PERFORMANCE OF CONCRETE MADE USING SINTERED FLY ASH LIGHTWEIGHT AGGREGATE- A REVIEW

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Abstract

Current work summarizes research done on potential of sintered fly ash lightweight aggregate based concrete and its suitability as an aggregate. The manuscript presents physical and chemical parameters of ingredients such as fly ash as well as binders adopted in manufacturing process covering effect of these materials on parameters related to pelletization like duration, angle of inclination and rotation speed and its subsequent effect of aggregate characteristics. The impact of sintering temperature and its duration on aggregate characteristics is also discussed. The physio-chemical and mechanical characteristics of sintered fly ash aggregate is briefly presented. The review of literature suggests that specific gravity and water absorption of sintered fly ash lightweight aggregate is low and high respectively as compared to conventional aggregate. The use of additives such as alkaline activators, styrene-butadiene rubber, quick lime etc. and additional treatments such as coating or vacuum impregnation has shown potential for reducing water absorption. The mechanical performance of sintered fly ash lightweight aggregate in concrete is different from normal concrete. Factors affecting compressive strength, flexural strength and modulus of elasticity apart from the characteristics of manufactured sintered fly ash lightweight aggregate are cement content, supplementary cementitious materials, additives used, treatment done to aggregate, aggregate content, shape index of aggregate etc. Studies have indicated no direct relationship between factors affecting concrete durability such as water absorption, mechanical perfromance, cement content, water penetrability and freeze-thaw resistance of sintered fly ash lightweight concrete. The sintering temperature, selection of binder, additives and internal curing plays vital role in quality of interfacial transition zone. Further research is needed to explain bonding mechanism between aggregate and matrix, shrinkage performance with increase in heating rate, relationship between factors affecting concrete durability such as water absorption, mechanical perfromance, cement content, water penetrability and freeze-thaw resistance of sintered fly ash lightweight concrete. The review suggests that sintered fly ash lightweight aggregate based concrete has great potential for its application in construction to obtain benefits such as reduction in dead load, improved thermal comfort and reduction in carbon footprint.

Keywords: Durability; Mechanical property; Sintered fly ash lightweight aggregate; Specific gravity; Water absorption.

1. INTRODUCTION

Fly ash is among major industrial bi-product generated in India. In last one decade, there is a huge focus towards utilisation of industrial waste in suitable ways thereby achieving sustainability and circular economy. Increase in use of renewable sources and other alternatives from industrial bi-products is a need of an hour to tackle huge demand of concrete as material in construction [1]. Fly ash is generated by thermal power plants during burning of pulverised coal. About 75-80 percent of produced ash by thermal power plant is fly ash and component of bottom ash is about 20-25 percent. The properties of fly ash vary depending upon combustion operating system and coal composition. Fly ash is either lignite or sub-bituminous coal based Class C with both self-cementitious and pozzolanic nature or bituminous or anthracite coal based Class F fly ash with pozzolanic nature [2]. As per Central Electricity Authority (CEA) report, more than 3800 hectares of land was needed for disposal of fly ash in slurry form and in this process more than 1000 cubic millions of water was needed on annual basis [3]. Combined consumption of India, US and China is in the tune of 70 % of world coal consumption [4]. Central Electricity Authority (CEA) [5] of India has estimated ash generation for year 2021-2022 to the tune of around 270 million metric tonnes in India from combustion of about 759 million tonne coal or lignite. Fly ash utilization percentage from thermal power plants has increased from 56 % in 2014-15 to 95 % in 2021-22, but the biggest issue is the accumulation of unutilized ash stock over the years. Number of sectors where ash utilization done in past years has been mentioned below in Figure 1. Utilisation of stock of legacy ash is still a concern and challenge for the society. Most utilisation is done in the field of cement, brick manufacturing, reclaiming of low lying area and ash dyke

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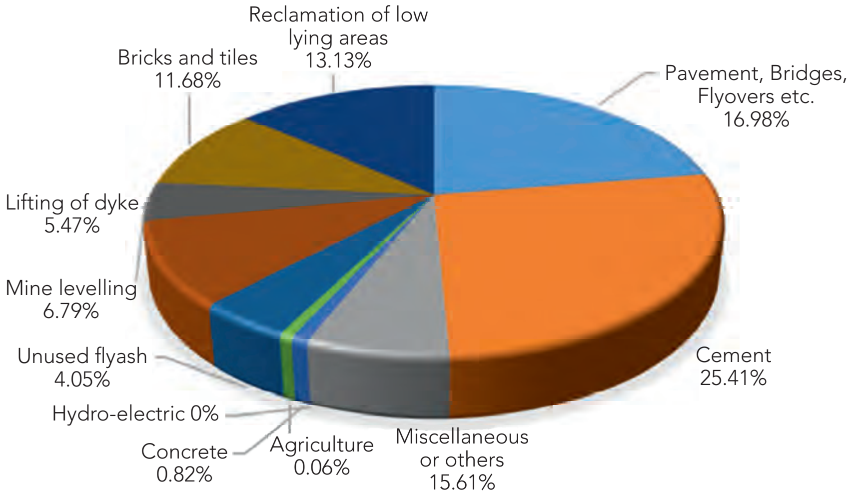

Figure 1: Major modes of ash utilization during the year 2021-22 [5]

raising. To use fly ash as replacement or substitution of clinker, superior quality fly ash (low carbon content fly ash) is preferred in cement manufacturing. Whereas lower quality fly ash with high and wide variation in carbon content is being used in landfills [6]. Keeping in view that large quantities of the fly ash stock still remains unused, the production of a good quality artificial sintered fly ash lightweight aggregate can be a great leap towards use of a huge quantity of fly ash thereby achieving significant environmental benefits along with circular economy.

Concrete system generally occupies 65-80 % aggregate by volume and can be solution to another critical concern of natural aggregate resources getting depleted. Artificial aggregate can be produced from fly ash by (a) cold bonding, (b) hydrothermal treatment (c) sintering process wherein utilisation of fly ash in terms of percentages for these techniques are 70 %, 45 % and 95 %, respectively [7]. Higher utilisation possibility of fly ash through sintering process provides an opportunity for bulk utilisation of ash. Application of sintering process for production of sintered fly ash lightweight aggregate was first used in 1960 [8]. Pollytag, Lytag, Aardelite etc. are few commercial fly ash lightweight aggregate in world. Adoption of sintered fly ash lightweight aggregate based concrete will lead to multiple benefits in terms of decreased dead load and reinforcement as well as economy in transportation, improvement in pace of construction , lower CO_2 emission, preservation of natural resource etc. [9]. In India and across world, fly ash lightweight aggregate based concrete usage is mostly in non-structural concrete and limited use is found in structural applications. Review has been conducted to understand and highlight effect of parameters involved in aggregate manufacturing and its influence on physio-chemical characteristics of sintered fly ash lightweight aggregate. Effect of sintered fly ash lightweight aggregate on mechanical and durability characteristics of concrete has also been discussed.

