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# Using of Adhesives and Binders for Agglomeration of Particle Waste Resources

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**ABSTRACT**

This review presents the usage of adhesives and binders for agglomeration of particle materials, including waste, in order to obtain strong bodies. The binding materials were classified into three categories: inorganic binders, organic binders, and compound binders. Many examples of the agglomeration effect of binders in view of their adhesive and thickening reveal that they have a significant impact on the qualities and use of waste lumps. Binders for fine waste granulation, briquetting, and pelletizing were demonstrated in-depth. In all cases, the mechanical strength of the agglomerates produced was increased. It was observed that the majority of the additives may be easily obtained from waste resources, posing a minimal environmental risk.

**Keywords:** adhesives, binders, waste, fine coal, fine-grained iron, fly ash.

## INTRODUCTION

Binders are commonly utilized in the agglomeration of particulate materials in order to produce robust bodies. Binders influence the formation of the bodies' hardening process from their freshly formed condition.Binders interact with moisture and material particles, altering the capillary and viscous forces that connect individual particles. Binders control the stability of moisture during agglomeration, intensify moisture distribution within the granule structure, and slow down moisture deposit.Some binders can also help with granule spalling during the drying process [1]. With binders, the thermal tolerance temperature is usually raised, and then hot drying can be employed to reduce drying time.The moisture content of the material in pelletizing drums and discs has a substantial impact on agglomeration development [2]. Insufficient moisture may prevent nucleated seeds from developing, resulting in tiny clusters of particles that are difficult to expand; the final pellets are porous and fragile in these conditions. Excess moisture, on the other hand, causes rough pellet surfaces, facilitates rapid and uncontrollable merging, and converts the processing material into "mud". Other binders can be used in this scenario to absorb the remaining moisture, resulting in a more stable agglomeration process [3]. The following is a list of the binder used in the agglomeration process [4]:

1) Inorganic binder – advantages include a large resource pool, low cost, high thermostability, and hydrophilicity. The use of an inorganic binder has been linked to an increase in body toughness.
2) Organic binder – advantages include strong bonding and little ash formation during burning. Pellets are flammable when heated, but their mechanical strength and thermal stability are low.

3) Compound binder – they are made up of at least two binders, each of which serves a particular purpose. The compound binder can minimize the amount of inorganic binder used, as well as increase agglomeration quality and processing performance.

Binders are essential in agglomeration processes because they hold particles together for transit and storage. The composition of the binder also influences the toughness, thermal stability, combustion property, and cost of the body [5, 6]. Many studies have shown that different binders have distinct agglomeration bonding processes [7–10]. The features that an agglomeration binder must usually have are as follows: strong bond, pollution-free, has no influence on heat release or combustibility, has no interference with usage, is ecologically acceptable, and is cheaply accessible [11].

The purpose of this scoping review is to demonstrate the wide range of adhesives and binders that may be used for the granulation of raw or recycled fine materials, including industrial wastes, to improve the physicochemical and functional properties of the bodies produced.

## INORGANIC BINDERS

Limestone, clay, bentonite, cement, sodium silicate, iron oxide and magnesium oxide, calcium oxide, and calcium hydroxide are all types of inorganic binders. The primary benefits of inorganic binders used for agglomeration are: good thermal stability, good hydrophilicity, good sulphur retention, and low cost; however, the following are the primary disadvantages: high ash content, low heat, poor waterproofing properties, and poor water repellence [12].

Cement is a typical binder for combining mineral resources. The cement percentage in granulation varies between 2 and 15%. The amount of water bound in the granules is reduced when cement is added to the mix. Because of the shorter drying period, Portland cement or ground clinker cement is used for fine waste agglomeration [13].

