or magnesium oxides. They hydrate easily, especially also during storage at high or even ambient humidity, only more slowly in the latter case. Since this reaction is coupled with a large increase in volume, when natural hydration occurs, with time even small amounts (> 0.5%) of alkaline earth oxides tend to lower the strength of any agglomerate, including high-quality briquettes, and, in many cases, eventually result in complete destruction. Therefore, if such components are present, an appropriate amount of water is mixed with the dust in a preparatory step

**Fig. 8.27** Cold crushing strength of briquettes from metal-bearing dust and sludge containing different amounts of dry lignosulfonate binder (called “sulfite waste powder”) with and without reinforcement by the addition of swarf [B.48, B.97]



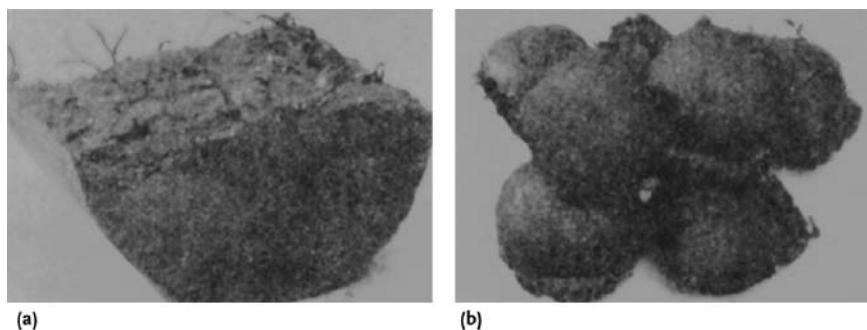


**Fig. 8.28** a) Broken cylindrical compact that was manufactured during process development with a laboratory punch-and-die press; b) actual briquettes obtained in an industrial plant [B.48, B.97]

and the oxides are allowed to hydrate prior to agglomeration. If afterwards additional moisture is required alone or as part of a binder system, a second blender must be installed in the agglomeration plant.

Because the design of agglomeration plants, especially of those using briquetting, can be very compact, they are often suitable for installation at or near the dust-collection system(s) (Fig. 8.29). They are fully automatic, needing practically no operator attention, and can be monitored from a nearby control room. In the case of dust recirculation from specialty steel production, the briquettes that were reinforced with alloyed steel grinding swarf were an excellent feed addition for electric arc fur-

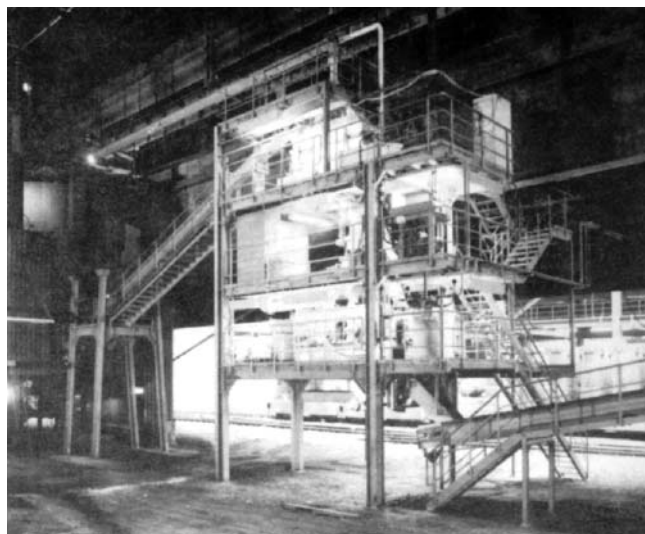


**Fig. 8.29** Compact briquetting system for metallurgical filter dust. Capacity 11–20 t/h, depending on feed characteristics (courtesy: Thyssen Stahl AG, Krefeld, Germany)

naces. Some 98% of the chromium and 99% of the nickel contained in the residue can be recovered by this practice [Section 13.3, ref. 103].

Fig. 8.30 shows how, by employing size enlargement by agglomeration, almost all solid wastes within, for example, the steel industry can be recycled (furnace and converter dusts) or processed into secondary raw materials (Waelz oxide, sinter), resulting in very little terminal residue going to disposal or to outside use (road building material). Hot and cold briquetting with roller presses are the predominant methods for size enlargement in this case because it can handle materials of varied composition, sizes, and properties. The rotary kilns shown in front of the hot briquetting machines are used for heating the feed to the required temperature. Alternative methods of heating can be chosen, too. Other agglomeration processes shown in Fig. 8.30 apply hot nodulizing (a tumble/growth method) in the Waelz kiln and sintering (agglomeration by heat).

Sometimes, when wastes are recycled, technological, physical, and/or chemical, limitations must be considered. For example, it is not possible to continue re-using steel mill dust (as shown in the right part of Fig. 8.30) indefinitely. Because of decrepitation and attrition, this would result in the production of an ever increasing amount of new dust and briquettes. Therefore, a maximum amount of briquettes in the feed per charge must be determined and the rest must be sold to other users. Also, an

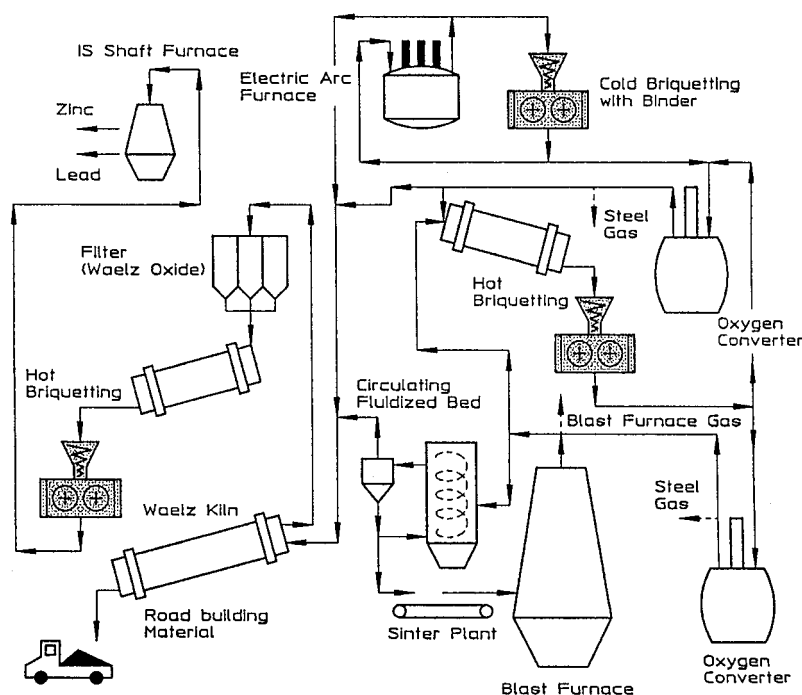


**Fig. 8.30** Size enlargement by agglomeration in iron and steel making for the minimization of terminal residue through recycling and the production of secondary raw materials [Section 13.3, refs 129, 166]

enrichment of contaminants, particularly zinc, takes place in the dust with each cycle. To determine its level, dust must be sampled and analyzed regularly. Once a certain concentration of zinc is reached, the entire dust that is in the system at this time is passed to the Waelz plant. The Waelz oxide is briquetted hot and treated in an Imperial Smelting (IS) shaft furnace to recover zinc and lead. As an example [8.2.2], in one plant, 3–4 t of briquettes are charged per heat and enrichment from about 5% to more than 17% of zinc occurs in 3–4 weeks. At that time, 350–400 t of briquettes are removed from the cycle for reprocessing in the Waelz kiln.

Certain processes shown in Fig. 8.30, such as the manufacturing of Waelz oxide and the recovery of zinc and lead, can not be supported by and operated economically in a single steel mill. Therefore, independently owned plants are often processing the waste from several producers and are, preferably, located in the geographical center of an industrialized area where suppliers of the metal-bearing dusts, users of the recovered metals, and customers for the by-products (road building materials) are close by. Also, with a trend away from the giant integrated steel mills towards smaller regional producers and the application of alternative iron units for steel making (direct reduced iron, Section 6.9), the treatment and recovery of metallurgical wastes is no longer economically feasible in these new facilities, although, in plants that are also using rolling mills and wire drawing operations for the manufacturing of intermediate products such as slabs, sheets, rods, and coils, they may additionally include mill scale and metal grindings, sludges, and slimes.

This situation is generally found in all industries generating recoverable and recyclable waste. In response, maximum amount tolling processors (Section 9.2) and specialized service companies are being created to take wastes and convert them into beneficially useable products or treat them for safe disposal. These companies fulfil the desires, requirements, and/or charter of the industry and of governments to conserve resources and to reduce the need for increasingly expensive disposal and scarce, often specially designed and protected deposition sites. While many are serving a small number of customers and are strictly of regional importance (see below), some operators are becoming large, even multi-national, globally active corporations.

