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MATERIALS AND METHODS OF SINTERED FLYASH LIGHTWEIGHT AGGREGATE PRODUCTION

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Abstract: The utilization of industrial waste as a construction material is a big leap towards sustainable development. Flyash is a waste material obtained from thermal power plants during combustion of pulverized coal. Though there are many practices to use flyash as a construction material in past few decades; manufacturing of sintered flyash aggregate is one of the best practices to dispose flyash in a large quantity. The research in relation to the use of sintered flyash aggregate to produce structural lightweight aggregate concrete is summarize in this paper. The structural concrete produced using sintered flyash aggregate have to ensure certain mechanical and durability characteristics. The manufacturing process and control parameters of sintered flyash aggregate also reviewed in the present paper. The physical, mechanical properties of sintered flyash aggregate and the mechanical and durability properties concrete produced from the same are discussed. The review of the literature showed that depending on the ingredient properties and the production environment the specific gravity of these aggregate were16 to 46 % less than that of the normal weight aggregates and it can be used as aggregate for the production of structural concrete.
Keywords - Sintering; Fly ash; Aggregate; Lightweight aggregate.

I. Introduction

Utilization of industrial wastes as construction material is a healthy sustainable practice to dispose the waste and conserve the available resources for future generations. Flyash is a by-product of coal based thermal power plants. If not properly disposed of, flyash can cause water and soil contamination consequently interrupts the ecological cycles. China, USA and India together consuming around 70% of the total coal consumption around the world[1]. According to CEA report [2] about 166 Million tons of flyash is generated from 132 thermal plants annually in India. About 56 % of flyash is utilized effectively through various methods as shown in Fig.1,and the remaining flyash is still a concern to the society. Most attention is devoted towards the commercial applications like replacement of cement. This process simultaneously consumes the generated industrial wastes and reduces the requirement of cement clinker. A high quality fly ash with low carbon content is used as mineral additives in cement and concrete production. Lower quality fly ash with higher and variable carbon content is normally used in land filling [3].

Production of artificial aggregates form flyash is a great leap towards the flyash disposal in large quantity. Generally aggregate phase occupies 60-80 % of concrete matrix by volume. Artificial aggregates can be manufactured from flyash through various processes like sintering, hydrothermal treatment and cold bonding. Various percentage of flyash utilization for the above mentioned methods are 90-100%, 47% and 60-75% respectively [4]. This indicates that sintering is the suitable procedure for bulk utilization of flyash. Sintered flyash lightweight aggregate is a possible potential material to replace the natural aggregate. These lightweight aggregates can be used for various structural and non-structural applications. The commercial production of artificial lightweight aggregates from flyash through sintering has started in1960s [5]. Aardelite, Lytag, Pollytag, Fa-Light are some of the commercially available flyash LWAs around the world. It was found that the inclusion of these lightweight aggregates in high strength concrete for the production of off shore structures is highly beneficial [5,6]. The utilization of these waste materials in concrete leads to sustainable concrete and reduces environmental impact from the manufacture of concrete using conventional materials [7].

Therefore the main objective of this paper is to review the production process of sintered flyash aggregate for the development of structural lightweight concrete. A thorough review was conducted to categorize the physical and chemical properties of sintered flyash aggregate. In view of the available literature, significant improvements can be attained by analyzing and summarizing the properties of sintered flyash aggregates.

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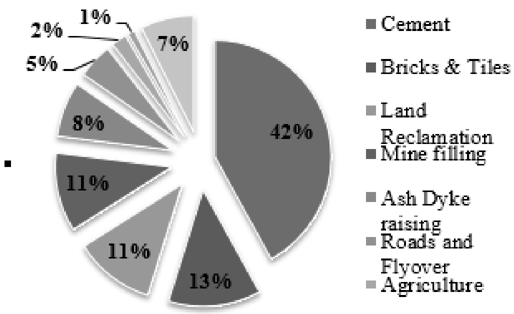

Figure 1: Different modes of utilization of fly ash in India [2]

II. Sintered Flyash Aggregates Manufacturing Process

The fundamental production process of the artificial aggregates from flyash mainly consists of three stages-mixing of raw materials, pelletization and hardening as shown in Fig. 2. During mixing, well-proportioned ingredients were combined together till the required consistency is achieved. Pelletization process consists of agglomeration of fine particles using suitable binding agent. The hardening of the fresh pellet is possible either by sintering, autoclaving or cold bonding. Sintering process hardens the pellets by fusing the fly ash particles together at the points of mutual contact [8]. Sintering is an energy consuming process; research carried out on more energy efficient ways to produce artificial aggregates from flyash, like cold bonding process [9]. The major disadvantage of cold bonding process is, it takes long duration (more than 28 days) to produce aggregate shaving required strength and also it requires cementitious materials. Also, it is noticed that the physical and mechanical properties of the sintered flyash aggregates is better than that of the cold bonded aggregates [10, 11]. Various artificial flyash aggregate production processes has been detailed earlier by Bijen [12].