The earliest binders to be added to briquettes were lime and clay. When lime is used alone, the amount added is substantial, ranging from 25 to 30 wt%. In the level of 6–8 wt%, bentonite clay is a suitable binder. Bentonite gives pellets strength at every stage of processing since it can withstand high temperatures and does not burn away due to induration. Bentonite has the drawback of containing 45 to 65 wt% silica ($SiO_2$) impurity, which is eliminated during the upgrading process. The inclusion of silica can raise the energy and flux costs [14]. Srivastava et al. [15] investigated calcium hydroxide ($Ca(OH)_2$), sodium silicate ($Na_2SiO_3$), calcium carbonate ($CaCO_3$), sodium carbonate ($Na_2CO_3$), and calcium chloride ($CaCl_2$) as inorganic binders. Binder pellet dose ranged from 0.5 to 5% by weight. The compressive strength of the pellets produced using $CaCO_3$ and $Na_2CO_3$ was insufficient. The strength of indurated bodies formed from inorganic binders was often more than the acceptable perimeter; however, this was not the case with green pellets. For all of the inorganic binders, the pellet strength was below the limit.

Inorganic binders, primarily limestone and Portland cement, were employed to agglomerate stone dust as a low-cost construction material. The aggregates with a cement concentration of 15 wt% provided satisfactory results. Briquettes must be cured for at least 48 hours. Because the porosity of the indurated pellets reduced as a result of the inorganic binder, the agglomerates' compression strength improved [16]. Stone cobble cubes can be produced with a cement concentration of up to 20% by weight. However, increasing the amount of binder in the agglomeration composition does not always provide favorable results [17].

Pelletizing coal fly ashes is typically implemented using the granulation process with mineral binders. Borowski and Hycnar [18] tested the granulation of fly ashes in the presence of phosphogypsum as a binder. Phosphogypsum is a by-product of the production of phosphoric acid. It contains 93.4 wt% gypsum, as well as minerals such as silicon oxide, aluminum oxide, iron oxide, phosphorus oxide, fluorides, and chlorides, as well as fluorides and chlorides. After 5 minutes of mixing, the ash and phosphogypsum had reached a moisture content of 5.0%. Granule diameters ranged from 5 to 20 mm, with an average of 5 to 15 mm. Borylo et al. [19] observed higher concentrations of radioactive radionuclides in phosphogypsum deposits. The high amounts of polonium isotopes in the waste are due to migration of these nuclides, whereas uranium isotope concentration is low. Shredded phosphogypsum granules with a 20 wt% phosphogypsum content were added to the clinker. The amount of radioactivity generated by the cement was negligible. As a result, the use of phosphogypsum has not been determined to be hazardous to the environment.

The three mineral binders used in the lignite and coal fly ash mixes in amounts ranging from 5 to 7 wt% are hydrated lime (calcium hydroxide $Ca(OH)_2$), portland cement (clinker), and phosphogypsum. Depending on the kind of ash, the moisture content of the combination ranged from 24.74 to 30.62%. Binders had a positive effect on body hardness depending on the cure duration, however, toughness reduced after 72 days of curing. The results revealed that coal fly ash granules were of higher quality than lignite ash granules [20].

## ORGANIC BINDERS

Starches including corn, wheat, rye, sorghum, and soybean were the earliest organic binders for pellets. Starch was utilized alone or as a gel to equally distribute other binders throughout the bodily structure. Because of its capacity to increase physical quality at all stages of agglomeration, bentonite clay has long been used to produce pellets. For particular briquettes, molasses, sugar, petroleum coke and oil, and sodium silicate were claimed as binders [21]. The amount of organic binder varies from 0.1% for starch or carboxymethyl cellulose to 5% for bitumen or molasses.

Organic binders are employed for a variety of reasons, with the most common advantage being a reduction in pellet silica concentration. During the high-temperature fire process, organic materials are combusted, leaving practically no ash behind in the slag. Lowering the silica concentration in pellets may be advantageous due to lower air-flux requirements and reduced slag volumes in burning processes. It has been observed that lowering silica levels can save energy and money [22]. Another advantage of utilizing organic binders is that they enhance the porosity and reducibility of burned pellets. High porosity (basicity from 0.2 to 1.6) to peat moss combustion before a liquid slag phase emerged was seen in iron ore pellets produced with peat moss and bentonite binders [23]. When compared to bentonite, the ball porosity of organic-binder pellets is much greater. The large porosity of the pellet aids the reduction process by making it easier to remove oxygen from the oxides in the pellet. More surfaces in contact with the reducing gases equate to a bigger volume of macro and micro holes in the pellet microstructure. As a result, achieving a reduction target requires less time. For instance, substituting bentonite with an organic binder increased the porosity of the pellets by 29.1% [24].