2. MANUFACTURING TECHNIQUE FOR SINTERED FLY ASH AGGREGATES PRODUCTION

The production technique for manufactured lightweight aggregates through sintering can be divided in four parts: (a) raw material handling, (b) pelletization, (c) sintering (d) finish product handling (Figure 2) [10-15]. Details of raw materials is given in subsequent section. Mixing process consists of mixing of ingredients upto the point when desired consistency is obtained. Pelletization method deals with fine particles agglomeration with binders such as bentonite, lime or some organic substances like dextrin or alkali compounds etc. Hardening of pellets can be done through (a) sintering, (b) autoclaving, or (c) cold bonding. Sintering technique achieves hardened pellets through fusion of fly ash particles together at mutual contact point [10]. Sintering technique is energy intensive as compared more energy efficient method such as cold bonding process. Whereas cold bonding method consumes around 28 days to obtain sufficient aggregate strength and high binder dosage is also needed. Characteristics of aggregate produced by sintering method are better than aggregate produced using cold bonding process in terms of both physical and mechanical performance [11-15]. Green pellet formation is a key in obtaining fly ash based aggregate. Optimum moisture presence in fly ash particles

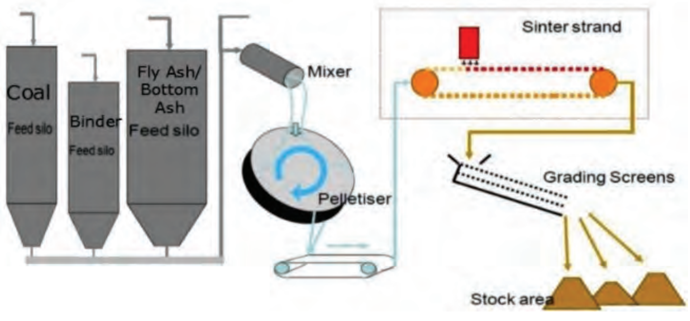

Figure 2: Flow diagram for production of sintered fly ash aggregate [15]

causes formation of liquid film around individual particle and when they come in contact with each other inter-bond between particles is developed gradually with help of rotating pelletizer or through externally applied force. The properties of produced pellets including particle size distribution can be well managed by adopting pelletizer in form of disc in comparison to cone or drum type. Green pellet strength depends upon porosity, surface area and surface tension of binding liquid [11-16].

Factors affecting pelletization process such as, (a) angle and speed of pelletizer (b) duration (c) raw material composition (d) particle size distribution of mix constituents (e) moisture content and (f) particle wettability has significant influence on produced aggregate characteristics [11, 16]. Pelletization parameters and mix constituents from previous studies are given in Table 1. Swelling characteristics of bentonite depends on dosage of bentonite and moisture content and for a given size of pellet, it is independent of speed, angle and duration of pelletization [10, 39].

The production of lightweight aggregate by sintering is done either through (a) rotating kiln or (b) sinter strand or (c) shafts. Kiln consists of burner for ignition of organic matter into green pellet. Whereas, firing, sintering and cooling are three stages of sintering through strand. Fresh pellets are fired to firing zone having 1000 to 1300°C temperature range from the movable sintering strand [17]. At next step, cooling of pellets are done and then it is moved through breaker to detach fused aggregates. In the end, the rounded shape aggregates are collected in silos in different size between 2 mm to 16 mm down to fines. These sintered aggregate were subsequently screened as per required sizes and is ready for use. Carbon combustion and moisture loss during pelletization causes fusion of ash particles into a cellular type of bonded structure. Below temperature of 1000°C, fly ash

Table 1: Production parameters for aggregate

FLY ASH TYPE	FINENESS (m^2/kg)	BINDER USED	BINDER DOSE (%)	MOISTURE CONTENT (%)	PELLETIZATION THROUGH DISC			SINTERING TEMP. (°C)	DURATION (min)	REF.
					ANGLE OF DISC (°)	SPEED (RPM)	DURATION (min)			
Class F	427	Cement, Bentonite, Lime	8-30	-	55	40	-	1100	60	[10]
Class C	392	Cement, Lime	8	-	35-50	35-55	6-20	-	-	[11]
Class F	401	Bentonite	20	25	36	55	15	950	-	[13]
Class F	428	-	-	15-35	40-70	20-40	5-20	1100	60	[21]
Bitumi-nous pond ash	252	Clay, Bentonite	5-25	24-33	50	50	-	900-1100	45-120	[22]
Lignite pond ash	281	Kaolinite, Bentonite	-	-	-	-	-	-	-	-
Class F	288	Bentonite, Glass powder	-	22-25	43	45	20	1100-1200	165-180	[23]
Bottom ash	212	Kaolinite, Metakaolin, Clay, Bentonite	5-20	26-33	55	50	-	800-1100	30-120	[24]
Class F	-	Shale	30-50	18	-	-	-	950-1100	120	[25]
Class F	257	Bentonite, Kaolinite	4-30	23-35	35-55	35-55	8-16	-	-	[26]
Class F Class F	320 -	Bentonite Lime, Cement, Silica fume	20-25 -	15-25 15-30	35-55 35-55	35-55 35-55	8-16 8-20	1100-1300 900-1100	30-120 30-120	[15] [122]
Class F	-	Calcium Bentonite and Sodium Bentonite	1	10-20	60	25	5	1000	60	[123]
Class F	-	-	-	20	-	-	-	1050-1300	5-60	[17]
Class F	-	Fly ash, Coal dust, Clayey soil	-	15-20	-	-	-	1050-1250	30-60	[16]

particles are not bound properly and leads to weak matrix and high water absorption. Rate of heating plays important role in compactness and shrinkage behaviour of aggregate. Findings in this area is contrary where few researchers are of opinion that shrinkage reduces with increase in heating rate whereas others suggest that densification occurs at fast heating rate. Further research is needed in this area as the quality of aggregate gets influenced by the sintering temperature and rate of heating. Aggregates strength with binder above 1200°C gets dropped due to bloating effect leading to more number of blocked pores.

Fly ash particles fuse around 1200°C and sintering at lower temperature than 1200°C has been achieved with optimisation and selection of appropriate binding agent [18, 19]. Increase in temperature leads to drop in peak value of quartz and mild increase in peak of mullite when x-ray diffraction analysis of aggregate is done [20-27, 122-125]. For producing the lightweight aggregate at the lower sintering temperature, research in past has been done with addition of few other binders along with fly ash in raw mix such as (a) metakaolin with sintering temperature around 900°C, (b) sewage sludge and river sediment with sintering temperature around 1050-1100°C. Combination of fly ash and metakaolin usage in raw mix design of pellets improves energy efficiency as the sintering is possible around lower temperature in the range of 900°C to produce aggregate [28]. Production of high strength lightweight aggregate has been achieved in past through geopolymerization process wherein composite blend of fly ash and silica fume have been used [29]. Pozzolanic materials with high concentration of SiO_2, Al_2O_3, and CaO can be other option for producing lightweight aggregate through alkali activation or geopolymerization [30]. Though, sintering method undertakes a high amount of energy, the characteristics of lightweight aggregates is found to be viable option for producing concrete with lighter weight [29-30].

3. RAW MATERIALS FOR SINTERED FLY ASH LIGHTWEIGHT AGGREGATE PRODUCTION

Coal ash generated from thermal plants is major constituents of sintered fly ash lightweight aggregate and both bituminous or lignite coal can be used [27]. With proper raw mix design, it is possible to use fly ash or bottom ash and Class C or Class F fly ash in lightweight aggregate production [10, 11, 27, 29]. Bentonite, lime, ground granulated blast furnace slag (GGBS), industrial sludge, marine clay, shale, cement, quartzite tailings etc. mixed with suitable amount of water are other ingredients when used in different combination and composition through optimisation. Additives such as alkaline activators, styrene-butadiene rubber, quick lime etc. have also been used for improving quality of fly ash based lightweight aggregate [26-30]. Major challenge involved with fly ash as main ingredients for aggregate production is huge variation in fineness. The average fraction of produced aggregate increases with enhancement in fly ash fineness compared to coarser fly ash which requires more moisture to achieve similar fraction of aggregate [10]. To convert coarser fly ash into aggregate is difficult and more energy is required. However, it is possible to use coarser fly ash with proper selection and dosage of binders. Carbon percentage in fly ash is important and if it is more than 12 %, addition of bentonite, clay or other suitable binders is needed for diluting carbon concentration. Other way around if carbon percentage is on lower side then coal dust needs to be added for achieving proper mix [6, 10].