Formation of proper green pellet is the primary crucial step in the manufacturing of flyash aggregates. Moisturisation of fine flyash particles leads to the formation of a thin liquid film around the surface of each particle. When the moisturized particles contact each other bridges are formed at points of contact and bonding forces develop gradually when these particles are rotated into balls. The green pellet produced either by the force generated by itself inside the rotating pelletizer [9, 13] or due to the external applied force; makes the aggregates relatively denser and stronger compared to those of pelletized aggregate [12]. Disc granulation is widely adopted to agglomerate the fine particles, because it is easier to control the pellet size distribution. Strength of the green pellets is directly proportional to the surface tension of the binding liquid, specific surface area of the particle and the porosity of the green pellet [12]. Pelletization process parameters such as the speed of revolution of pelletizer disc, angle of pelletizer disc, moisture content, and duration of pelletization significantly influence the properties of the fly ash aggregates produced [12,13]. Table 1 summarizes the available pelletization parameters and the aggregates properties from previous studies. Pellets attain strength also by mechanical forces, which are produced when the green balls smack against each other and against the walls of the pelletizer [11]. The earlier study also concludes that speed of the pelletizer is the primary factor that governs strength and porosity whereas moisture content governs the size of the pellet [14]. There are methods available to produce flyash aggregates without pelletization also [15]. Those trials are mainly conducted on laboratory scale so the authors minimize the priority towards them.

Sintering temperature is another important factor that has significant influence on the properties of the aggregates. During sintering, the flyash particles are fused together at the points of mutual contact. The sintering temperature depends on the physical and chemical properties of fly ash, but usually ranges from 1000 to 1300^0C [16]. It was reported that sintering below 1000^0C, pellets contains loosely bound fly ash particles, which causes weak matrix and higher absorption whereas full densification of fly ash aggregates are possible by the addition of binders and sintering at temperatures above 1200^0C. The flyash particles generally fuse at 1150^0C, this fusion temperature can be brought down to 1100^0C by the addition of suitable binder [17, 18]. XRD analysis indicates that as the temperature treatment on aggregate increases the reduction in the quartz peak, with only mild increase in the mullite peak were reported [19]. Flyash exhibited expansion above 1200^0C and the final expansion depends upon the sintering temperature. It is also noticed that inclusion of certain metal has the capability to alter the sintering temperature [20]. Heating rate adopted during the sintering has significant role in densification and shrinkage of the aggregates. The existing findings are contrary to some of the other claims that the maximum shrinkage reduces as the heating rate increases [20] while the other study reported higher densification at faster heating [21]. Though heating rate is an important parameter as far as the quality of the aggregate is concerned more research has to take in this direction to reach a proper understanding.

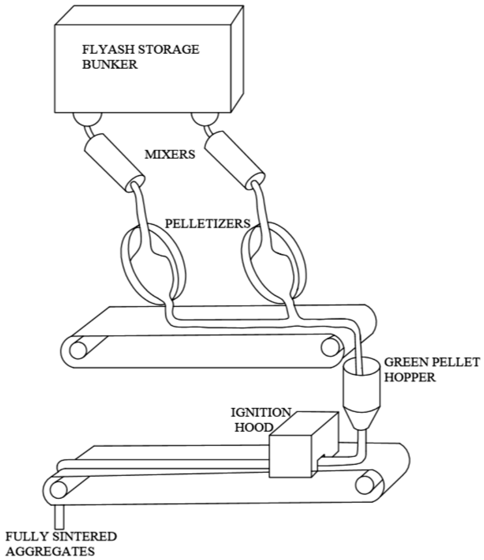

Figure 2: Flyash aggregates manufacturing process flow chart [22]

III. Raw Materials

Coal ash, also referred to as coal combustion residuals is the major ingredient of sintered flyash aggregates. Bituminous or lignite based coal ash can be used for the production of sintered flyash aggregates [23]. With proper preparation it is also possible to manufacture aggregates from all categories of coal ash irrespective of whether it is flyash or bottom ash[23-25] and class C or class F[8,9,11,14,26].Flyash is the most common and abundantly available form of coal ash. Physically flyash exists as fine particles with average size of <20µm and has high surface area (300-500 m^2/kg) and light texture [1].Suitable mineral (clay, shale or slate) and proper amount of water are the remaining ingredients.