An example of a large, multi-national service provider is Heckett MultiServ (Section 15.1). In their own words, this company, “delivers specialist services to more than a quarter of the world’s steel production, operating at over 160 sites in 33 countries and employing more than 9000 people. (Currently) every year (they) process 40 million tons of slag and debris, recover 9 million tons of steel, handle 11 million tons of scrap, and transport 10 million tons of liquid slag and 6 million tons of liquid steel. (Heckett MultiServ) design, build, and operate facilities for materials handling and preparation, waste processing, and environmental services ... (They work) within customer’s own premises and plants, providing tailor-made services using specialist technologies and equipment operated by their own highly-trained people”.

The above indicates that the services offered by this group include much more than processes that are related to size enlargement by agglomeration. In regard to the latter the corporation states that they have “extensive experience with a variety of steel industry by-products and that all processes offer the recovery of iron units and valuable metal-bearing components as well as reduced disposal costs”. Using binder systems,

both pellets (Fig. 8.31) and briquettes (Fig. 8.32) are made from the most appropriate by-product blends, meeting the demands of the iron and steel making process and the local environment. Tab. 8.6 lists materials that are successfully pelletized or briquetted by Heckett MultiServ around the world. Fig. 8.33 depicts stacks of pellets (left) and briquettes (right) that are ready for recycling.

Pelletizing (Fig. 8.31) is applied to convert waste and by-products from a steel mill that also operates a sinter plant into agglomerates with improved handling characteristics. The pellet composition is site specific. It depends on the number of components to be incorporated and their physical and chemical characteristics, including moisture content. By preparing the materials in this way, not only is recycling achieved but the productivity of the sinter plant is also enhanced. The inputs and ratios depend on the mill's specifications for so-called control elements, such as zinc, alkali, and oil. To date, Heckett MultiServ operates two pelletizing plants, both in Europe, with annual capacities of 100 000 and 200 000 t/year.



**Fig. 8.31** Disc pelletizer for the recycling of waste dusts, slurries, and plant fines (courtesy Heckett MultiServ, Butler, PA, USA)



**Fig. 8.32** Briquetting plant for and typical briquette from steel mill by-products (courtesy Heckett MultiServ, Butler, PA, USA)

**Tab. 8.6** Materials that are successfully pelletised or briquetted by Heckett MultiServ (Section 15.1) around the world

- 
- Sinter plant dusts
  - Blast furnace dusts
  - BOS grits and sludges
  - Magnetic fines from desulfurization and steel slags
  - Mill scale and oily mill scale sludges
    - EAF dusts
    - AOD/CLU/VOD (converter) dusts
    - Grindings and swarf
- 



**Fig. 8.33** Stacks of pellets (left) and briquettes (right) that are ready for recycling (courtesy Heckett MultiServ, Butler, PA, USA)

Briquetting (Fig. 8.32) is used for the recycling of particulate wastes and by-products in steel mills if a sinter plant does not exist or the inputs are unsuitable for the sinter plant/blast furnace route. In addition to the accurate proportioning and mixing of the materials with a suitable binder, control of the blend's moisture content is critical. At the present time Heckett MultiServ is operating seven briquetting plants with tonnages ranging from 7500 to 150 000 t/year in Canada and Europe and is in the process of installing another one in Australia.

#### 8.2.4

##### **Applications in Regional and Municipal Material Recycling Plants**

As a further example of major recycling efforts that use agglomeration methods to convert sorted wastes into recyclable secondary raw materials, regional material recycling facilities (MRF) [8.2.3] and municipal waste processing plants shall be discussed. Beginning in the 1980s, MRF were developed in several countries (USA – MRF; Germany – DSD, Duales System Deutschland) to separate, through process design, tech-

**Tab. 8.7** Commonly considered advantages of material recycling facilities [8.2.3]

- Since MRFs permit co-mingling, public participation is made easier as less sorting is required by the waste generator. This leads to higher recycled volumes and unburdens the conventional municipal solid waste collection and processing.
- Collection costs can be reduced since less expensive equipment can be employed and time consuming sorting at the curb is eliminated or reduced.
- Higher volumes of recyclable materials offer greater market influence and acceptance since industry quality standards can be better met by producing superior forms of secondary raw materials.

nology, and human inspection, co-mingled recyclable materials and convert them into marketable commodities. These facilities are in addition to the conventional municipal solid waste processing plants. While for the latter wastes are picked up indiscriminately from households or collection points, the feed for MRF, although still more or less co-mingled, has been pre-sorted by the originators and is collected from curb sides or special collection containers. Tab. 8.7 lists the three principal characteristics of MRF that are commonly considered as advantages and Tab. 8.8 provides a breakdown of MRF separated recyclables in a specific plant, typical processing costs, and expected market prices of the resulting secondary raw material [8.2.3].

**Tab. 8.8** Breakdown of MRF separated recyclables in a specific plant as well as typical processing costs and expected market prices (US Midwest, end of 1992) of the resulting secondary raw material (adopted and modified from [8.2.3])

| Material        | % of total | Processing cost<br>US\$/t | Market price<br>US\$/t |
|-----------------|------------|---------------------------|------------------------|
| Paper           | 50         |                           |                        |
| Newsprint       |            | 33.59                     | 0–20                   |
| Cardboard       |            | 42.99                     | 10–30                  |
| Mixed           |            | 36.76                     | 5–25                   |
| Cans            | 10.50      |                           |                        |
| Steel           | (6.4)      | 67.53                     | 49–78                  |
| Aluminum (UBCs) | (4.1)      | 143.51                    | 500–900                |
| Glass           | 29.00      |                           |                        |
| Clear (flint)   | (11.8)     | 72.76                     | 50                     |
| Brown (amber)   | (3.9)      | 111.52                    | 25–40                  |
| Green           | (4.7)      | 87.38                     | 5–15                   |
| Mixed           | (8.6)      | 50.02                     | 0–30                   |
| Plastic         | 7.75       |                           |                        |
| HDPE            | (5.1)      | 187.95                    | 40–160                 |
| PET             | (2.5)      | 183.84                    | 40–200                 |
| Polystyrene     | (0.08)     | –                         | –                      |
| Foil            | (0.07)     | –                         | –                      |
| Waste Residue   | 2.75       | –                         | –                      |

Tab. 8.8 shows that the most valuable material in MRF recycling streams are used (aluminum) beverage cans (UBC) which, with the exception of paper (see below), represent the only material that, at the assumed market conditions, can be sold for a profit. More recently polymer recycling has become feasible too (see below). As discussed in Section 6.9.2, the aluminum industry has one of the most advanced and complete recycling programs in the metals market [Section 13.3, refs 120, 132, 137]. The major reason for this is that the production of aluminum from Bauxite requires large amounts of electrical energy so that, today, most of the producers are located in areas where cheap (hydroelectric) power is available. Transportation from these locations to the finishing mills adds substantially more to the cost of the virgin material.

Aluminum is becoming one of the major metals used for packing, replacing steel and, in many cases, glass. As a result, a large segment of aluminum recycling is based on the collection and processing of used beverage cans (UBC) and other aluminum (food) containers [Section 13.3, ref. 132]. Competitively priced high-quality can stock can be made from re-melting aluminum containers after they have been decoated (delacquered) by solvent or, more commonly, thermal processes.

The objective of decoating is to remove paint, lacquer, plastic, paper, and other contaminants (food residues) with minimal modification of the metal. The nature and amount of the coatings vary widely. They include organic chemical compounds, which are predominantly volatile (VOC, volatile organic compound), inorganic components, which are added for coloring and mass, plastic or paper laminates, and oil and water from machining and forming operations. After proper decoating, it is also possible to recycle, in addition to UBC, such materials as clean foils, printed foils, painted packaging, paper- and plastic-laminated foil, food containers, litho plate, and contaminated extrusions.

The raw aluminum scrap separated, for example in an MRF, from the other materials is rather voluminous and, if decoating is not available on site, which is the most common situation, are baled, an agglomeration process typically using hydraulic presses (Section 6.9.2, Fig. 6.9.19) for transportation to the thermal treatment facility. There, the key to efficiently producing a quality decoated aluminum scrap product is feed preparation, which includes shredding during which bales are broken-up and larger parts are reduced in size to less than about 50 mm. This material is then subjected to screening to remove fines < 3 mm, which are discarded, and to magnetic separation.