Microstructure of sintered fly ash lightweight aggregate hugely depends upon chemical characteristics of fly ash which affects sintering process and viscosity of mix. Other than this, the ratio of Ca / Si, CaO and Na_2O percentage affects the viscosity and microstructure of finished product apart from the particle size, specific gravity and glass content in fly ash [27]. The addition of alkaline activator for pozzolanic constituents improves the development of calcium silicate hydrate gel and sodium aluminosilicate hydrates through alkali activation. The lightweight aggregate produced through geopolymerization has shown superior strength and lower porosity in aggregate because of additional calcium silicate hydrate gel and Ca/Si ratio leading to better microstructure. Low sodium hydroxide concentration can cause inappropriate dissolution of fly ash leading to formed gels not getting fully occupied between particle spaces [31-32]. Role of binder is very critical in obtaining improvement in plasticity of pressed pellets for sintered fly ash lightweight aggregate production and maintaining requirements with respect to shrinkage, efflorescence and color changes. Binder type and dosage affect the green and dried strength of pellets which subsequently affects the physical and mineralogical properties of fired pellets [10]. Physical and mechanical characteristics of fired pellets depend upon size and shape of particle and mix porosity. Commonly used binders are cement, lime, shale, bentonite, alkali compounds, industrial sludge, marine clay, quartzite tailings etc. Bentonite as a binder has shown reduction in specific gravity in contrast to comparatively higher specific gravity when binder is lime or cement [24-27]. Without binders, the water absorption in the range of 20-25 % at test age of 24 hours is reported for sintered fly ash aggregate.

Marginal reduction in water absorption with lime as binder is noticed and whereas cement as binder has shown superior performance in reducing the water absorption. Inclusion of about 20 % sodium bentonite has shown optimum strength and minimum water absorption. The use of binder has considerable impact on specific gravity of aggregate with sintering temperature around 1200 °C because of bloating. Past research done has indicated that around 2 % addition of $Ca(OH)_2$ can improve pelletization efficiency [33]. Use of borax has been done for improvement in mechanical performance and reduction in firing temperature which results in energy saving [34]. Now a days additional additives have been used for enhancing the characteristics of lightweight aggregate. Salt additives (NaCl) having capabilities to lower viscosity and to develop bigger pores inside aggregate has helped in producing ultralight aggregates. But the application of Na_2CO_3 as an additive, which is low cost and low corrosion hazard, allows the creation of ultra-lightweight aggregates [35]. Reduction in apparent density of aggregate has been achieved through addition of coke [36].

Usage of styrene butadiene rubber (SBR) has led to improvement in microstructure and mechanical performance of lightweight aggregate [32]. The waste glass powder inclusion in mix composition has produced aggregate with low water absorption and enhanced porosity by inflating pozzolanic materials [37]. The amount of water to be mixed in preparation of pellet should be optimised keeping in view the void ratio desired for produced lightweight aggregate. Moisture content governs the capillary state where inter particle voids are fully occupied with water and surface water on pellet is negligible inorder to achieve maximum tension force between particles [38]. Finest of variation effects the capillary force and leads to destruction thereby affecting mechanical performance of produced pellets.

Harikrishnan and Ramamurthy [10] observed that the quantum of moisture which can be considered in fly ash based aggregate production lies in between 15 to 35 percent and beyond this muddy balls formation takes place instead of pellet formation. 5 to 8 minutes of pelletization is considered optimum for pellet formation. Water getting entrapped in lightweight aggregate should not be considered as mixing water due to its immediate non-availability. Based on the apparent strength of pellets, two levels of optimum duration reported in past are 10 and 20 minutes as low and high, respectively. Shuguang [38] carried research for improvement in engineering properties of sintered fly ash lightweight aggregate by modifying the mineralogical composition. The assumption here was that when cordierite ($2MgO.2Al_2O_3.5SiO_2$) formation takes place at the time of aggregate cooling; formation of micro cracks will be on lower side due to better thermal shock absorption capabilities of cordierite. But inclusion of Mg in form of carbonate or hydroxide caused its decomposition during heating and sintering. The produced CO_2 and H_2O has effect on pellet's porosity and clear cut conclusions about its effect on strength was difficult [39-40].

4. PHYSICAL CHARACTERISTICS OF LIGHTWEIGHT AGGREGATE PRODUCED THROUGH SINTERING

Effect of sintered fly ash lightweight aggregate as a concrete ingredient and overall perfromance as structural concrete has still not been fully understood in various aspects. Specific gravity, density, crushing strength and water absorption of sintered fly ash aggregate are properties which are different from conventional concrete. Mechanical characteristics of this aggregate is dependent upon fineness of fly ash, characteristics and percentage addition of binder, additives, pelletization process, temperature and duration of sintering. Angle of pelletization, rotation speed of disc and moisture content has significant effect on size and shape of produced aggregate. Physical characteristics of sintered fly ash aggregate investigated

Table 2: Physical characteristics of sintered fly ash lightweight aggregate

LOOSE BULK DENSITY (kg/m^3)	SPECIFIC GRAVITY	WATER ABSORPTION (%)	CRUSHING STRENGTH (MPa)	10 % FINES (Ton)	REF.
-	1.75-2.35	16.00-22.00	-	1.75-4.25	[10]
-	2.00-2.35	28.8-33.90	-	-	[11]
900	1.57	1.75	18.34	-	[13]
845	1.59	12.40-13.10	-	-	[15]
-	-	19.00-30.00	-	0.8-2.20	[21]
-	-	7.50-24.00	-	0.5-2.50	[22]
-	1.51-1.93	0.70-18.40	5.1-19.30	-	[23]
-	1.80-1.92	19.00-20.00	-	2.90-4.20	[24]
750	1.34	17.90	-	-	[40]
650-890	-	6.10-8.00	5.6-10.10	-	[1]
835	1.77	12.00	-	-	[126]
1110-1180	1.40-1.66	5.59-13.10	3.7-5.4	-	[127]
760	-	0.87-7.73	6.48	-	[128]

Figure 3: Sintered fly ash lightweight aggregate [15]

(a)

(b)

Figure 4: Microstructure of sintered fly ash aggregate (10 μm and 1.5x) [15]

by past researchers has been presented in Table 2.

The shape of the aggregate has role in packing of particles and interlocking between the aggregates in concrete system. Sintered fly ash lightweight aggregate is brown in color as shown in Figure 3 and has black central portion because of iron in oxidised form and combustion of carbon. The main minerals present are quartz, glass, orthoclase-feldspar etc. The mineral present along with morphological and microstructural property of aggregates (Figure 4) indicates its potential as pozzolanic materials. When compared with fly ash, quartz peak is similar and not much modification is observed [15]. No significant reaction between alumino silicates and reactive quartz has been reported during sintering process [28]. Aggregate produced are round to medium round in shape with rough outer surface. The aggregate with angular shape having higher shape index gives better strength compared to lightweight aggregate having round shape and lower shape index. The rough texture on lightweight aggregate can have influence on its properties during fresh state because of surface frictional phenomena. Rough texture and porous characteristics of sintered aggregate has numerous lentils in form of hook creating adhesion among aggregate and paste cement hydration products getting penetrated into large size pores [17, 41, 42].