Table 1: Aggregate production parameters and properties

Flyash	Fineness (cm^2/g)	Binder	Dosage (%)	Moisture content (%)	Sintering Temp. (C^0)	Duration (min)	Reference
Class F Class C	2570 4140	Bentonite, Kaolinite	4 - 30	23-35	-	-	[27]
Class C	3928	Cement , Lime	8	-	-	-	[9]
Class F	4280	Bentonite, Cement, Lime	10 - 30	-	1100	60	[8]
Class F	4280	-	-	15-35	1100	60	[14]
Class F	2880	Bentonite, Glass powder	-	22-25	1100-1200	165-180	[24]
Bottom ash	2120	Kaolinite, Metakaolin, Clay, Bentonite	5 - 20	26-33	800-1100	30-120	[25]
Bituminous pond ash Lignite pond ash	2520 2810	Clay, Bentonite Kaolinite, Bentonite	5 - 25	24 - 33	900 - 1100	45-120	[23]
Class F	-	Shale	30 - 50	18	950-1100	120	[26]
Class F	4000	Bentonite	20	25	950	-	[11]

3.1 Effect ofFlyash

The characteristics and the dosage of the ingredients are very critical elements while considering the quality of the produced aggregates. Flyash is the major raw material required to produce sintered flyash aggregates.One of the major concernsassociated with fly ash is the variation of its fineness [27].As the fineness of flyash increases the average size of the produced aggregate also gets increased andcoarser flyash particles demand more moisture content to produce a particular size fraction of aggregate [14].Also it is difficult to convert all the coarser flyash into aggregates through pelletization. Grindingthe coarser particle will consume high energy, whereas addition of proper binders wasrecommendedto improve the properties and production efficiencyof the aggregates[8].It also desirable that fly ash should contains approx. 10 - 12% carbon which is most suited for making aggregates [3]. If the carbon content exceeds these limits then the clay or bentonite can be added in a suitable proportion to dilute the carbon concentration. If the carbon content is less than the required limit then addition of suitable amount of un-burnt coal dust is preferable to make the mix proper [3, 13]. Chemical composition of flyash affects viscosity and sintering behavior during production process, andhence the nature of microstructure of sintered aggregates also. The crystalline- glass fraction of flyash will have significant role in sintering behavior. Generally quartz and mulliteare the crystalline phases detectedin most of the flyash.It is well known that the elemental oxide composition influences the viscosity, consequently the sintering behaviour of flyash aggregate.The network forming componentSiO_2 having a positive impact on viscosity whileCaO or Na_2O act negatively by modifying the silicate network structure [20]. Apart from the chemical composition, other morphological characteristics of the flyash should be also taken into account as reactivity of flyash can be affected by a number of properties such as particle size, surface area and glassy phase content etc.[28].

3.2 Effect of Type of Binder

It is important to employ suitable bonding agent during the generation of green pellets to maintain the size and shape of them till it hardens. Binder is added to fly ash in order to improve plasticity of pressed specimens and properties of sintered fly ash, without having negative effects on shrinkage, color alteration or efflorescence. Binders also affect the green and dried strength of balls and fired strength of pellets, and adjust the chemical and mineralogical consistency and quality of fired pellets [8]. Conventionally used binders in the metallurgical practices are bentonite, lime, cement, and some organic substances like dextrin, sulfate waste liquor, tars and alkali compounds [29]. Among them bentonite is the most common binding material used for the aggregate production. Bentonite dosage beyond certain limit resulted in sticking of pellets to each other leading to formation of muddy balls [27]. Also usage of bentonite facilitates the massive utilization of pond ash in the production of artificial aggregates [23]. Mu et al. [26] found out that shale isalso a good binder to produce sintered fly ash aggregates. Type of binder is insignificant while considering specific gravity and water absorption of the aggregates. It is also evident that by use of low binder content and high temperature increases the specific gravityof the pellet [24]. Manikandan and Ramamurthy [30] suggested that there is no favorable effect of addition of cementitious material or usage of class C flyashin the sintering process. This may be due the disintegration of the cementitious compounds during sintering.Geetha and Ramamurthy [25] studied the effect of different binders on the production of sintered bottom ash aggregates. The study concluded that the properties of the aggregates will be enhanced at higher binder content, sintering temperature and time.Vasugi and Ramamurthy [23] suggest the use of $Ca(OH)_2$ as apelletization enhancer and the dosage is recommended up to 2%.The incorporation of borax as a flux will enhance the mechanical propertiesdue to the formation of solid mass [23, 31]. Also borax reduces the firing temperatureresulting in energy savings [31].