Decoated aluminum scrap leaves the thermal treatment unit in particulate form with a temperature of about 500 °C. Since, in most cases, the remelting furnaces are also at a different location, the product is again baled (hot) and sold as premium “old” aluminum scrap to secondary aluminum smelters.

A disadvantage of using baling at this point is that, prior to feeding the scrap into remelting furnaces, these bales must be torn apart again because:

- the bales are too large for direct charging,
- operators want to make sure that the scrap quality is consistent throughout, and
- bales may have picked up excessive amounts of moisture, which must be removed.

A disadvantage of using the resulting loose scrap, although found of acceptable quality, is that considerable oxidation losses (dross) occur during melting.

As an alternative to baling, particulate decoated aluminum scrap can be converted into highly densified ( $>2.0\text{--}2.3\text{ g/cm}^3$ ) slabs using roller presses (Section 6.9.2) [Section 13.3, ref. 140]. Fig. 8.34 shows in the upper part different processed MRF aluminum wastes. They are from left to right: light foil, dense foil, and UBC. Densifying these materials in roller presses as described in Section 6.9.2 yields products as depicted in the lower part of Fig. 8.34. Although UBC do not reach a density of more than  $2.0\text{ g/cm}^3$ , even if they are hammer-milled or mixed with other, heavier aluminum wastes before compaction, a considerable improvement of recovery is obtained with a product as shown in the right lower part of Fig. 8.34. The slabs are particularly advantageous as feed for reverberatory furnaces. They can be easily charged and the metal losses experienced during the melting of loose, particulate aluminum scrap, which typically amount to 15–20%, are reduced to 2–4%.

In general, for the compaction of clean processed metal swarf, two methods are available. The non-continuous confined volume punch-and-die process and the continuous compaction in the nip of two counter-rotating rollers (Section 6.9.2).

With the punch-and-die process clean, delacquered, and crushed UBC can be compacted to yield a relatively high apparent density. The product shape is normally cylindrical with diameters between 80 and 190 mm, heights between 30 and 120 mm, and weights between 0.4 and 7.3 kg (Section 6.9.2). Although the punch-and-die technology is by far the most widely applied choice for the compaction and shaping of UBC-based aluminum scrap it also has a number of disadvantages of which the most important is the relatively slow movement of the (hydraulic) rams. Therefore, it is used when relatively small amounts of processed aluminum cans and containers must be compacted.

Influenced by developments in connection with the briquetting of aluminum home scrap (Section 6.9.2), the continuous compaction between two rollers is now a feasible

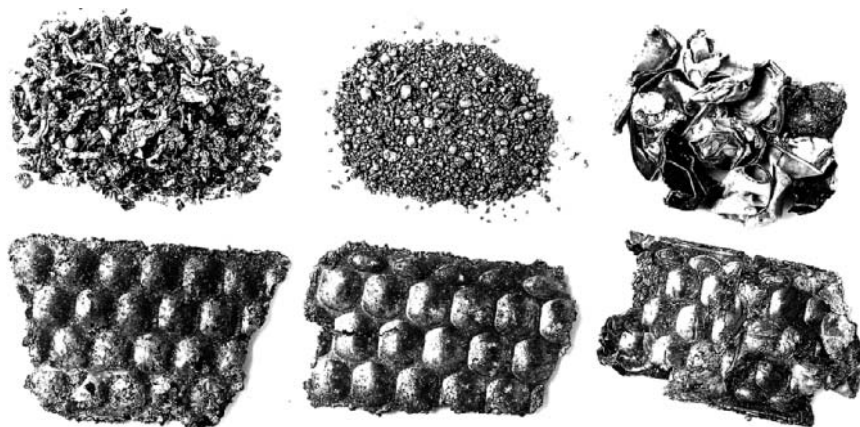


**Fig. 8.34** Three different MRF aluminum wastes as collected and processed (top) and after roller press compaction [Section 13.3, ref 132]. From left

to right: loose foil, densified (granulated) foil, delacquered and hammer-milled used beverage cans (UBC)

alternative. It offers the advantages of large capacity and high apparent density. However, since an endless sheet is formed with these machines, there is no hope of producing directly individual compacts, such as cylindrical briquettes from the punch-and-die process that can be easily charged into the remelting furnaces. Similar to the solution presented in Section 6.9.2 a suitable cutting device (shear) must be employed to divide the strip into slabs, pieces with acceptable dimensions.

Other examples of regional processors and recyclers are modern modifications of the conventional municipal waste disposal plants. Until recently there were two alternatives for the removal, handling, and elimination of municipal wastes. Originally, after pick-up from the curb or from specific collection points, the entire mass was disposed of in landfills, either filling natural or excavated holes or building mountains, which, after completion, were covered with dirt and topsoil and left to rot. Aside from the scarcity of suitable land near population centers to accept the exponentially growing masses of waste, problems arose with time from the leaching of harmful chemicals into aquifers and the production of increasing amounts of methane within the waste. These required the rehabilitation of many of the older, sometimes already abandoned landfills and triggered environmental laws, severely restricting the use of existing and opening of new landfills and/or requiring special design considerations (such as leakproof liners, collection and removal or use of methane gas, etc.) for new disposal sites thus making this method expensive and unattractive.

Efforts to entice consumers (households) to segregate wastes into recyclable components, such as paper, metals, and plastics (see above), and rejects, reduced the amount of materials to be disposed of but created mostly organic discards, which become smelly and produce gases and other environmental contaminants if not properly handled and stored. The logical solution to this problem, the municipal waste incinerator, often faces public opposition. Therefore, communities and waste processors, supported by new laws that require the conversion of solids with a certain heating value into (industrial) fuels, are forced to develop new methods for further segregation of wastes and the processing of the resulting components.

Since not all regions have adopted the separate collection of recyclables and not all waste generators accept the desire to segregate, the first processing step in a modern municipal solid waste treatment plant is to segregate the waste by scalping (screening, size), manual and visual selection (paper and paper products, wood, plastic containers), shredding of large pieces, re-screening (size), magnetic separation (metals), jigging (density, plastic), etc. Metals, divided into magnetic and non-magnetic (aluminum) varieties, are sold as iron-bearing (magnetic) and non-iron, heavy scrap or transferred to aluminum scrap processing (see above). Increasingly, natural and man-made organic materials that can be burnt are converted into a secondary solid fuel product.

The latter is exemplified with the description of a recently installed (1999) large plant in Schwarze Pumpe, Germany, for the production of pellets from municipal (household) solid waste, the light fraction from a shredder plant, DSD (see above) plastics, and waste wood (chips, saw dust, crushed, or reduced to fibers). Typically, the mixture to be pelleted consists of 50% household waste, 10% light shredder fraction, 25% DSD plastics (with up to 75% foil), and 15% wood. Depending on the composition of these ingredients (Tab. 8.9), the feed can be coarse and light (20–60 mm long,

**Tab. 8.9** Approximate compositions of two common feed mixtures to the pelleting machines of the secondary solid fuel manufacturing plant at Schwarze Pumpe, Germany (Courtesy Amandus Kahl, Reinbek, Germany)

| Description/Component        |                     | Light mixture | Fine mixture |
|------------------------------|---------------------|---------------|--------------|
| Size range                   | [mm]                | 20–60         | 0–20         |
| Thickness                    | [mm]                | < 5           | < 5          |
| Moisture content             | [mass %]            | approx. 10    | approx. 10   |
| Bulk density                 | [t/m <sup>3</sup> ] | 0.06–0.25     | 0.06–0.46    |
| Paper, cardboard             | [%]                 | 22–50         | 5–10         |
| Organic waste                | [%]                 | 8–15          | 50–70        |
| Composit (packing) materials | [%]                 | 7–16          | 0.5–2        |
| Wood                         | [%]                 | 1             | {            |
| Foils                        | [%]                 | 5–15          | {            |
| Hygiene articles             | [%]                 | < 3           | { 20–25      |
| Plastics                     | [%]                 | 5–15          | {            |
| Glass, stone, sand, ash      | [%]                 | < 1           | < 1          |
| Textiles                     | [%]                 | 1–7           | –            |
| Foams, rubber, felt          | [%]                 | approx. 1     |              |

< 5 mm thick, bulk density < 0.25 t/m<sup>3</sup>) or fine and somewhat heavier (0–20 mm long, < 5 mm thick, bulk density < 0.46 t/m<sup>3</sup>).