Specific gravity of sintered fly ash lightweight aggregate indicates wide variation from 1.34 to 2.35 (Table 2). The specific gravity of this aggregate is one tenth to half that of conventional aggregate. Increase in specific gravity is reported without binder at higher sintering temperature. However, when binder is added, reduction in specific gravity is noted due to bloating effect. Lightweight coarse aggregate produced from combination of bentonite and water glass has shown specific gravity around 1.60 even at sintering temperature of 800°C [43-44]. Inclusion of additives has shown improvement in specific gravity but curing temperature plays a critical role. The use of foaming agent as additives also has indicated reduction in the specific gravity [28]. From microstructure study, the permeable nature of sintered fly ash aggregate is quite evident. Aggregate with high water absorption are not considered positive for producing durable and strong concrete. Researchers have highlighted that sealing of pores for producing sintered fly ash lightweight aggregate is not a viable solution as it will enhance the density of aggregate [27]. Wide variation has been observed in water absorption values of lightweight aggregate researched by past researchers (Table 2). The variation is very high ranging from 0.70 to 34 percent. However, commercially found aggregate has water absorption in range of 10 to 20 percent. Ramamurthy *et al.* [10] concluded that with 20 % addition of bentonite a decrease in water absorption can be achieved upto 30 percent. Water absorption of sintered fly ash lightweight aggregate stabilizes after sometime because of its porous structure and similar pore structure of inner and outer portion compared to expanded clays or shales (Figure 4) [10, 15]. The initial rate of water absorption for sintered fly ash lightweight aggregate of size fraction 4-8 and 8-16 mm also referred as low density aggregate (LDA) is significantly high (Figure 5) [15]. In first hour itself, water absorption were 9.01 and 9.09 % respectively indicating that more than 70 % of water absorption happens in first sixty minutes [15].

Techniques have evolved to reduce water absorption by various ways. Reduction in water absorption in the range of 0.5 to 7.75 %

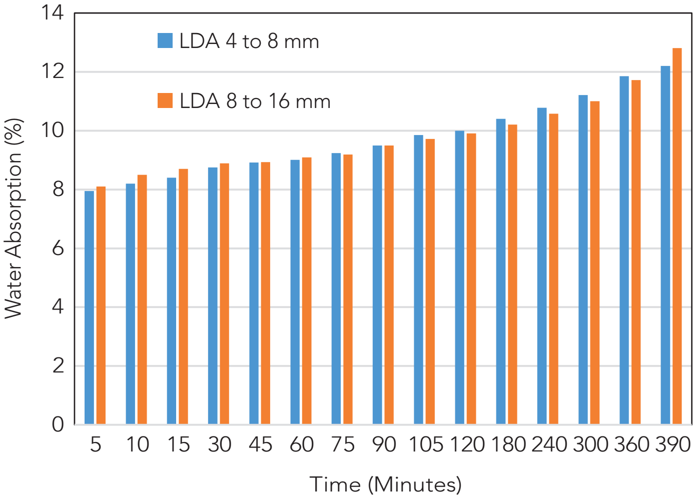

Figure 5: Variation in water absorption of sintered fly ash lightweight aggregate with time [15]

has been observed with inclusion of waste glass powder in lightweight aggregates manufacturing [45]. Addition of styrene-butadiene rubber (SBR) has shown to reduce water absorption from 12.1 to 8.58 % when it was added in range of 1 to 3 % in lightweight aggregate, causing minimisation in voids [32]. Fly ash based aggregates produced through alkali activation has shown enhancement in water absorption at 80°C curing because water present in aggregates participates in geopolymerization process, thereby improving strength of pellets [46, 126-128]. Liu *et al.* [47] has concluded that reduction in water absorption can be achieved around 1100°C sintering temperature. Lightweight aggregate made up of metakaolin as a binder has shown enhancement in water absorption beyond 900°C sintering temperature and leads to formation of closed pores [47-48]. Bulk density of aggregate used in concrete has role in paste volume needed for mix and has influence on fresh properties of concrete and economy of mix [49]. Bulk density in dry loose condition in the range of 880-1120 kg/m^3 is permitted by ASTM C 330 [50] for production of structural concrete and variation in bulk density depends upon size of aggregate. Values mentioned in Table-2 indicates that loose bulk density varies from 750-900 kg/m^3. Increase in pellet size leads to reduction in bulk density ultimately affecting strength of aggregate. The large size pellets are less compacted compared to smaller size pellets and larger voids are developed in its outer layer. Sediment based lightweight aggregate produced by sintering with bulk density around 850 kg/m^3 had shown crushing strength more than 13 MPa indicating effect of bulk density on strength of aggregate [51]. 10 % Na_2CO_3 in combination with fly ash and clay getting sintered around 1215°C has given the pellet strength more than 4 MPa [52]. Factors like variation in mineralogical composition, binder's melting temperature, sintering dependent densification, aggregate bloating and internal affects caused by thermal stresses affects crushing strength of aggregate [27].

From Table 2, the wide variation in crushing strength from 5.10 to 19.30 MPa is noticed and factors mentioned above has role to play in such wide variation. Increase in crushing strength has been highlighted by past researcher's upto 1150°C and beyond 1200°C reduction has been reported due to bloating [12]. Crushing strength for sintered aggregate is three to four times compared to cold bonded aggregate produced from fly ash of same properties [53]. Kamal and Mishra [54], highlighted that binder addition in raw mix during manufacturing leads to pellet getting wrapped and voids resisting compression in better way. Styrene-butadiene rubber (SBR) used as an additive has shown lower impact value thereby producing strong aggregate [32]. Cement based fly ash aggregate when cured at appropriate temperature has shown better resistance to impact due to enhancement in hydration reaction [55]. Study by Gomathi *et al.* [13] indicated that hot water curing is more suitable for lightweight aggregate based concrete than steam curing. In fresh state, lightweight concrete density can be either fresh density having full compaction and minimum air content or demoulding density which is normal compaction and curing under sealed environment upto 24 hours. Guneyisi *et al.* [53] have shown fresh density of lightweight concrete in range of about 1980 kg/m^3-2100 kg/m^3. Demoulding density is used for self-weight determination in design of high performance lightweight aggregate [9].

5. MIX DESIGN OF CONCRETE WITH SINTERED FLY ASH LIGHTWEIGHT AGGREGATE

The concrete mix design with sintered fly ash lightweight aggregate concrete is more cumbersome as compared to conventional concrete as number of design parameters such as water absorbed in concrete mixing and proportioning of different aggregate sizes etc. are needed [27]. Mix design method adopted in past [6, 27] has been reported to be on the basis of fixing the aggregate or paste content without taking into account the aggregate properties and strength requirements. Reduction in free water available to cement paste in concrete with sintered fly ash aggregate is due to higher water absorption of aggregate and it has influence on compressive strength of concrete also. If not taken into account it leads to higher paste content for achieving desired strength and workability. Lower optimum paste content in concrete improves microstructure and packing of aggregate thereby improving strength and durability properties particularly resistance to chloride ingress [56]. Factors critical in any mix design of concrete are water to binder ratio, quantity of cement and aggregate. To achieve proper packing the grading of aggregate is important. Modified fullers curve have been found to be suitable for fly ash based aggregate. Based on the outcome of past research [57-60] curve A of DIN 1045 [] is preferred for normal consolidated concrete and curve B of DIN 1045 [57] is preferred for self-compacting concrete. Dhir *et al.* [61] proposed a mix proportioning steps for expanded clay or shale aggregate but developed procedure did not consider absorption characteristics which is critical for sintered fly ash lightweight aggregate. ACI 211 [62] mix proportioning method for structural lightweight concrete proposes either weigh batching or volume batching of the constituents and series of trial and error was required to obtain the specific mix parameters. Yang *et al.* [63] suggested a preliminary mix design method for structural lightweight concrete based on regression analysis of more than 300 data points generated on clay or expanded fly ash aggregates but water absorption corrections was not taken into account properly. Nadesan *et al.* [64], highlighted the difference in relationship between water to binder ratio for sintered fly ash aggregate concrete and normal concrete (Figure 6). However, when water-binder ratio increases, the strength converges at water-binder ratio 0.4.