3.3 Effect ofMoisture Content

When flyash particles are moisturized, a thin liquid film on the surface of the particlecauses the formation of meniscus between the grains.The surface tension of the binder is highly significant while considering the stability of the fresh pellets.The amount of water to be used in the process must be predetermined with respect to the desired void ratio of the final product with respect to process efficiency. This amount of moisture represents the optimized state or the capillary state. The most suitable state for pellet formation is capillary state, where all inter granular spaces are completely filled with water and no water film exists on the surface of the pellet; which enables the highest tension force between the particles [32]. Even minor changes in the optimum moisture content lead to the destruction of the capillary force, which then causes a great variety in the size and engineering performance of the pellets produced [9]. Harikrishnan and Ramamurthy [14] suggest the moisture content that can adopted for the production of flyash lightweight aggregate varies between 15to 35 %. Moisture content beyond this limit may lead to the formation of muddy balls instead of pellets. A minimum of 5–8 min is needed for the formation of pellets and by observingthe apparent strength of pellets (dropping from a specified height) the two (low and high)levels of optimum duration are 10 and 20 min [14].

IV. Physical Properties of Sintered Flyash Aggregates

The relation between aggregate properties and performance in concrete is not yet completely understood in several aspects. Aggregate properties have profound influence on concrete properties and proper understanding of these is very much mandatory for the development of high-quality concrete. Low density and high absorption are the key properties of the sintered flyash aggregates. It is also evident that the mechanical properties of sintered flyash aggregates are highly governed by type and dosage of the binder as well as sintering temperature and its duration. Whereas, the dimensional properties of the aggregates were influenced by the moisture content and angle of pelletization used. The available physical and mechanical properties are summarized in Table 2.

Figure 3: Sintered flyash aggregates

Table 0-1: Physical properties of sintered flyash aggregates

Specific gravity	Absorption (%)	Strength (MPa)	10% fine (ton)	Reference
2-2.35	28.8-33.9	-	-	[9]
1.7-2.35	16-22	-	1.75-4.25	[8]
-	19-30	-	0.8-2.2	[14]
1.51-1.93	0.7-18.4	5.1-19.3	-	[24]
1.8-1.92	19-20	-	2.9-4.2	[25]
-	7.5-24	-	0.5 - 2.5	[23]
1.33	2.7	6	-	[47]
1.46	15	8.7	-	[4]
1.57-1.60	0.8-19.3	5.1-23.1	-	[10]
1.57	1.75	18.34	-	[11]
1.6	18	-	-	[37]
1.72	8.5	-	-	[48]

LBD: Loose bulk density, RBD: Rodded bulk density

4.1 Shape and Texture

Shape of the aggregate has significant influence on the particle packing and internal aggregate interlocking within the matrix [33]. The sintered flyashaggregates are spherical in shape (Fig. 3) and are of brown color with an internal black core. This is attributed to the carbon content and the state of oxidation of iron. The microstructure is smooth but, on the micro-scale, it is relatively rough with open pores [3]. The structure of the pores of about 10–200 µm in size and are distributed as shown in Fig. 4. The surface texture of the aggregate can affect the surface frictional properties of a mix and consequently on the harshness of the mix during the fresh state.It is also believed that for porous aggregates or aggregates with a rough surface, the cement paste or cement hydration products may penetrate into cavities or large pores on the aggregate surface. These acts as multiple "hooks" binding the aggregate phase and the paste phase together [34].

4.2 Specific Gravity

From Table 2it can be observed that specific gravity of the sintered aggregates varied from 1.33 to 2.35. Though the literatures indicate that there exists a lot of variation, thespecific gravity is 13- 46 % less than that of the normal aggregates. The specific gravity increases as the sintering temperature increases in the absence of binder [18]. In the presence of binder the specific gravity found to be reduced at higher sintering temperature (1200^{0}C). This may be due to the bloating effect caused by the generation of more gas during the sintering operations [17]. Theformation of dense structure and higher specific gravities may be due to the excessive glass formation at higher sintering temperatures [35].