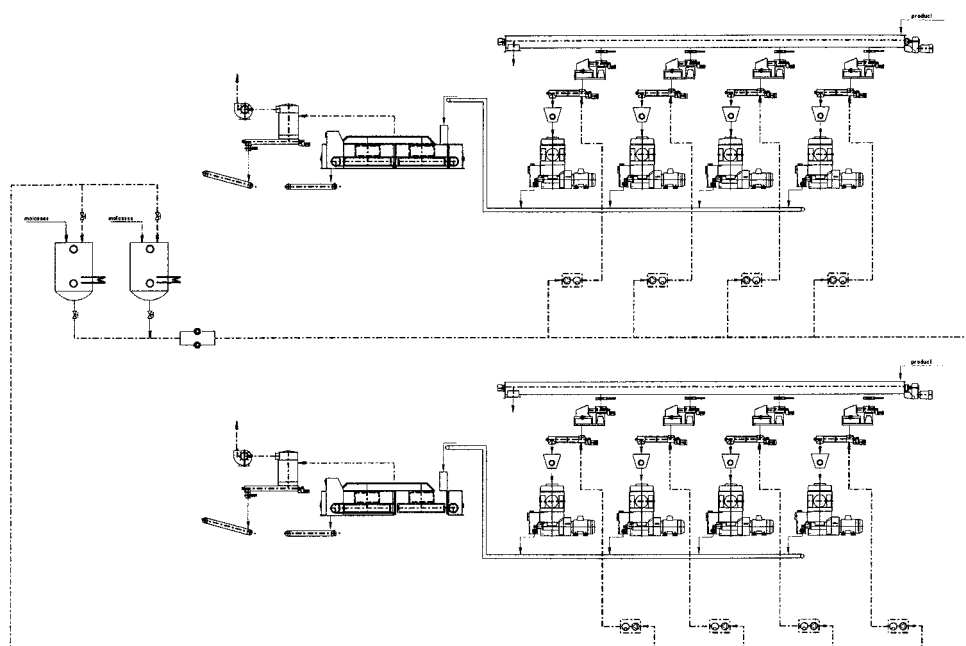


**Fig. 8.35** Flow diagram of the pelleting section of the secondary solid fuel manufacturing plant at Schwarze Pumpe, Germany (courtesy Amandus Kahl, Reinbek, Germany)

Fig. 8.35 is the flow diagram of the pelleting section of the plant that is equipped with two identical lines. Each line (Fig. 8.36) features four flat die pellet presses [B.48, B.97], which are fed volumetrically from a common chain conveyor and individually with screw feeders, in which, if applicable, a liquid binder (molasses) can be added. Although a liquid binder system is installed, pellets with good quality can often be produced without a liquid additive if up to 15% wood fiber is present in or added to the feed mix. Each press produces up to 2.5 t/h of green (< 10% moisture content) pellets with a diameter of 16 mm and 50–70 mm in length, which are collected and transferred to a belt cooler. During pelleting heat is produced by the conversion of mechanical into thermal energy and friction, which is removed in the coolers. At the same time, some of the moisture is evaporated, increasing the heating value of the product. Problems can arise from the presence of metals, stones, long items (video tapes, stockings, foils, etc.), non-compactible materials (glass, hard rubber, and similar materials with a thickness > 5 mm), tropical hardwood, and broken plywood. Tab. 8.10 describes some of these limitations in more detail. For the safety of the pelleting system it is imperative to limit the tramp material contents in the feed accordingly.

With the increasing availability of materials that should, preferably, no longer be deposited in landfills and are recyclable, entrepreneurs are developing new regional processing plants that serve particularly the building industry. The manufacturing of artificial aggregate, dense and lightweight, is currently the most common application. Fig. 8.37 is the generic block diagram of a versatile plant using extrusion [B.48, B.97] for the agglomeration step in the production of lightweight aggregate from waste materials [8.2.4]. To achieve bloating during firing of the green extrudates, chemistry within certain ranges is required. Materials that meet all or most of these criteria are clay and clay-like wastes, including flyash, bottom ash, contaminated river, lake, and harbor bottom solids, and fines resulting from igneous rock washing. In addition to these primary wastes, secondary materials can be added, such as various waste sludges. Sludge may make up as much as 25–30% of the dry weight of an aggregate mix. However because drying is not generally economical, the sludge can carry at most the amount of water that is required for the extruder feed. Solid fuel (coal) fines add heating value that will lower the process energy requirement during the firing stage.

Other new developments aim to enhance the value of the materials to be recycled while producing the secondary raw material. In particular, iron-bearing solids from

**Tab. 8.10** Limitations on the contents of tramp material in the feed to the pellet presses for the production of secondary solid fuels from waste (Courtesy Amandus Kahl, Reinbek, Germany)

- 
- Stones and glass with diameters of up to 2 mm are acceptable without influencing operation.
  - Stones and glass with diameters < 10 mm are acceptable but may reduce die life.
  - Removal of ferrous, particularly also stainless steel, and non-ferrous metal parts from the feed must be guaranteed.
  - The presence of up to 3% of oversized material, other than mentioned above, does not reduce the plant's performance. Higher percentages and long items (see text) may cause a number of problems resulting in unscheduled downtime.
-

**Fig. 8.36** Four flat die pellet presses of the secondary solid fuel manufacturing plant at Schwarze Pumpe, Germany (courtesy Amandus Kahl, Reinbek, Germany)

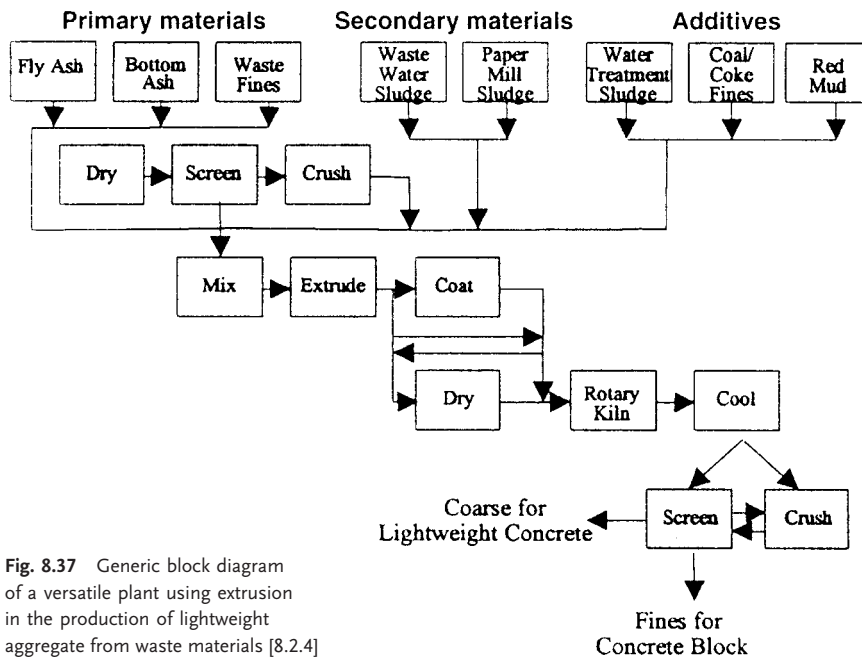


**Fig. 8.37** Generic block diagram of a versatile plant using extrusion in the production of lightweight aggregate from waste materials [8.2.4]

different sources are reduced to yield a value added material containing a certain percentage of metallic iron. The mostly gas based direct reduction processes for iron ores (Section 6.9.2) are only economical if operated at large scale ( $>500\,000$  t/y). Regional recycling plants must be profitable at much lower capacities. One possibility to achieve this is using a rotary hearth furnace (FASTMET) for the processing of pellets from blast furnace and steel making dusts (Fig. 8.38). Iron-bearing oxide fines, reductant (coal), and binder are mixed, agglomerated on an inclined pan, and dried (Section 6.8.1) prior to feeding the rotary hearth furnace. The carbon in the pellets acts as a reducing agent (reductant), reacting with the iron oxide and leaving a direct reduced iron (DRI) with a high metallic content. The hot product may be directly transferred to an electric arc furnace for melting or briquetted (Section 6.9.2) for external marketing. Zinc recovered from the off-gas can be also recycled. A further new technology uses agglomerated dusts, coal, and air in a multiple hearth furnace (PRIMUS) to recover high-purity lead and zinc and produce highly metallized (90–95 %) iron concentrate (Fig. 8.39).