The downsides of organic binder include greater fines prior to pellet manufacturing. Organic binders have historically resulted in pellets with low compression strength and gravitational-dump resistance. This might be due to pellets' high porosity and lack of glassy phase. The strength of the pellet rises as the porosity decreases, reducing the amount of macropores [25]. The use of sodium carboxymethylcellulose (Na-CMC) as a binder resulted in a smaller ball size dispersion during agglomeration. Because the organic binder tightened the size distribution and increased particle permeability, the magnetite pellets oxidized on the grate sooner than planned. As a result, the pellets were fired at a lower temperature. Starch has been linked to higher levels of surface wetness. Water seeps onto the surface of the pellets, allowing them to develop more quickly. The rough surfaces of these pellets can readily abrade during pellet handling, resulting in increased quantities of fines. Some suggest that utilizing cross-linked superabsorbent polymers in addition to starch will address the problem. Although starch is simple to manipulate, no comprehensive study of the impact of starch structure on binding characteristics has been published [26]. The general structure for a model organic binder was proposed by Qiu et al. [27]:

- hydrophilic functional groups to favour binder dispersion into moisture and to execute the particle wettability;
- polar functional groups to support binder adhesion to chunks formation, and
- a hard and thermally stable "backbone" created.

Organic binders enable granules to expand excessively quickly and have a wet and rough surface. Stronger balls are produced by slower growth and higher loads in rotary drums combined with a high viscosity binder. The completed balls have less moisture, which allows them to travel more easily on rollers and screens. Figure 1 depicts the agglomeration procedure using an organic binder. Organic binders are made up of a polymer binder and a non-inorganic ingredient. Sodium carbonate ($Na_2CO_3$) softens pellet moisture by precipitating calcium and magnesium out of solution as solid carbonates [21], as well as acting as a fluxing agent during sintering. Similarly, as binders are added to agglomeration, the quality of green and sintered pellets improves.

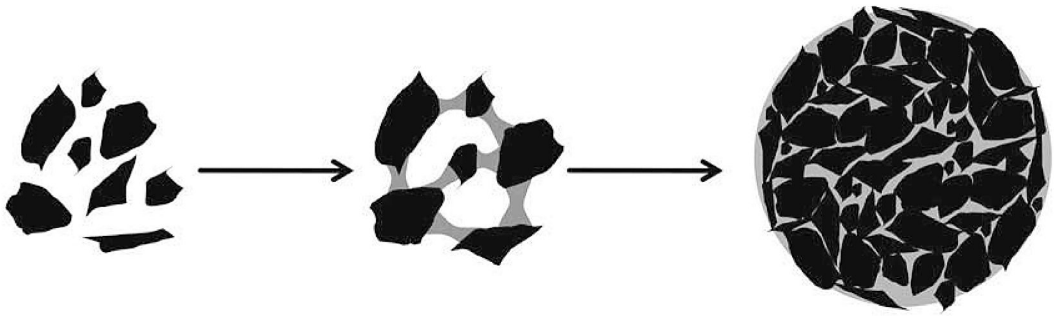


**Fig. 1.** The process of agglomeration mechanism with organic binder [1]

Dispersants and chelating agents, according to various studies, improve the physical appearance of organic binders. Sodium citrate, sodium tripolyphosphate, and sodium hexametaphosphate, as well as sodium silicate, are among these additions [28–30]. Calcium and magnesium ions in pellet moisture may be captured by sodium tripolyphosphate and sodium citrate, which then adsorb to particle surfaces. This may prevent organic binders from precipitating excessively on particle surfaces, allowing for improved moisture dispersion.

The additives should spread colloidal particles into the pellet, according to Dilsky et al. [31]. While moisture vaporized via drying, colloidal particles enhanced the viscosity of the binder and deposited at contact sites in pellets. The addition of the sodium tripolyphosphate dispersant increased the resistance to drop and the strength compression of CMC-bonded pellets [32]. Due to their adhesive and thickening properties in the vicinity of pellet factories, a variety of organic resources have been studied as binders.