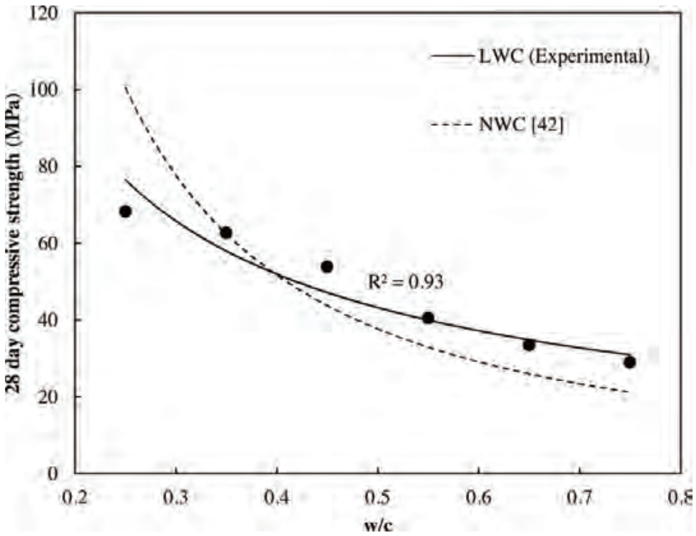

Figure 6: Compressive strength to water cement ratio relationship of lightweight concrete [64]

Mix proportioning procedure developed based on study done by Nadesan *et al.* [64] is very simple. At first step, from above curve water to cement ratio is fixed for desired strength. Then water content is decided for achieving required workability and cement content is calculated from *w/c* ratio. Fine and coarse aggregate volumes are determined as per curve given in DIN 1045 [57]. To take care of absorption of water by porous lightweight aggregate an additional water is added. Low dosage of admixture has been required to achieve similar workability for spherical shaped sintered fly ash lightweight aggregate in contrast to angular normal aggregates [12, 64]. Variation in workability and compressive strength of both air dried and pre-soaked aggregates are reported to be similar when care is taken during mix proportioning and correction towards requirement of additional water is done keeping in view the porous nature of lightweight aggregate [65-66]. Adequate curing is needed for normal concrete to ensure development of hydration products but sintered fly ash lightweight aggregate having absorbed water inside it during mixing helps in internal curing at later stages and can compensate for loss of moisture. Studies have also indicated that chloride curing is found to be effective in the strength gain of lightweight aggregate based concrete whereas chloride curing has negative effect on normal strength concrete [67-70].

6. SINTERED FLY ASH LIGHTWEIGHT AGGREGATE CONCRETE-MECHANICAL PROPERTIES

The satisfactory mechanical performance of sintered fly ash lightweight aggregate in structural concrete will promote its wider application in construction. The interfacial transition zone (ITZ) is one of the key factor which influences its performance as structural concrete [71]. Compressive strength is one of main design parameter in structural design of structures. RILEM [72] document states that concrete with compressive strength above 15 MPa and densities between 1600 kg/m^3-2000 kg/m^3 is considered as structural concrete [72]. Sintered fly ash lightweight aggregate has low strength but the strength of paste matrix and arching action extent determines the strength of concrete [73]. This indicates that ITZ has significant role on compressive strength and related mechanical properties of concrete. The parameters affecting compressive strength test of concrete such as size of specimen, rate of loading, axial stresses in multiple direction has minimum effect in lightweight concrete to that of conventional concrete thereby highlighting different correlation between cube strength to cylindrical strength of lightweight concrete [74]. The development of concrete strength apart from aggregate quality depends upon both physical and chemical action happening in concrete particularly in interfacial transition zone. Densification of ITZ takes place in lightweight concrete because in the initial stage aggregate starts absorbing water. The chemical phenomena which takes place is due to deposition of calcium hydroxide on outer shell of aggregate. The wide

Table 3: Mechanical properties of concrete with sintered fly ash lightweight aggregate

COMPRESSIVE STRENGTH (MPa)	FLEXURAL STRENGTH (MPa)	SPLIT TENSILE STRENGTH (MPa)	MODULUS OF ELASTICITY (GPa)	REFERENCES
23.12-44.06	3.13-4.36	2.0-3.60	17.71-22.32	[13]
27.78-44.19	3.79-4.25	3.13-3.50	20.69-22.35	[15]
51.00-60.70	3.65-4.40	3.15-3.60	25.40-26.90	[69]
30.10	2.45	3.16	19.70	[78]
70.00	-	2.49-3.63	-	[64]
57.90-67.90	-	3.40-7.40	20.80-21.80	[70]
44.60-53.40	-	3.70	16.70-19.00	[66]
40.00-46.00	3.60-5.07	3.00-4.50	20.00-24.00	[77]
32.00-36.00	4.60-5.60	2.20-2.80	-	[44]

variation in compressive strength test results from study conducted by various researchers has been observed (Table 3). Apart from characteristics of manufactured sintered fly ash lightweight aggregate, the variation in compressive strength can also be attributed to cement content, supplementary cementitious materials, aggregate content and shape index of aggregate etc.

Study has indicated higher value of compressive strength for concrete with sintered aggregate without pelletization and better than granite type aggregate for same mix constituents. This indicates that only strength is not a governing factor for lightweight aggregate based concrete but factors such as volume and shape index of aggregate is also important [75]. Binder strength and type of binder adopted in concrete production has effect on compressive strength of lightweight concrete even though densities can be similar. Adoption of fly ash cenospheres of micro size in concrete mix has shown reduction in density and improvement in mechanical performance of concrete by creating small size cell like structure in cement paste matrix which arrests crack formation [76]. The compressive strength of styrene butadiene rubber (SBR) admixed lightweight aggregate concrete (SLWA) gets increased with enhancement in SBR dose in pellets. Improvement to the tune of 5-15 % and 7-20 % has been observed for water to cement ratio of 0.50 and 0.30, respectively at 90 days test age in SLWA mixes as compared to normal lightweight aggregate [32]. Mortar of fly ash having 8 molarity concentration of sodium hydroxide has shown significant improvement in bulk density and compressive strength of lightweight aggregate. Positive impact of fibres addition on compressive strength of lightweight concrete system has been reported in past due to its crack arresting mechanism and can be used for structural application [77-79].

The tensile properties such as flexural or split tensile strength of sintered fly ash lightweight is lower than conventional concrete owing to low strength and stiffness of porous lightweight aggregate. Some researchers have achieved split tensile strength in similar range to that of normal strength concrete. As per ASTM C 330 [50] minimum split tensile strength requirement is 2 MPa. In case of sintered fly ash lightweight concrete, the homogenous and dense ITZ highlights better bonding between paste aggregate [12]. According to Al Khaiat *et al.* [69] the curing impact on tensile properties of concrete is limited. The ratio of split tensile strength to compressive strength of lightweight concrete varies from 5 to 10 % (Table 3). Whereas ratio of flexural strength to compressive strength of lightweight concrete is varying from 7 to 10 % (Table 3). ACI 318 [27] and FIP 1983 [27] codal equations underestimate the split tensile strength whereas EN 1992 [27] overestimates. EN 1992 [27] codal empirical equation is near to the experimental results as highlighted by Nadesan *et al.* [27]. However, there is need to develop empirical equation for prediction of split tensile strength or flexural strength more accurately. Similar to tensile properties, elastic modulus of lightweight concrete is significantly lower than conventional concrete mainly due to increase in paste content and decrease in stiffness of aggregate. Shape index and aggregate content in lightweight concrete mix has significant impact on elastic modulus.