While many cellulosic wastes, particularly wood, can be and are being converted to secondary solid fuels (see above and Section 6.10.2) efforts are also undertaken to produce agglomerated, value-added secondary raw material that can be used in the manufacturing of engineered wood products. One such method is described in Swiss patent SP 530 261 [Section 13.3]. It shows that saw dust, which is produced in large

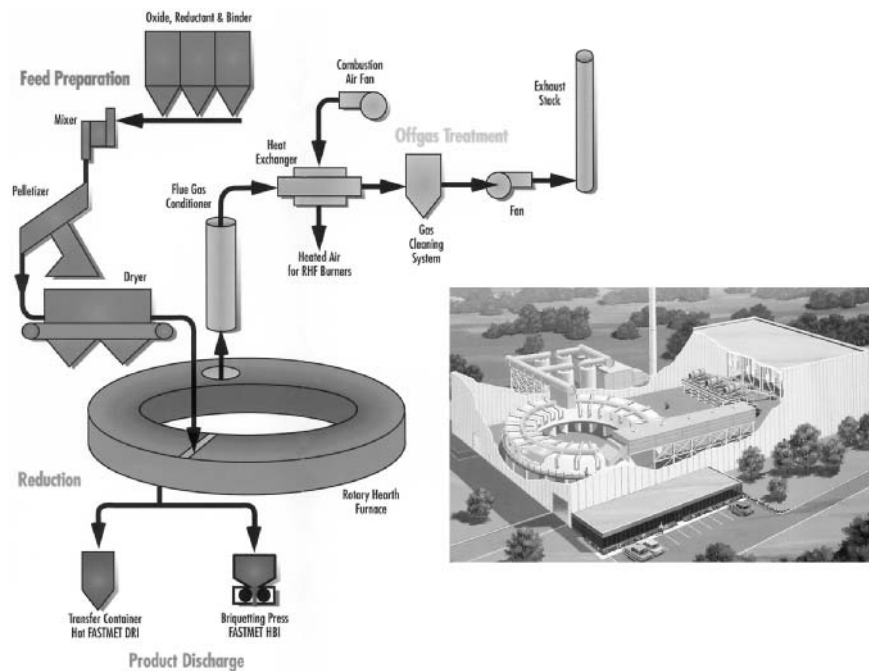


**Fig. 8.38** Flow diagram and artist's impression of a recycling plant for the production of secondary raw material (DRI) from iron-bearing oxide fines,

employing a rotary hearth furnace (FASTMET) for the reduction of pellets with coal as reductant (courtesy Midrex, Charlotte, NC, USA)

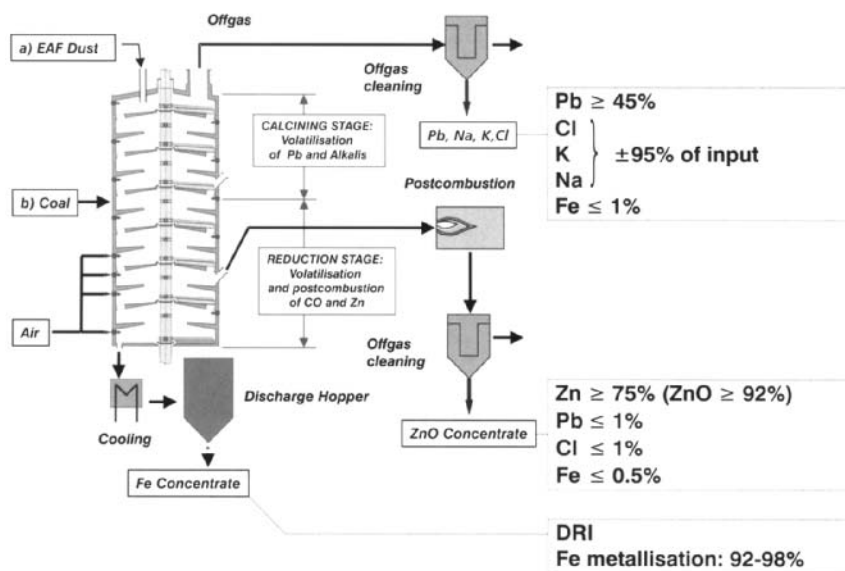


**Fig. 8.39** Flow diagram of a recycling plant for the manufacturing of secondary raw material (DRI) from iron-bearing dusts, employing a multiple hearth furnace (PRIMUS) for the production of highly metallized iron concentrate with coal as reductant and the recovery of high-purity lead and zinc (courtesy Paul Wurth, Luxembourg)

amounts during the cutting to size of plywood and pressboards in their manufacturing plants, can be converted into small, thin, chip-like briquettes with roller presses and used, together with virgin wood chips, in the center layer of plywood pressboards. The adhesive (binder) that is contained in the saw dust and causes environmental concerns when burnt in, for example, boilers, is activated by the heat produced during briquetting (conversion of mechanical into thermal energy) and participates in the bonding of the artificial secondary wood chips. Using this technology conserves natural resources and avoids environmental pollution.

As in other industries, within recycling facilities, agglomeration equipment is increasingly used for other applications than originally anticipated (Section 6.11.2, high-pressure roller mills). An example, utilizing flat die pellet mills, will be described in the following. A German recycler of wood and building materials feeds bulky wastes, carpets, parts of man-made plastics, textiles, cardboard, and wood that have all been pre-crushed to 90% <40 mm, contain 10–20% moisture, and have a bulk density of 50–110 kg/m<sup>3</sup>, to flat die pellet presses, featuring 22 mm diameter die holes. Fig. 8.40 depicts the arrangement and flow diagram of the plant, showing the potential to ultimately install six pellet mills, and Fig. 8.41 is a photograph of the system in its current four-mill execution. Each machine has a throughput capacity of about 5 t/h. As the feed materials are compressed by the press rollers and forced through the die holes they experience a further reduction in size and leave the press(es) as a partially pelleted, easily handleable, and free flowing “fluff” that can be readily

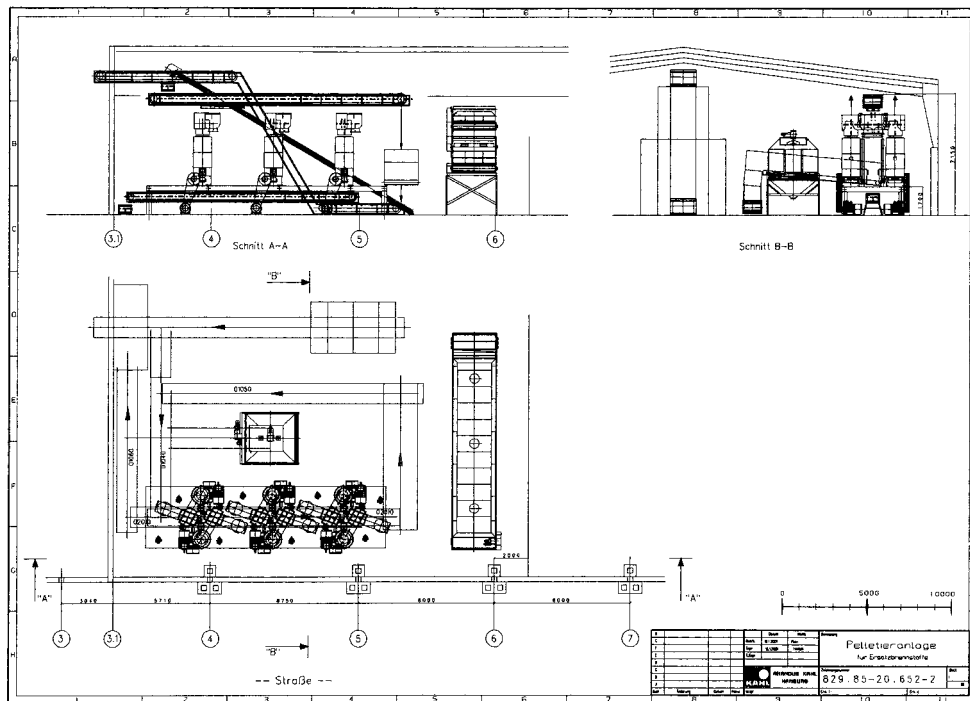




**Fig. 8.42** Pelleted secondary fuel, right, from combustible domestic and industrial waste, left (courtesy Amandus Kahl, Reinbek, Germany)

As mentioned several times before, in most developed countries massive disposal of organic municipal refuse into landfills is prohibited. Sludge from waste-water processing and cleaning facilities poses a particular problem that requires new solutions. Biological digestion, dewatering, and drying is often used to arrive at a material that, with a residual water content of 1% or a solids content of 99%, can be burnt if suitable boilers are available. However, as shown in Tab. 8.11 the dried digested sludge powder, for example from OCUA (see below), is very fine and light [Section 13.3, ref. 107]. Because the incinerator is normally not nearby, considerable storage and transportation problems are experienced (Chapter 4).