Organic binders, such as asphalt, tar, molasses, cellulose derivatives, dextrin, starch, wax, paraffin, sulphite lye, and resin, are advised for the briquetting of particulate iron waste from metals treatment for metallurgical application. The binder type had a considerable effect on the briquette toughness of iron waste, and the addition of molasse solution was important [33]. The fine iron and binder combination was brought to a humidity level of 4.5–6.5%. The briquettes were cured for at least five days, resulting in a mechanical strength increase of 10 to 15%. The thermal treatment process (hot briquetting) determines the highest toughness of the briquettes with molasse binde. At temperatures over 185 °C, the sucrose in molasses decomposes, resulting in the creation of caramel. Caramel has far better adhesive properties than molasse, which assists to reinforce the briquette's mechanical structure. The process of sugar carbonization and the production of a particularly robust briquette structure occurs at temperatures exceeding 220 °C.

The benefits of industrial control of particle iron grinding waste were demonstrated in studies on the briquetting process. Molasse, starch, and dry hydrated lime with molasse (compound binder) were added to the homogenized waste mixture [34]. With the addition of water spray, the fine iron with a binder was combined in an electric paddle mixer for 3 to 6 minutes. The percentage of binding additives varied between 2 and 6 wt%. The body size was about 50×20 mm. With a moisture level of 8%, the gravitational-dump test yields favorable results. After at least 3-days of curing, the strength of the briquettes produced increased. These briquettes were introduced to a steelmaking furnace as a feedstock for melting. The organic binder was completely burnt without harmful emissions into the atmosphere due to metallurgical smelting.

## Starch

The properties of starch are highly dependent on the source. Corn, potato, wheat, rice, cassava, and tapioca are all reliable sources of starch, with corn being the most common [35]. For a long time, corn has shown to be a reliable source of starch and dextrin. Because the starch granules are really not water soluble (which is suitable for pellet binders), they are cooked to improve their binding properties. Dextrin is a starch by-product obtained by hydrolyzing starch in an acidic solution. By adjusting the reaction's breakdown extent, a variety of product solubility and viscosity may be produced.

To manufacture robust briquettes, a 4–8% starch content is required in most cases. However, due of its high cost and low waterproofing, starch is not widely employed in the industry. The performance of modified starch, such as gelatinized starch and alkaline starch, is excellent. Scientists added admixtures to the starch to increase the binding capabilities. Manzhai et al. [36] investigated the effect of polyvinyl alcohol on starch briquette compressive strength. According to their study, the compressive strength rose dramatically as the polyvinyl concentration increased. However, polyvinyl was easily degraded at high temperatures, resulting in poor thermal properties. The impact of carboxyl methyl starch on body-caking was investigated by Zhong and Cao [37], who revealed that the modified starch had important binding properties. The acid treatment improved the quality of the items.

Corn starch has been used as a binder for iron ore concentrate briquettes, indurated pellets, and cold-bonded pellets [38]. They used 0.2–0.5% starch with 2–8% finely ground sponge iron powder as a binder for pellets, and claimed that raw wheat starch can be added to the pelletizing mixture (3–7%) and heated to gelatinize the starch. Igawa et al. [39] used wheat flour as a binder for the pellets fed to rotary hearth furnaces. Drying was carried out at 150–200 °C at a low rate, so the starch could sufficiently gelatinize before moisture was evaporated. Wheat was added at a dose of around 5%, in addition to bentonite (0.1–0.3%) and NaOH (0.01–0.03%). Osmundson [40] applied starch as a binder for rotary hearth pellets. Starch was added at 0.7–1.2% by mass, and aged for 0.5–4 hours before pelletizing. Dextrin was also used for the iron concentrate-coal composite pellets [41]. The dose of 4% dextrin was added to pellets with 10–12 mm in diameter, prepared on a disc pelletizer. The granules were air cured for 4–7 days, and strengths of 35–40 kg/pcs were obtained.