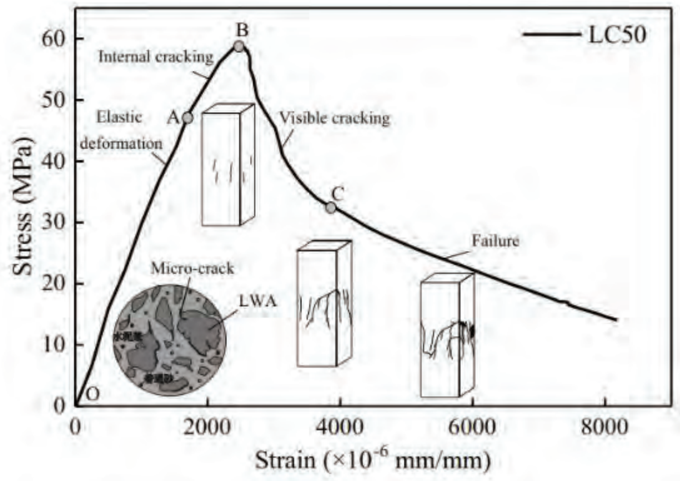

Figure 7: Typical Stress-Strain curve for lightweight concrete [81]

The stress-strain curve is comparatively straight in case of lightweight aggregate in comparison to conventional aggregate. Lui *et al*. 2019 [81] investigated the stress-strain behaviour of lightweight aggregate based concrete. From the study (Figure 7), it was found that stress-strain relationship from initial point O to A is linear. The slope of ascending portion indicates initial stiffness to be on lower side compared to that of normal concrete. After point A onwards as shown in Figure 7, the rate of increase in stress is steady but rate of strain increase is more which is highlighting stage where crack formation has started leading to decrease in stiffness.

The portion between A and B (Figure 7) is continuous and frequent crack formation compared to normal concrete was reported due to low strength of lightweight aggregate. After point B, the rate of decrease in stress was rapid compared to strain highlighting brittle nature of lightweight concrete. Beyond point C, the decrease in stress was slow compared to increase in strain owing to frictional resistance and remaining stress providing limited capacity across cracks [80-81]. This indicates lower elastic modulus and less ductility in post cracking failure region. Normal concrete gives higher elastic modulus than lightweight concrete due to higher moduli of conventional aggregate than lightweight aggregate. As per ACI 213R-03 [27], elastic modulus of lightweight concrete varies from 0.5 to 0.75 % that of normal concrete of similar strength grade. Nadesan *et al.* [27] have reported that NS-3473 [27] and ACI-213 [27] empirical equations underestimate elastic modulus of lightweight concrete whereas, EN-1992 [27] and ACI-318 [27] overestimate. According to them NS-3473 [27] predicts modulus of elasticity closer to expected value but more accurate empirical equation needs to be developed for estimation of elastic modulus of lightweight concrete.

As per ASTM C330 [50], drying shrinkage of concrete specimens shall not exceed 0.07 %. Yamamoto *et al.* [82] work on shrinkage study showed that shrinkage as double for lightweight concrete compared to normal concrete. Variation in shrinkage between 600 to 1000 micro-strains has been observed when both coarse and fine aggregates are lightweight in nature. Concrete shrinkage beyond 850 micro-strains is generally not permitted in reinforced concrete construction as per AS 3600 [66]. The increase in drying shrinkage for lightweight aggregate concretes is noticed even after a year as per ACI 213R-03 [66]. Contradicting to this, few experimental studies indicated that shrinkage in same range to that of conventional concrete, sintered fly ash aggregate with no pelletization has shown 30 % lower shrinkage than granite aggregate based concrete [66]. Study in past has shown that prewetted lightweight aggregate can avoid problem of both autogenous shrinkage and cracks at initial age under sealed curing environment because sintered fly ash lightweight aggregate has shown better restraining capabilities due to development of sufficient strength of matrix [66]. Lightweight aggregate impregnation can cause hindrance to internal curing from absorbed water inside aggregate, thereby creating higher autogenous shrinkage and higher rate of drying shrinkage as well as deterioration of interfacial transition zone [83-84]. Study has indicated that pre-coated treatment of lightweight aggregates with initial moisture affects performance of impregnation in concrete wherein decrease in water absorption recorded was around 40 %, while increase in strength was upto to 32 % [85].

The more brittle nature of lightweight concrete in comparison to normal concrete creates possibilities of splitting cracks and separation of cover concrete [86]. Study by Bjerkeli *et al.* [86], highlighted that bond strength by direct pull-out test is lower in lightweight concrete as compared to normal concrete. The bond perfromance of lightweight concrete under flexure test of beams were also found lower compared to normal concrete in study conducted by Ornagun [87] but in direct pull-out test the similar results were obtained for both sintered fly ash lightweight concrete and normal concrete. The lower bond strength in flexure test of beams can be due to the improper compaction and lower shear strength of lightweight concrete. Little influence on bond performance of deformed bars and self-compacting lightweight concrete has been revealed in study done under lateral pressure [88]. It has been reported that bond strength of cement based lightweight concrete is in the range of 10.3-15.58 MPa which is higher than that for geopolymer based lightweight aggregate concrete which is in the range of 10.04-11.34 MPa [89]. Studies has shown decrease in the results of the bond strength ranging between (7 %-43 %) when using bars of diameters between 8-25 mm [89]. Guneyisi *et al.* [53] have shown marginal decrease of 3 percent in bond strength when aggregate substitution was increased from 45 to 60 percent.

According to Guneyisi *et al.* [53], water curing and addition of steel fibres in lightweight concrete has shown improvement in bond strength of lightweight concrete. Bond strength of lightweight concrete having deformed steel bar is more compared to other types of bar. Coating has indicated improvement in bonding of reinforcing bar with lightweight concrete. The effects of bar diameter and bond length are significant in determining the bond strength of lightweight concrete wherein lower bar diameter and less bond length has shown improvement in the bond strength. The lateral confinement through stirrup has indicated superior bond strength. But still no conclusion could be drawn related to peak slip and bond stiffness of lightweight concrete and its post-failure behaviour which is more brittle compared to normal concrete [90]. Due to presence of superior aggregate paste bond in sintered fly ash lightweight concrete, the fracture plane moves through aggregate rather than paste matrix whereas in case of normal concrete the fracture plane passes around aggregate [91]. Balendran *et al.* [92] investigated toughness properties of a lightweight high strength concrete with density and strength of 2000 kg/m^3 and 90 MPa respectively as per procedure laid down in ASTM C 1018 [78]. Study conducted by them indicated that toughness of lightweight high strength concrete is not much affected by specimen size compared to high strength concrete made of conventional aggregate. The fracture behaviour of sintered fly ash lightweight aggregate based concrete has been reported to undergo linear elastic fracture mechanics [78]. Study by Bjerkeli *et al.* [86] indicated that bond slip correlation between normal and lightweight concrete is much different but expression for tension stiffening effect and crack width for normal concrete can be used for lightweight concrete.

Fracture energy, fracture toughness and characteristic length of lightweight alkali-activated concrete using sintered fly ash ceramsite are reported in the range of 93-100N/m, 0.48-0.74 MPa.m$^{1/2}$ and 150-192 mm, respectively, for compressive strengths range of 26.10 to 50.29 MPa. But the fracture characteristics of normal alkali activated concrete are 121-154 N/m, 0.62-1.02 MPa.m$^{1/2}$ and 187-275 mm, respectively, for compressive strengths range of 23.99 to 43.84 MPa [93]. Past studies have indicated improvement in impact energy by addition of crumb rubber and reduction in compressive and flexural strength [94]. In case of lightweight concrete, elastic modulus of paste and aggregate are closer to each other than normal concrete which leads to consistent stress distribution and reduction in stress accumulation where failure happens in aggregate which is comparatively weaker. Studies have indicated that lightweight concretes gives higher creep than concrete with strong aggregates for similar strength grade [95]. Sintered fly ash lightweight concrete has shown higher rate of creep at early ages but the final creep for both sintered fly ash lightweight aggregate and other lightweight aggregate have been reported to be in same range with lower difference [27]. High strength lightweight concrete in few studies done in past have indicated similar and in few cases even lower creep compared to normal concrete of similar strength [96-98]. Thermal treatment of aggregate has shown lower creep in lightweight concrete. Autoclaving has shown lower creep by 60-80 %. Shrinkage and creep of lightweight concrete with expanded blast furnace slag, expanded shale from rotary kiln or sintering, expanded clay from sintering at various substitution percentage of fine aggregate in concrete showed that both shrinkage and creep decreased with increase in fine aggregate content. In case of complete substitution of lightweight aggregate, the reduction in creep coefficient was up to 30 % to concrete with reduced replacement proportions of fine aggregate and lightweight aggregate [99-100].