Some years ago, Ocean County Utility Authority (OCUA), NJ, USA [Section 13.3, ref. 107], with the help of the US Environmental Protection Agency (EPA), searched for an innovative approach to their sludge processing. This summer vacation and resort area has the additional problem of seasonally changing amounts of waste water; the actual daily quantities of dry sludge solids in the 1990s were 31 t/d in summer while the yearly average was only 25 t/d. It was forecast at the time that this relation will change to 39 t/d (summer) and 35 t/d (yearly average). The four major components of a sludge management system, processing, storage, transportation, and disposal or utilization were first investigated. It was decided to develop a site-specific method of

**Tab. 8.11** Characteristics of OCUA (Ocean County Utility Authority, NJ, USA) dried sludge powder [Chapter 13.3, Lit. 107]

| Parameter              | Unit                | Value             |
|------------------------|---------------------|-------------------|
| Moisture content       | [%]                 | 1                 |
| Particle size range    | [mm]                | 90% >0.1 and <0.5 |
| Temperature (cooled)   | [°C]                | <65               |
| Organic solids content | [%]                 | 60                |
| Bulk density           | [t/m <sup>3</sup> ] | 0.56              |
| Angle of repose        | [°]                 | 37                |

“sludge drying and beneficial use”. To obtain the aforementioned amounts of waste solids that render advanced processing feasible and economical, even in winter, the sludge from three water pollution control facilities (WPCF) had to be combined. Each WPCF features similar treatment systems, including primary clarifiers (Section 8.1), activated sludge secondary treatment and thickening, and anaerobic digestion of mixed primary and activated sludge. The digested sludge is dewatered (by filter presses) and, heretofore, has been disposed in local sanitary landfills. A diagram of the new overall sludge management is shown in Fig. 8.43.

It was decided to install an innovative new sludge drying system using mechanical vapor recompression (MVR, Carver–Greenfield process). The resulting powder (Tab. 8.11) is biologically inactive but tends to dusting, poses fire and explosion hazards, easily picks-up static electricity, features an explosion limit of 0.2 g/L and tends to self-ignition above 150 °C. Because of the high organic solids content and a considerable amount of agronomically available nitrate it was assumed that, after a suitable size enlargement by agglomeration, the material could be used as a soil conditioner component in fertilizer bulk blending plants (Section 6.6.2).

For many years already, the Milwaukee (WI, USA) Metropolitan Sewerage District used pelleting with cylindrical dies (Chapter 5, Fig. 5.10b5) to create “Milorganite”, a soil conditioner/fertilizer product. In this application, fines, produced in rotary sludge dryers, are converted into cylindrical pellets, which are crumbled (crushed) and screened into a granular product featuring a particle size range of 0.25–1.4 mm. A number of reasons precluded the use of this technology for the OCUA project. To be suitable as a component in bulk blending fertilizer plants, the particle size range must be between 1 and 3.3 (<4) mm. When pellets are broken, only smaller particles can be made because the interior of such extrudates remains relatively weak and friable (Section 6.1, Fig. 6.1-7). The low moisture content of powder from the Carver-Greenfield MVR plant, resulting from an EPA requirement of “further reducing pathogens”,

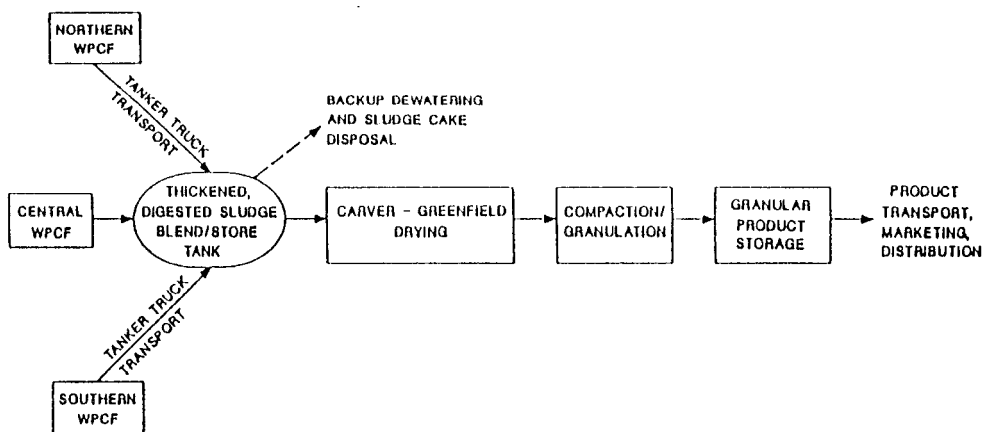


Fig. 8.43 Diagram of the new overall sludge management of OCUA  
[Section 13.3, ref. 107]

and the high content of sand (mostly in summer from vacationer's beach activities) threatened excessive wear (already a major problem in Milwaukee) of the extrusion dies and uneconomically high costs.

For the above reasons, OCUA decided to install a compaction/granulation system utilizing a roller compactor for the manufacturing of a highly densified sheet, which is crushed and screened to yield the desired product (Section 6.6.2). Fig. 8.44 is the flow diagram of the plant. Some specific considerations for this project were the following [Section 13.3, ref. 104].

#### 8.2.4.1 Influence of Fibers, Strings, etc.

During the preliminary testing, fibrous ingredients in the sludge powder were identified as a potential problem during granulation (crushing) of the compacted sheet. However, this was not confirmed in large scale operation; although short (2–5 mm since earlier processing steps did grind all sludge material) fibers, hair, pieces of cord, and other stringy material are present and visible in the powder, the recycled material, and the product, there is no evidence that they had a negative effect on the process. Nevertheless, caution must be exercised since over longer periods of operation fibrous materials may accumulate and cause problems; they may blind heat exchangers (in the drying section), screens, fans and filters requiring unscheduled shut-downs and maintenance.

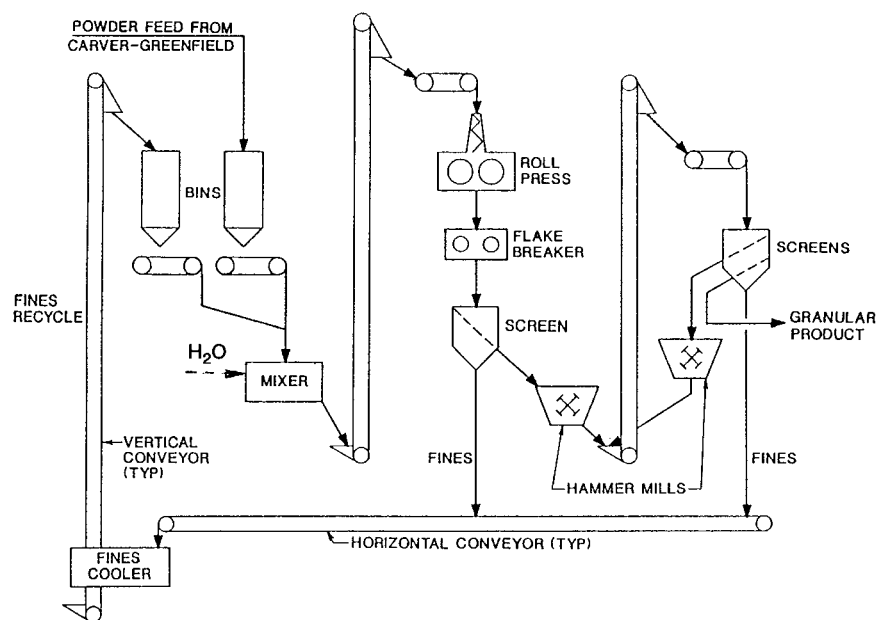


Fig. 8.44 Flow diagram of the compaction/granulation system at OCUA [Section 13.3, ref. 104, 107]

#### 8.2.4.2 Influence of Temperature

Prior to entering the compaction/granulation system, the dried powder is cooled to  $<65^{\circ}\text{C}$ . For proper compaction, a small amount of water must be added to the mixer in which fresh powder and recycled material are combined, adjusting the feed moisture content to about 8%. During blending the temperature of the material increases by about  $25^{\circ}\text{C}$  because of exothermal chemical reactions and the input of mechanical energy. For the latter reason, a further temperature rise of at least  $20^{\circ}\text{C}$  occurs during compaction and a small increase in temperature must be expected during milling. Because, as a result of this, the material in the plant may reach temperatures around or exceeding the boiling temperature of water, steam must be expected in all parts of the system. Although this may be advantageous from the point of view of suppressing the explosion hazard it has to be considered during plant design. All equipment must be well vented. Particularly the product silos, which are installed outside (Fig. 8.45), must also be insulated to avoid condensation. Final dust removal and odor control must be carried out wet. Finally, the recirculating material must be cooled to keep the temperatures in check.