Two types of charcoal briquettes were produced with the inclusion of native wheat starch or modified wheat starch [26]. Wheat starch was originally a carbohydrate made up of glucose molecules. It has a low resistance to physical stress. Physical, enzymatic, and chemical changes were used to produce modified wheat starch from native starch. The rheological characteristics (stability of emulsions and suspensions) were enhanced, and adhesion was reduced as a result of these changes. This helps to ensure that particles are distributed evenly during mixing. The improved heat resistance of the modified starch may be seen when compared to the natural starch. The starch content of the combination was determined to be best at 8.0 wt%. The burning properties of the charcoal briquettes generated for the experiments varied greatly depending on the type of starch used, as shown in Table 1. The firing timing, burning period, temperature distribution, and smoke intensity were all different. The agglomerates with native wheat starch binder were shown to be more appropriate for grilling [26].

## Humic acid binders

Decomposition of organic materials produces humic chemicals. Soil, peat moss, carbonaceous shale, lignite, brown coal, and other sources of these chemicals can be produced [42]. Humic substances are made up of a collection of colloidal particles kept together by hydrophobic interactions and hydrogen bonding [43]. According to their solubility under pH values, humic substances may be divided into three fractions: (1) insoluble humic substance, (2) humic acid, which is alkaline soluble but not acid soluble (pH < 2), and (3) fulvic acid, which is soluble under all pH values [44].

The humic-rich substances such as brown coal, seaweed, and peat moss were causticized before being used as a pellet binder. The organic material was converted into a form of a colloidal gel. Humic acid and fulvic acid, depending on the binder share, have recognized thermal stability, and interact with particle surfaces, which affects the binder property [45]. The binder performance depends on the source of the humic acid.

**Table 1.** Comparison of two starch binders for charcoal briquettes [26]

| Specification | Charcoal briquette with a binder: | |
|---|---|---|
| | Native wheat starch | Modified wheat starch |
| Time of smoke (min:sec) | 9:34 | 10:45 |
| Firing up time (min:sec) | 13:53 | 16:21 |
| Burning time of temperature above 180 °C (min) | 264 | 299 |
| The maximum temperature (°C) | 307 | 285 |
| Burn-up factor (%) | 97 | 95 |

## Biomass addition

Biomass could be a valuable source of binder because of its vast availability, low cost, and high heating values. This binder was used to make briquettes, and it had a lower ignition temperature, a lower slagging index, and a lower ash percentage than other binder options. As a result, biomass as a binder has only lately come to the attention of domestic and international industries [46, 47]. According to Shao et al. [48], a binder was combined with several types of biomass, including agricultural waste, aquatic plant, forestry biomass, and aquatic plant. The technology not only skillfully blends renewable and nonrenewable energy (coal), but also provides options for biomass energy consumption. As a result, environmental issues have been addressed, and coal combustion performance has improved.

Zhang and Xu [49] studied the opportunity of rice straw treatment with sodium hydroxide used as a binder for coal briquette production, and found that the principal factor that influences the binder performance was sodium hydroxide concentration. The crush compression strength was 244 $N \cdot cm^{-2}$ and drop test strength of briquette reached 82.2%, when the sodium hydroxide was 2.1%. With the increasing of sodium hydroxide share, the strength of briquette decreased. This was because the undecomposed fibers after alkali treatment combined and stretched the coal particles together, as well disintegration of biomass harvest sugars, pectin, tannin and others, that effect on the binding. Furthermore, the silicon in the biomass ash reacted with sodium hydroxide to form sodium silicate, which also outcome on binding. The binding capability of the solid component is higher than the liquid fraction. As soon as the concentration of sodium hydroxide increased, the binding ability as well as the briquette strength decreased [50]. Huang et al. [51] examined the structures of the biomass binder prepared with corn stalks or treated corn stalks, and found that there was a great agreement of bio-fibers in the binder, which formed a network structure in the body and achieved the cohesive action for coal particles. Cohesiveness keeps going by 24 h when the briquette contacting with water.

Lignin is natural biomass polymer that role is to provide the cellular structure of plant. It has been described that 12–39% of wood constituents are lignin, which long time has been considered as unwanted by-product during the paper production

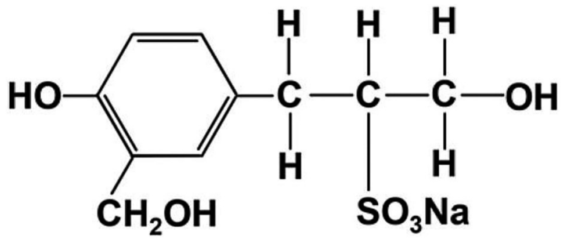


**Fig. 2.** General structure of lignin [52]

[52]. Through the pulp production with the sulphite method, lignin is made soluble by including the $SO_3^-$ groups into the structure (Figure 2) and separated from cellulose. Lignin used as a binder for pellets, that can be burned for heat or recovered in industry.