7. DURABILITY OF CONCRETE PRODUCED WITH SINTERED FLY ASH LIGHTWEIGHT AGGREGATE

Along with mechanical properties of sintered fly ash lightweight concrete, the durability properties are equally important to meet the designed service life of structures. The permeability of sintered fly ash lightweight aggregate and wide variation in its water absorption potential has effect on durability performance of lightweight concrete. The inter-connectivity of pores and volume of pores determines the penetrability of ions in concrete which could lead to deterioration of concrete. The durability performance of lightweight concrete can be a complex in nature and effect of material characteristics and production parameters of lightweight aggregate are deciding factor in its durability performance. The results of durability studies done by past researchers has been presented in Table 4. Permeation of ions in concrete matrix depends upon size of pores and porosity. Although lightweight concrete is made up of aggregate having higher water absorption its resistance to water penetration has been found to be comparable or better compared to normal concrete. Past studies, has shown a comparable water penetrability for both lightweight and normal concrete with w/c ratio of 0.4 and aggregates having water absorption at 24 hours in range of 10-15 %. The permeability phenomena in lightweight concrete is related to internal curing because as the duration gets reduced permeability gets increased [20, 70, 101-103, 129]. Study by Zhang and Gjorv [104], indicated that type and quantity of cement and supplementary cementitious materials also influence water tightness of lightweight concrete. Addition of silica fume has shown reduction in permeability of lightweight concrete [40, 53]. The higher depth of water penetration for concrete made with lightweight aggregate compared to natural aggregate having similar mix constituents, has been reported with cold bonded lightweight aggregate due to open pores inside aggregate [105]. Resistance to chloride in case of lightweight concrete as reported by past researchers indicated that, penetration of chloride ions is lower in lightweight concrete compared to normal concrete of similar strength and mix composition [101-104]. This lower penetration of chloride or water in lightweight concrete can be attributed to superior interfacial transition zone. Review carried out by Bogas and Real [106] have highlighted that resistance to chloride penetration and carbonation depends upon composition of paste, aggregate type, curing regime and duration, test setup, penetration phenomena and water content of concrete [106].

The depth of carbonation in case of lightweight concrete is higher than normal concrete with higher gas permeability and more water absorption capabilities of lightweight aggregate. The absence of dense outer layers makes sintered fly ash lightweight aggregate more susceptible to higher carbonation [27, 40, 106]. Structural lightweight concrete and normal concrete of similar mix composition have also shown comparable chloride diffusion coefficients with chloride content on surface of lightweight concrete tends to be more than normal concrete, which can cause higher long-term chloride penetration. Proper dispersion and participation of lightweight aggregate particles by dense paste matrix is required to achieve the better durability performance of structural lightweight

Table 4: Durability parameters of concrete with sintered fly ash lightweight aggregate

WATER PENETRATION DEPTH (mm)	RCPT (COULOMBS)	GAS PERMEABILITY ($\times 10^{-16}$ m^2)	CARBONATION COEFFICIENT (mm/year$^{0.5}$)	ACCELERATED CORROSION (DAYS)	REFERENCES
12.33-14.67	3829-5823	-	-	-	[15]
-	1384-3378	3.04-14.02	-	63-135	[53]
-	2423-4356	-	-	-	[27]
19-23	590-700	-	-	106-123	[20]
-	-	-	12-70	-	[106]
12.40-24.20	2385-3620	-	-	-	[129]
40	-	-	-	-	[70]
-	-	-	10-55	-	[40]

concrete [106]. Limited study on resistivity of lightweight concrete [107-108] have reported resistivity value around 37-40 $k\Omega$-cm. No correlation is existing between type of aggregate and resistivity value. As the water-binder ratio decreases, the resistivity of lightweight concrete increases similar to normal concrete, which indicates that mix composition is more critical. Performance of sintered fly ash lightweight concrete is better than conventional concrete in terms of its corrosion resistance owing to larger negative potential value and negligible corrosion current potential [66, 108]. The presence of excess moisture in cement paste matrix of lightweight concrete reduces the diffusion of oxygen towards reinforcement. Based on ratio of carbonation depth to length of crack, the rate of carbonation under actual site conditions gets enhanced by 80 % in cracked concrete [109]. Considering type of lightweight aggregate and water to binder ratio between 0.5-0.6, even for most aggressive environment, the structural lightweight concrete with cement matrix of low to medium quality will not induce dominant degradation related to carbonation-induced corrosion when appropriated cover is taken in design. Study have indicated that average carbonation depth of structural lightweight concrete with water cement ratio less than 0.65 would take beyond 50 years to attain 30 mm under air dried environment. Similar conclusions have been drawn by Bogas and Gomes [111], for lightweight concrete with porous volcanic lightweight aggregate. Previous studies have shown that lightweight concrete without entraining admixtures have shown better frost resistance compared to normal concrete [110-112].

The confirmation were also drawn through assessment of concrete in existing structures subjected to freeze-thaw [113,114]. It has been also highlighted that use of dry aggregate gives similar or superior frost resistance of lightweight concretes compared to normal concrete with similar mix composition [115]. Sintered fly ash lightweight aggregate with moisture content upto 18 percent showed improvement in the water penetration resistance. However, good performance in terms of freeze-thaw resistance was not evident. For producing concrete with better freeze-thaw resistance, limit on w/c and use of lightweight aggregate with minimum fraction of crushed particles is important. Use of dry sintered fly ash aggregate with paste matrix having absolute w/c = 0.37 has shown improvement in water and ion penetrability along with a full freeze-thaw resistance even when air entraining admixture is not used [116].

8. MICROSTRUCTURE AND INTERFACIAL TRANSITION ZONE OF SINTERED FLY ASH LIGHTWEIGHT AGGREGATE BASED CONCRETE

Microstructural analysis of sintered fly ash lightweight concrete has shown superior bonding among paste and fly ash present in aggregate regardless of original moisture content of aggregate. Lightweight concrete superior bond interlocking mechanism is due to porous aggregate absorbing cement and mixing water together in contrast to aggregate absorbing cement paste mainly in normal concrete. Interfacial transition zone (ITZ) plays an important role in deciding structural performance of concrete. ITZ characteristics are dependent on aggregate characteristics like water absorption, type, density, surface texture, porosity and moisture content [116]. Results of scanning electron microscopy studies have revealed absence of wall effect in lightweight concrete and partial penetration along with covering of hydration products on periphery of lightweight aggregate is found. Study from Kong *et al.* [117] has indicated higher ITZ thickness and hardness value of lightweight concrete in comparison to normal concrete. Past studies have highlighted, superior quality of ITZ in case of a sintered fly ash aggregate (Figure 8) [117-118]. But the philosophy was not true when lightweight concrete was made with pre-saturated aggregate. For pre-wetted lightweight aggregate,