4.3 Water Absorption

Porous nature of the aggregate as shown in Fig. 4is responsible for its high absorption. This high absorption is not encouraging the development of good concrete, unless proper counter measures are available. Sealing all the pores is not a suitable practice to reduce the absorption, because it will lead to increase in the density of the aggregates.From Table 2 it is noticed that the absorption of the flyash aggregates varies from 0.7% to 34%. Most of these results are obtained from the laboratory investigation. From the literatures it is also noticed that commercially available flyash aggregates possess a water absorption capacity of 10-25% [37-39]. Surface coating by certain polymer will also reduce the absorption capacity of the aggregates [19]. It is observed that the water absorption of the LWA decreases as the sintering temperature increases[32]. At higher temperature, formation of glassy texture on the surface of the aggregates willoccurr which may hinder the inter pore connectivity [40].Significant reduction in water absorption potential of the aggregates was also observed by the addition of binder in the manufacturing of the aggregates irrespective of type of binder used. In this connection Ramamurthy and HariKrishnan [8] reported that use of bentonite up to 20% as a binder will reduce the water absorption by around 30%. Average pore sizes on the core of the aggregates were observedto be around 10 to 20 µm and thecritical pore diameter continuously decreased with temperature rise [18].

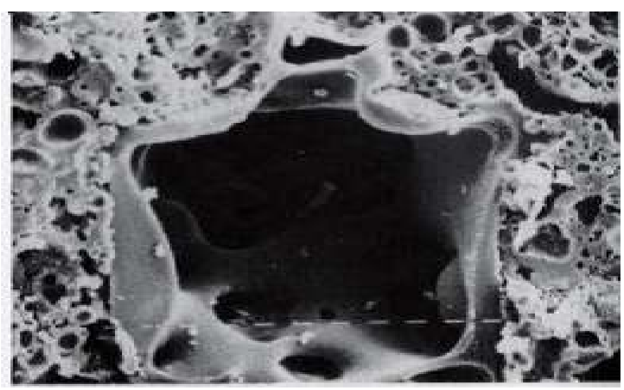

Figure 4: Microstructure of sintered flyash aggregate (×320, scale 10 µm) [37].

4.4 Bulk Density

Bulk density of the aggregates determines the paste volume requiredfor a concrete matrix and thus richness and economy of the mix [33].European Standard specifies that an aggregate having mineral origin should not exceed its oven-dry particle density more than 2000 kg/m^3 or loose dry bulk density above 1200 kg/m^3[41]. Depending upon the size of the aggregates loose dry bulk density of 880- 1120 kg/m^3 is permissible for the production of structural concrete according to ASTM C 330 [42]. As the size of the pellet increases the bulk density decreases, this causes the reduction in strength of the aggregates. The relationship between size and strength is a function of compaction and consequent void formation during sintering. The larger pellets are less compacted in their outer layers with resultant larger voids[3].

4.5 Mechanical Properties of The Aggregates

Porosity alone never governs the crushing strength of the lightweight aggregates [8, 19]. Several co-related factors such as change in the mineralogical composition, melting temperature of binders, margin of densification occurs during sintering, bloating of the aggregate and internal defects due to thermal stresses also have significance in the crushing strength.The crushing strength of the normal density aggregates usually expressed in 'aggregate crushing value'. But it is recommended that for aggregates having crushing value less than 30, 'ten percentage fineness values' is preferred [43]. The individual crushing strength of aggregates having smaller size was found to be higher than large sized [11]. From Table 2 it is noticed that crushing value and ten percentage fineness value of the aggregates varies from 23.5 to 740 and 0.5 to 4.25 respectively.Aggregate produced with binders exhibited increase in crushing strength as the temperature increasesup to 1150^{0}C. A reduction in strength was reported at 1200^{0}C. This may be because of the formation of large pores due to bloating [18]. Certain type of materials,expansion also occurs at higher temperatureduring the aggregate production [44, 45]. It is also evident that heat and polymer treatment on the aggregates enhances the crushing strength of the aggregates [19].Guneiysis [46] found out that the crushing strength of sintered flyash aggregate is 3 to 4 times greater than that of the cold bonded aggregates manufactured fromthe same flyash. Soundness tests conducted on flyash aggregates by use of sodium sulphate indicates the loss of weights is well below 12% [9].

V. Summary and Conclusion

From the literatures it can be seen thatsintered flyashaggregate production process and different production parameter that has significant influence on the aggregate properties. The physical, mechanical and durability characteristics of sintered flyash LWAC were discussed. Based on the review, following conclusions can be made:

1. Fineness of the flyash influences the properties of the produced aggregates. Among different binders bentonite is the commonly used one. Its preferable dosage is between 15 to 35% of the powder content. The sintering temperature usually adopted is varies from 1000 to 1200^{0}C.
2. Aggregates are spherical in shape having specific gravity varies from 1.33 to 2.35 and loose bulk density between 765 and 936 kg/m^3. Though the literature shows absorption capacity between 0.7 and 33.9%, commercially available aggregates possess water absorption capacity around 18%.

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