The precise lignosulfonate structure is not well known, they are a group of complex polymers. The general structure of a lignosulfonate monomer includes a phenylpropanoid unit (6-carbon aromatic phenyl group with a 3-carbon propene tail) with quantities of -OH, $-CH_2OH$ and $-SO_3Na$ groups. The anionic $SO_3^-$ group influence to water solubility, while the hydrogen and -OH groups assemble to bonding. Lignosulfonates were tested as organic binder in the mining processing for hardening pellets, as a binding support for starch and in direct-reduction pellets. Lignosulfonates are relatively cheap because of waste product from wood processing. Though, these binders introduce sulphur into pellets, which can be emitted during firing. A lignosulfonate-based material at a 1% dose, was used for the agglomeration of the magnetite-coal composite pellets [53]. The temperature of treatment ranged from 500 to 900 °C. The pellets were 11.2–12.7 mm in diameter, with compression strength of 22 N/pellet were reported. Lignosulfonates helped processing the coal material under difficult conditions to a solid fuel. Lignosulfonate increased the coal wettability in disc pelletizers, which reduced large air inclusions in pellets and increased the strength.

Lignosulfonate is a by-product of the paper mill, and contains sugar, lignin derivatives, organic acids, organic acid salts, free sulphite and free sodium hydroxide. A lignin derivative has robust adhesive strength, so was used as a binder. Lignin has the benefits when used as a binder, alike low cost and ash content, as well environmentally safely. With high temperature, the organic matter decomposed and burning, so the bonding performance decreased. Thus, lignosulfonate and other binders are mixed in compounds to produce good quality briquettes [54].

### Molasse

Molasse is a by-product of the sugar manufacturing process. It comprises a dense solution that remains after sugar crystallizes [55]. The principal components are sugars that were not recovered after processing (30–60 wt%), proteins (<10 wt%), and inorganic minerals (<10 wt%). Molasse can be utilized as an animal feed addition due to its high nutritional value. Molasse is frequently combined with lime, which provides calcium for the reaction with sucrose sugar (Eq. 1). Calcium interacts with sucrose to generate a calcium-sucrose complex (calcium saccharate), which then reacts with $CO_2$ to form calcium carbonate and recrystallized sucrose (Eq. 2). During this process, the sugar acts as a catalyst [56], forming a binding calcium carbonate system. These binders can be cured for many days or reacted with $CO_2$.

$$\begin{gathered}\textit{Lime + sucrose (sugar)} \rightarrow \\ \rightarrow \textit{calcium saccharate + water}\end{gathered} \tag{1}$$

$$\begin{gathered}\textit{Calcium saccharate + carbon dioxide} \rightarrow \\ \rightarrow \textit{sucrose + calcium carbonate}\end{gathered} \tag{2}$$

A molasse dose of 3% was positively used to pelletize iron ore concentrate from the Sokolovsko-Sarbaiskoye mining factory [57]. The green pellets were then either dried and roasted at 1200 °C before metallization, or dried and metallized immediately at 950 °C. The pellets exhibited a compressive strength of 0.65–0.7 and a metallization degree of 0.65–0.7, according to the studies. The unroasted pellets were thin and brittle, although they were practically metallized. The pre-roasted concentrate with molasse binder has a dried pellet strength of 10–15 kg/pellet.

Molasse was also generally used in combination with calcium hydroxide or slaked lime, dextrose, and sodium polyacrylate as a binder [56]. A disc pelletizer was used to make granules with 10% calcium hydroxide and 5% molasse. By flowing $CO_2$ gas over the pellets, they were cold bonded. Using lime and a $CO_2$ reaction, the maximum compressive strength was 299 N/pellet. Under the same conditions, using dextrin instead of molasse resulted in a strength of 357 N/pellet.