**Fig. 8.45** Photograph of the outside product storage silos at OCUA (courtesy Ocean County Utility Authority, Toms River, NJ, USA)

#### 8.2.4.3 Alternative Product Use

Chemical analyses of the powder revealed that its actual composition changes with the seasons and as a result of many other factors. In view of its intended use as an agriculturally beneficial soil sweetener, a significant amount of heavy and other metals raised concerns. Based on legislation, valid at the time of project execution and during the immediate future, the contaminant levels were considered acceptable for partial use in Florida's citrus groves. However, to provide a process alternative that could be used if the granular material is no longer accepted by farmers and/or brokers as a fertilizer conditioner, diverter gates are installed after the product screen to alternatively discharge the large pieces from the top as product and recycle the two other, finer streams, bypassing the secondary hammer mill. In this case, the larger pieces (<50 mm) are used as secondary solid fuel in industrial boilers, utilizing the heating value of the mostly organic solids. If the lower size limit of this product must be larger than 4 mm the top deck of the double deck screen should be changed and, to avoid the recirculation of exceedingly large particles to the feed mixer and roller compactor, a small change of the flow diagram will direct the middle fraction to the secondary hammer mill (grate bar distance and hammer tip speed may have to be readjusted). The discharge of the mill goes directly to the recycling loop.

#### 8.2.4.4 Energy Efficiency

Among other plant components, the OCUA solids management project also includes facilities for waste energy usage. Firstly, an energy recovery system is associated with the sludge drying process. A fluidized bed reactor is installed to burn waste sewage oil and scum and a waste heat boiler produces steam. Secondly, a co-generation system, consisting of six turbo-charged, lean burn, digester gas driven engine/generators with a total electrical output of 1800 kW became part of the project. With this system, a significant portion of the electrical requirements for the northern and central WPCFs (Fig. 8.43) is produced.

When producing a partially dried (about 90% solids content) digested sludge that does not contain large amounts of abrasive contaminants (sand), it can be also converted into a secondary solid fuel by pelleting and drying. Fig. 8.46 is the simplified flow diagram of a facility using a flat die pellet press and a belt dryer/cooler and Fig. 8.47 shows photographs of the pellet press and the dryer/cooler in an actual plant (City of Nürnberg, Germany). The pellets can be easily stored, transported, and, for example, metered as complementary solid fuel into the stoker of coal-fired power plants or boilers.

### 8.2.5

#### Other Applications

Sometimes, simple tumbling motions, for example on the slope of stock piles or on other inclined surfaces, are sufficient for the formation of crude agglomerates [B.48, B.97]. These low-cost particle size enlargement processes are primarily used in a spe-

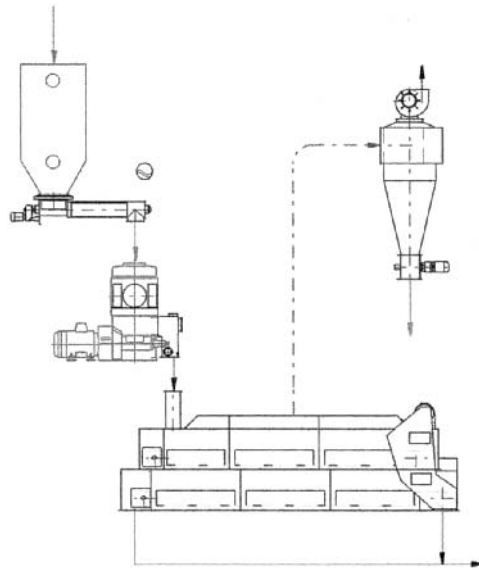


**Fig. 8.46** Simplified flow diagram of a facility using a flat die pellet press and a belt dryer/cooler for the production of secondary solid fuel from digested sewage sludge (courtesy Amandus Kahl, Reinbek, Germany)

cial segment of secondary raw material processing and for the production of agglomerates during the processing of refuse for disposal (Section 8.1).

Applications in the first area are, for example, in the recovery of small amounts of valuable, mostly metallic ingredients, such as gold and silver from previously discarded tailings of older mines. Originally, these rejects could not be economically processed. In the meantime, a technology was developed for the extraction of valuable components in very low-grade ores, called “heap leaching” [B.48]. It can be also used for the retreatment of tailings, which then become secondary raw materials. The main problem during these applications is the segregation of coarse and fine particles in the heap during its construction and/or the movement of fine particles with the leach solution. This primary and secondary segregation creates areas with significantly lower permeability as shown in a simulation of the liquid flow (Fig. 8.48, [8.2.5]). Consequently, the leach solution follows paths of least resistance through “open” areas and bypasses or only barely wets those containing large amounts of fines. This results in lower extraction efficiency, longer leaching time, and higher reagent (chemical or bacterial) consumption.

The percolation problems can be minimized if fines are attached to each other or to coarser particles by agglomeration. When building the heap, fines are now uniformly distributed and, if the bonds within the agglomerate are strong enough and do not deteriorate during leaching, remain immobile. A more uniform wetting (Fig. 8.49, [8.2.5]) and efficient operation is obtained.

Because the heap leaching technology is a low-cost process and the amount of recoverable ingredients is small, high expenses for agglomeration are not warranted. The basic principle of “cheap” size enlargement is demonstrated and used in stockpile agglomeration (Fig. 8.50, [B.48, B.97]). An inclined conveyor transports tailings that

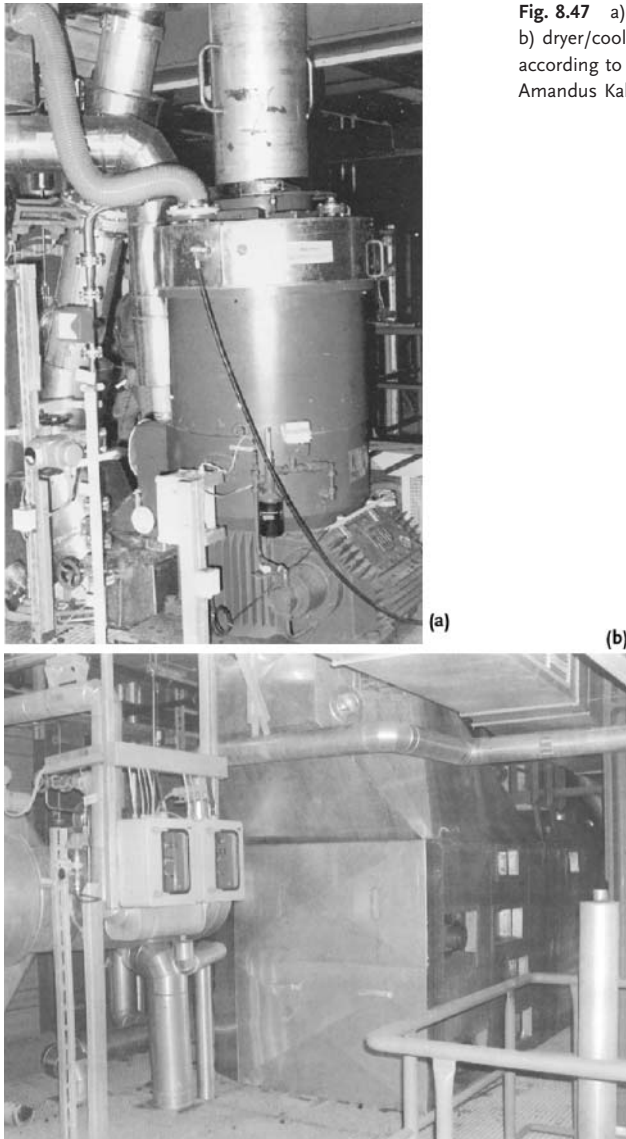


**Fig. 8.47** a) Pellet press and  
b) dryer/cooler in an actual plant  
according to Fig. 8.46 (courtesy  
Amandus Kahl, Reinbek, Germany)

were mixed with appropriate amounts of CaO, cement, and/or other suitable dry binders to a point several meters above ground. The stream of material falling from the end of the conveyor is wetted with water (and/or other liquid) sprays. Below the spray area, several heavy (dispersion) bars extend into the falling curtain and act as a simple, stationary mixer. The wetted mass then tumbles down the slope of a stockpile and agglomerates into lumps that collect at the foot of the pile. Strengthening occurs by natural curing, begins immediately, and continues until the cementitious reactions