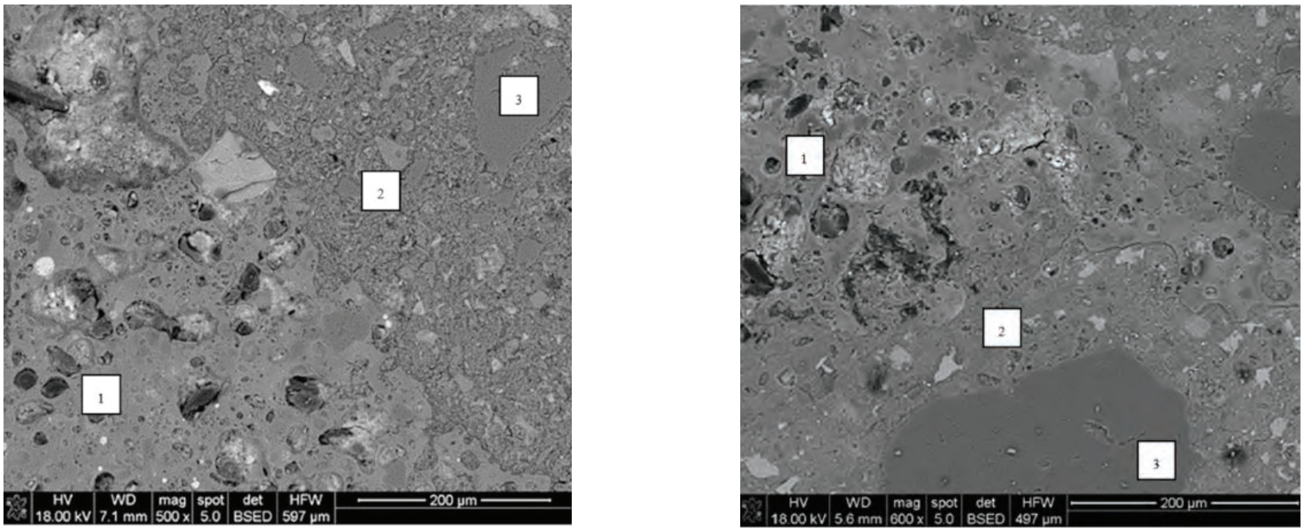

Figure 8: ITZ in lightweight concrete with pre-saturated aggregate (figure on left side) and initially dried aggregate (figure on right side): 1. LWA; 2. Cement paste; 3. Sand particle [117]

ITZ was identified with more amount of ettringite along with micro-cracks which can create problem related to durability [116]. Other than the mechanical interlock, chemical reaction within ITZ of fly ash aggregate concretes affects its performance as structural concrete. The silica and alumina present in fly ash aggregate undergoes pozzolanic reaction. For conventional aggregate, $Ca(OH)_2$ gets liberated on aggregate surface due to nucleation effect and further formation of duplex film happens due to subsequent development of $Ca(OH)_2$ on surface of aggregate [119]. But lightweight aggregate has potential to soak the precipitated $Ca(OH)_2$ inside aggregate and can initiate pozzolanic activity on periphery of aggregate. Improvement in pozzolanic reaction of thermally treated lightweight aggregate has been noted in past studies [27].

The lower thickness of ITZ of sintered fly ash lightweight concrete in range of 40-50μm, which makes it difficult to study the chemical reaction products and its effects accurately. Some researchers have highlighted negligible pozzolanic reaction between fly ash and cement due to sintering leading to crystallization [120-129]. The chemical reactivity of coarse aggregate type lightweight aggregate is different from lightweight aggregate in powder form or in form of fine aggregate but most of the researchers highlight that there exist physical and chemical interaction which affects the ITZ and bond between paste and aggregate [116-129]. Lightweight aggregate produced from fly ash through geopolymerization indicated improved pore distribution and inter pore connectivity leading to more water getting absorbed inside aggregate. SEM indicates superior mechanical and durability performance due to development of dense microstructure [121]. The thermal conductivity of lightweight concrete is around 0.95 W/m.K compared to 2.0-2.95 W/m.K for normal aggregate. Lightweight concrete has shown thermal conductivity value on lower side which makes it suitable as thermal insulating material for construction. This will help in construction of building with thermal comfort and energy efficient [121].

9. CONCLUSIONS

The potential of sintered fly ash lightweight aggregate in production of structural concrete has been reviewed through the past studies done. The production process, quality of fly ash, binding materials and additives used in production of sintered fly ash lightweight aggregate impacting its physical, mechanical and durability performance has been presented in detail. From the detailed review, the conclusions drawn are given below:

1. Properties of fly ash, binders and additives influences the physical characteristics of manufactured sintered fly ash lightweight aggregate. The optimisation of angle of inclination, speed of pelletization and sintering temperature according to the raw mix constituents adopted for production of sintered fly ash lightweight aggregate is critical in achieving desired properties as wide variation in the properties of produced lightweight aggregate has been observed.
2. Rate of heating plays important role in compactness and shrinkage behaviour of aggregate. Findings in this area is contrary where few researchers are of opinion that shrinkage reduces with increase in heating rate whereas others suggest that densification occurs at fast heating rate. Further research is needed in this area as the quality of aggregate gets influenced by the sintering temperature and rate of heating.
3. The sintered fly ash lightweight aggregate has shown higher water absorption and lower specific gravity. The use of additives such as alkaline activators, styrene-butadiene rubber, quick lime etc. and additional treatments such as coating or vacuum impregnation has shown potential for reducing water absorption.
4. The mechanical performance of sintered fly ash lightweight aggregate in concrete is different from normal concrete. Factors affecting compressive strength, flexural strength and modulus of elasticity apart from the characteristics of manufactured sintered fly ash lightweight aggregate are cement content, supplementary cementitious materials, additives used, treatment done to aggregate, aggregate content, shape index of aggregate etc. Sintered fly ash lightweight concrete has shown higher rate of creep at early ages but the final creep for both sintered fly ash lightweight aggregate and other lightweight aggregate have been in same range with lower difference.
5. Prewetted lightweight aggregate has shown potential to overcome both autogenous shrinkage and cracks at early age under sealed curing environment because sintered fly ash lightweight aggregate has shown better restraining capabilities due to development of sufficient strength of cement matrix. For bond strength assessment no conclusion has been established related to peak slip and bond stiffness of lightweight concrete and its post-failure behaviour which is more brittle compared to normal concrete; this area needs to be further researched. Lightweight concrete has shown lower thermal conductivity which can act as suitable thermal insulating material for application in construction field.
6. Water permeability and chloride ion penetration of sintered fly ash lightweight aggregate based concrete are less than normal concrete. Corrosion resistance of sintered fly ash lightweight concrete is superior to conventional concrete because of higher negative potential value and negligible corrosion current potential. The carbonation resistance of sintered fly ash lightweight concrete is lower than conventional concrete of same composition and rate of corrosion in structural lightweight concrete is low due to its homogenous and superior ITZ. Studies have indicated no direct relationship between factors affecting

concrete durability such as water absorption, mechanical perfromance, cement content, water penetrability and freeze-thaw resistance of sintered fly ash lightweight concrete and further research is needed in this area.

7. Use of dry aggregate in lightweight concrete without entraining admixtures have shown better frost resistance in comparison to conventional concrete but the similar performance was not evident when initially wet aggregate were used in lightweight concrete production. The interfacial transition zone (ITZ) has key role in determining mechanical and durability performance of sintered fly ash lightweight concrete wherein denseness of microstructure and lower porosity leads to better crack penetration resistance and superior performance of structural concrete. The sintering temperature, selection of binder, additives and internal curing plays vital role in quality of ITZ. Further research is needed to explain bonding mechanism between aggregate and matrix.
8. Sintered fly ash lightweight aggregate based concrete has great potential for its application in construction to obtain benefits such as reduction in dead load, improved thermal comfort, reduction in carbon footprint.

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