### Bitumen binder

Bitumen binders include coal tar pitch, petroleum bitumen, and tar residue, which make the available acceptable quality of agglomerates. Bitumen has a similar chemical composition and structure to coal. Petroleum binders have a high wetting capacity for coal, which allows them to connect coal particles together after they have solidified. These binders, however, are hot-melt adhesives, and the bonding weakens as the temperature rises. When tar pitch or petroleum bitumen are used as binders, the temperature of the agglomeration process should be kept low [58].

Zhu and Wu [59] investigated a briquette binder made from tar residues and acid tar oil. This binder was used in the manufacturing of coal briquettes, with compressive and dump test strengths of 115.48 $N \cdot cm^{-2}$ and 95.88%, respectively. It met the strength requirements in the manufacturing, transportation, and charging stages. The coal binder helped to improve the quality of the coke. Although coal tar pitch was a common binder, the briquettes made with it and petroleum bitumen emit gases during combustion due to the volatile materials present. In the case of coal pitch, the amount of volatile matter is excessive. The bitumen binder is increasingly phased out as environmental protection regulations tighten [60].

## COMPOUND BINDERS

The thermal characteristics of agglomerates made with an inorganic binder are outstanding, but the fixed carbon content and combustion efficiency are low. Following that, organic binder-produced bodies have more strength, but their volatility is considerable, and the procedure is time-consuming. Compound binders are made up of two or more substances that have various characteristics together [61].

Leokaoke et al. [62] investigated the effects of adding bentonite clay and kaolin clay on bonding possession using sodium humate. They found that adding chemicals boosted the briquette's high-temperature strength and thermal stability. The bentonite addition had a stronger impact than the other additives. The kaolin had no effect on the quality of the briquettes. However, adding kaolin to the mix improved the temperature performance dramatically. The cold and high-temperature strength, as well as thermal stability, were 0.99 MPa, 0.47 MPa, and 58%, respectively, when 1% kaolin, 4% bentonite, and 3% sodium humate were added.

Jia et al. [63] proposed a cement-based binder that included 85–90% cement, 5–10% hydrated lime, and 5–10% polyvinyl alcohol. Because of its high strength, high water resistance, ease of manufacture, and low cost, the briquette made using this binder has proven to be advantageous. Zemlyanoi [64] used a binder made from humic acid, *Suaeda salsa* seed, and water to make briquettes, and found that the briquettes produced were strong enough. Brunerová et al. [65] described a binder made of bamboo fiber and sugarcane skin, claiming that the resulting body not only had outstanding strength but also increased productivity.

Zare-Shahabadi et al. [66] developed waterproof and wear-resistant binder manufacturing techniques by using asphalt as a cationic emulsifier solution. The obtained binder increases the waterproofing and adhesive affinity of the adhesives with pulverized coal when compared to the single emulsified asphalt. Cationic emulsified asphalt has a wide variety of applications, allowing it to be used with both high and low grade coal. A binder consisting of sodium lignin sulfonate, carboxymethyl cellulose, carboxymethyl starch, bentonite clay, and sodium tetraborate was described by Wang [67]. He claimed that adding 1% carboxymethyl starch, 6% bentonite clay, and 0.16% sodium tetraborate to briquettes increased their cold strength. Furthermore, the amount of bentonite clay in the mixture had a significant impact on the binder type.

Tong et al. [68] examined the bonding agent's response to alkali concentration, reaction temperature, reaction duration, and biomass addition. The potential of the compound binder made from modified biomass and inorganic ingredients seemed promising. 1% alkali concentration, 80 °C reaction temperature, 2 h reaction time, 10% biomass, 4% curing agent, and 25 MPa formation pressure were the best conditions for biomass. Wang et al. [69] described a thermoplastic phenolic resin, sodium bentonite, corn starch, and sodium carboxymethyl cellulose composite binder. The briquette may be used to substitute industrial gasification lump coal by adding 0.04% thermoplastic phenolic resin, 0.04% sodium bentonite, 0.27% corn starch, and 3.64% sodium carboxymethyl cellulose.