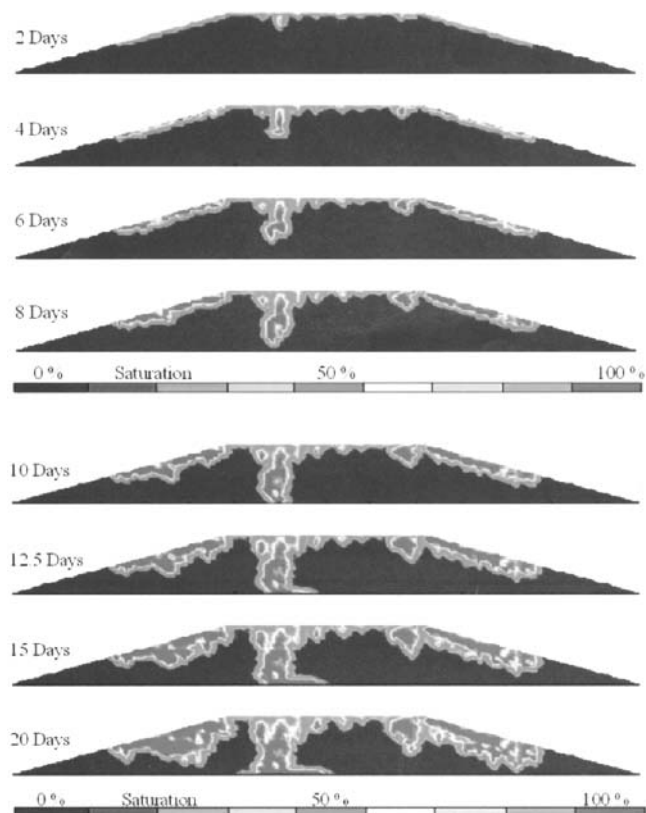


**Fig. 8.48** Simulation of liquid flow in a heap constructed of non-agglomerated ore [8.2.5]

are completed. A front-end loader picks-up the agglomerates from the periphery of the pile and transfers them into a dump truck or directly onto the leaching pad of a reclamation plant.

The same principle of agglomeration can be applied at multiple transfer points from belts to belts, on shaking or vibrating conveyor decks, or on steeply inclined belt conveyors where material tumbles downward against the upward motion of the belt [B.48, B.97] (Section 8.1, Figs. 8.14, 8.15, and 8.16).

### Further Reading

For further reading on the above subjects the following publications by the author, some of which were referenced above, are recommended (Section 13.3): 32, 44, 45, 46, 49, 50, 55, 58, 61, 62, 63, 71, 74, 78, 92, 103, 104, 107, 109, 113, 120, 122, 123, 124, 126, 129, 131, 132, 133, 134, 135, 137, 140, 142, 157, 166.

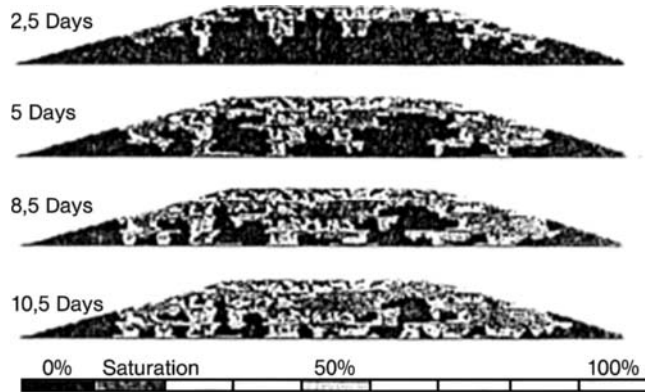


Fig. 8.49 Simulation of liquid flow in a heap constructed of narrowly sized (agglomerated) ore [8.2.5]

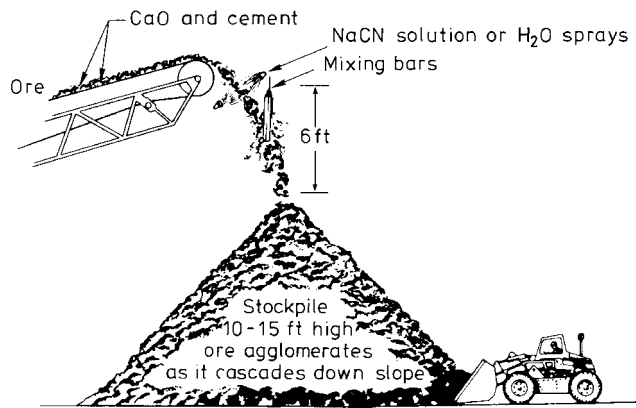


Fig. 8.50 Diagram of stockpile agglomeration [B.48, B.97]

### 8.2.6

#### Recycling of Polymers

Plastic man-made materials, mostly in the form of polymers, have become a major component of industrial and municipal (Tab. 8.8) wastes. While some modern materials are biodegradable and, therefore, can be disposed of in unsecured landfills, others are permanent contaminants and, if incinerated, may produce harmful compounds, such as dioxins.

Growing environmental awareness has prompted plastics recycling programs in most developed countries. In spite of this, however, currently only some 5–25 % of plastic waste is being recycled but, as worldwide consumption of plastics is set to grow, this will have to expand [B.83]. As shown in Tab. 8.8, plastics constitute about 8 % by weight of all MRF materials. By volume this represents about 18 % of which

40 % comprise packaging materials that are of particular concern because of their short use life. If these plastics go to a landfill, their low density, which make them prone to being picked up by wind, high visibility, and voluminous nature cause considerable public resentment.

Commercial incentives for the recycling of polymers include ecological reasons, consumer demand, recycling legislation, and the lowering of costs by reusing the waste's chemical components and inherent energy content by producing a secondary raw material. Until recently, these incentives had to be weighed against variable material composition, possibility of contamination, loss of mechanical properties because of degradation, lack of standards, and variations in supply. Now many of these problems have been solved through such measures as the use of sophisticated automated sorting, restabilization, implementation of recycled material quality standards, and integrated collection networks [B.83].

The three essential elements of polymer recycling are:

- a stable supply source, which involves reliable collection and sorting,
- an economical, established, and environmentally sound recycling process, and
- end-use applications for the recycled polymer that yield economic market values and capture consumer interest and confidence.

A recent book entitled *Polymer Recycling* [B.83] describes in detail the science involved, the technologies used, and the applications of recycled plastics. Its content covers:

- sorting and separation techniques,
- size reduction (and associated agglomeration) of recycled plastics,
- melt filtration of contamination in recycled polymers,
- recycling of PET (poly(ethyleneterephthalate)),
- recycling of polyolefines,
- recycling of PVC (poly(vinylchloride)),
- polystyrene recycling,
- nylon recycling,
- recycling of engineering thermoplastics,
- recycling of polyurethanes,
- recycling of polymer composites,
- rubber tire recycling,
- feedstock recycling: pyrolysis, hydrogenation, and gasification,
- incineration of plastic waste with energy recovery,
- plastic lumber based on recycled polymers.

Although some recycling methods are based on chemical (recycling of PET, nylon, and polyurethanes) and thermal treatments (melt filtration), most apply mechanical processes for the separation, cleaning, and granulation of the wastes prior to the manufacturing of parts from the secondary plastic raw materials. It is beyond the scope of this book to go into the details of polymer recycling. The aforementioned publication [B.83] is recommended for further reading.

It shall suffice in the context of the present review to point out that, while some products with high quality and value are being made from recycled plastics, most of the applications are low-cost manufactured parts. These include [B.83] the following.

- PET: staple fiber, filaments, non-wovens (Section 6.11.3), insulating fiber fills, carpets, strapping, sheet, films, non-food contact containers, injection moldings, large moldings, and engineering resins.
- Polyolefins: large molded containers (e.g., trash cans), blow molded bottles (e.g., detergent containers), bottle crates, pallets and large injection molded parts, drainage pipe, grocery sacks, garbage bags, structural applications (e.g., decking, fence posts, road posts, plastic lumber, etc.), battery cases, automobile bumpers.
- PVC: pipes, cladding, guttering, window frames, plastic wood, conduit for cables, pipe fittings, floor coverings, fibers, non-food bottles, surface coatings, sound protection panels, automotive acoustic insulation, floor mats.
- Polystyrene: packaging foam, loose fill, wood substitute, sorbent polymers.
- Nylon: engineered parts
- Rubber tires: filler, paviers, mats (skid resistant), athletic tracks, dock systems, playground cover, slope stabilization, road fill, rubberized asphalt and concrete.

Since most of these applications involve some sort of forming, first of the recycled material into a granular feed and then during the manufacturing of the final parts, agglomeration processes are widely used. After sorting, cleaning, and size reduction, pellets are formed in the mill itself by partial melting or by pressure agglomeration (pelleting, extrusion), which are then fed to the final shaping process. The latter mostly uses modified punch-and-die pressing and extrusion techniques, which are again methods of size enlargement by agglomeration.

#### **Further Reading**

Once again, for further reading the book “Polymer Recycling: Science, Technology and Applications” [B.83] is recommended.