Benk [70] developed the binder by combining coal tar pitch and phenolic resins. He demonstrated that the optimal quantity of coal tar pitch in the blended binder was 50 wt%. Curing the bodies at 200 °C for 2 hours was found to be sufficient for producing 50.45 $MN \cdot m^{-2}$ compressive strength briquettes. The cured briquettes were carbonized at temperatures of 470 °C, 670 °C, and 950 °C, and their strength steadily increased, eventually reaching 71.85 $MN \cdot m^{-2}$ at 950 °C.

The compound binders were employed to boost the compressive strength of fine coal granules. These granules, on the other hand, almost always require conditioning or additional heat treatment [71]. When there is too much water in the material, dehydrators are implemented to hinder or prohibit the processing. The additional dehydrators "bind" water and bind the grains of substance, potentially boosting physical strength [72]. Binders enhanced the desired properties of granulates destined for solid fuel combustion in furnaces, such as lowering $SO_2$ emissions in the exhaust gas, lowering iron oxide, and adjusting the melting point of combustion ash. A variety of substances were mixed in with fine coal as asphalt, bentonite, cement, sodium chloride, calcium chloride, dextrin, clay, organic glue, starch, silica, sulphite lye, molasses, pitch, ferrous sulphate, water glass, synthetic polymers, limestones, and lime [73]. Brief characteristics of some components which are additives with fine coals are presented below:

Bentonite – binds water and increases the compressive strength of granules. It consists of montmorillonite, capable of forming gels with a developed surface. Sodium-activated bentonites have a swelling capacity of 600 to 900%, while the not-activated ones – are 200%. The quantity of bentonite added depends on the material moisture content, and typically share is from 0.5 to 1%. The bentonite granules reach their maximum strength 4 to 6 hours after being prepared.

Quicklime (calcium oxide CaO) – it is frequently used as a supplement to granular coal. The calcite skeleton is formed when calcium hydroxide reacts with carbon dioxide to produce lime binding:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \tag{3}$$

The lime oxide reacts with the water to form of calcium hydroxide, and heat released:

$$CaO + H_2O = Ca(OH)_2 \tag{4}$$

After transformation, the granules needed to cure for up to 60 days. Place the granules in $CO_2$ to speed up the conditioning process. Granule strength grew after conditioning, but it began to decline after reaching its limit. The following reactions demonstrate how lime contributes to the decrease of $SO_2$ emissions in combustion gases:

1) The process of sulphur compounds in fuel being burned

$$S + O_2 = SO_2 \quad (5)$$

2) The calcium hydroxide dehydration process

$$Ca(OH)_2 = CaO + H_2O \quad (6)$$

3) The process of calcium carbonate decalcination

$$CaCO_3 = CaO + CO_2 \quad (7)$$

4) $SO_2$ bonding process

$$Ca(OH)_2 + SO_2 = CaSO_3 + H_2O \quad (8)$$

$$CaCO_3 + SO_2 = CaSO_3 + CO_2 \quad (9)$$

$$CaO + SO_2 = CaSO_3 \quad (10)$$

$$CaSO_3 + O_2 = CaSO_4 \quad (11)$$

The percentage of sulphite and calcium sulphate compounds generated ranges from 30 to 80% [74]. The amount of $SO_2$ eliminated from the exhaust is proportional to the amount of lime applied. Limestone, like the addition of lime to fine coal, has an effect on reducing the quantity of $SO_2$ in the exhaust. Natural limestone, dolomite, and chalk are also utilized as additives.

## CONCLUSIONS

The use of adhesives and binders for agglomeration of particle materials, including waste, in order to form strong bodies is discussed in this review. This study found that by combining waste with a binder, valuable pellets could be generated, and that the procedure was efficient. In the agglomeration process, adding adhesives to particle material has a major impact on body toughness. Binders made from recyclable materials are also an option. The addition of phosphoric acid, for example, was employed to aid pellet gelation and skeleton development. When a water-asphalt emulsion is applied to the combined substance, the bodies become hydrophobic and frost resistant. When the pellets were heated, the molasses, starch, and dextrin efficiently agglutinate the tiny grains. Organic resins (carbamide, polyvinyl, and acrylic) were also added as solutions or aqueous suspensions. It has been proven that adding binders and additives to agglomerates formed from industrial waste materials such as fine coal, fine-grained iron, or fly ashes improves their properties.

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