Geopolymer Aggregate Concrete: A review from fundamentals to developments

K Krishna Bhavani Siram¹², Dhanya Sathyan³*

¹Research Scholar, Department of Civil Engineering, Amrita School of Engineering, Coimbatore. Amrita Vishwa Vidyapeetham, India, 641112
²Assistant Professor, Department of Civil Engineering, Mahatma Gandhi Institute of Technology, Hyderabad, Telangana, India 500075
³Associate Professor, Department of Civil Engineering, Amrita School of Engineering Coimbatore. Amrita Vishwa Vidyapeetham, India, 641112

*corresponding author, email: s_dhanya@cb.amrita.edu

Abstract: Aggregates hold almost three-fourths volume of concrete. The tremendous increase in the growth rate of constructions has further accelerated the demand of aggregates. The utilization of aggregates to satisfy the demand has led to the inadequacy of aggregates. A unique method of developing non-conventional aggregates as a substitute of conventional coarse aggregates can be the justification of the issue. Meanwhile, considerable amount of fly ash produced from thermal power plants is disposed in landfills and ponds, creating hazard to the nature. Researchers have focused in utilizing fly ash to produce aggregates through the process of pelletization. Geopolymerization parameters such as Na₂O content, slope and speed of disc pelletizer influence the properties of fly ash based pelletized aggregates. The compressive strength of geopolymer aggregate concrete depicted a higher value than concrete with conventional aggregates. The objective of this paper is to present the factors affecting the production of geopolymer aggregate concrete and the properties of these novel aggregate concrete.

Keywords: Geopolymer aggregate (GPA), pelletization, binder, mechanical properties

1. Introduction

Concrete occupies the first place in the extensive usage of available man-made materials and second place, after water, in the most consumed source on Earth. Cement, the primary ingredient of concrete, is leading emitter of Carbon dioxide world-wide [2]. CO₂ emissions of cement occur during its manufacture, of which, the calcination reaction releases about half of the emission and fossil burning, to attain the high temperature needed for calcinations, emits additional 40% of Carbon dioxide. The fact is that either the chemical reaction of calcination or the heat requirement arrived by burning fossil fuels cannot be altered in the cement’s production [7]. Establishment of clinker-free options or partial replacement of clinker proportion with substitute materials like fly ash can be an alternative to reduce emissions from cement.

India stands in the third position in the production of coal. The fly ash produced from the existing 120 thermal power plants is approximately 120-150 million tons [1]. The major concerns with fly ash is the large land area requirement for dumping fly ash and these ashes contain heavy metals
originated during combustion, which causes toxicity when percolated in to ground water [1]. Hence, there is a demand to establish substitute building materials with innovative construction techniques, presenting a suitable solution to ecological balance, at the same time complying functional and technical specifications of construction.

There is a boom in the urbanization with the rapid growth in population on mother earth. Hence, there is a necessity to assess and capture global construction market at a rapid pace to accommodate the growing population [7]. This seriously affects the built environment, by creating depletion in the supply of resources available for construction. In this urbanization and industrialization, improvement in technical advancements linked with sustainability to create healthy environment is the gift we can present to our next generations.

Taking into account the above scenario, the review spotlights state-of-the-art developments of geopolymer aggregates as a potential technology to replace conventional aggregates, by achieving sustainability. The most exhaustive research in the area of geopolymers was conducted by Prof. Dr. Joseph Davidovits, who coined the term Geopolymer in 1979. He has proposed this concept by utilizing flyash in place of cement but cement takes the lead of binding all materials in concrete whereas fly ash is not a cementitious material [8]. Hence, he suggested Si and Al ions existing in fly ash to react with alkaline liquids to establish fly ash as a binder material. This process is said to be geopolymerization [2]. The alkaline solutions used for this purpose are the combination of sodium hydroxide and sodium silicate or potassium hydroxide and potassium silicate.

Despite the fact that geopolymer binders have no cement content present in it, they are considered to be novel binders, produced by polymerization of alumino-silicate by alkali activators. Pozzolanic materials rich in reactive Silica and Alumina such as fly ash, GGBS, metakaolin, rice husk ash or a combination of these are considered to be the raw materials. The solution of alkaline activator is a mixture of sodium silicate (Na$_2$SiO$_3$) and sodium hydroxide (NaOH) solution or potassium silicate (K$_2$SiO$_3$) and potassium hydroxide (KOH) solution. The Si and Al atoms present in mineral admixtures get dissolved into the alkaline activator solution [2, 8].

Aggregates occupy about 70% of the concrete’s volume and hence have a vital role in its contribution to the properties of concrete. Considering the expanding global population and its constructional needs, the world is running short of aggregates and now is facing the challenge of producing artificial aggregates to meet the demand of global concrete industry [23, 24].

Pelletization is a known technique to the world, but its usage was mostly restricted to iron, steel making and agricultural industries because of the resource availability in construction sector. But now, the usage of this technique is gaining importance recently to overcome the shortage of aggregates in meeting the demand of aggregates. Research on the manufacture of artificial aggregates utilizing the by-products from the industry like fly ash, bottom ash etc by agglomeration technique is studied [3]. Artificial aggregates can be produced by clustering fly ash into lumps in a pelletizer and then adopting hardening methods such as sintering, cold bonding, water curing, autoclaving and steam curing [4]. Among these, sintering is extensively used if fly ash has carbon content ranging between 2-6%. The other methods, cold bonding and autoclaving are dependent on the presence of binders such as CaO, irrespective of the carbon content [4]. However, cold bonding method absorbs very less energy in comparison to the other hardening techniques.

Along with the hardening methods used in producing pellets, the parameters influencing the pelletization efficiency depends up on the raw materials, binder type, angle of the drum, the speed of revolution, dosage and duration of pelletization [4-5]. Pellets can be manufactured from drum, disc, mixer and cone type pelletizers. Among these types, disc type pelletizer is preferable as it is easier to control distribution of pellet sizes [6]. The inclusion of chemical additives is crucial in the process of pelletization to improve the aggregate strength [26] and durability properties [10].

2. Significance of the study

The adoption of innovative alternate coarse aggregate in the production of concrete has the promising capability to reduce the dependence on conventional aggregates as well as utilising the waste disposal from thermal power plants, reducing its environmental impact on the globe. This review furnishes an extensive analysis of the updated information starting from initiation of GPA. The paper projects the
literature and investigations on the key parameters of the pellesting disc, hardening methods, alkali details, aggregate properties and mechanical properties of GPA for distinct factors.

3. Geopolymerization

Geopolymers are zero-PC binders formed through a polycondensation reaction of alumino-silicate sources, derived from waste by-products, in alkaline solutions [7, 25, 27]. Geo-polymerization produces inorganic polymers of 3D network with cross-linked polysialate chains [8]. In the ordinary Portland cement, calcium silicate hydrates (C-S-H) gel is the main binding compound, whereas the geopolymers are based on the polycondensation (termed as Geo-polymerization) of silica (SiO$_2$) and alumina (Al$_2$O$_3$) sources in highly alkali environment such as NaOH or KOH solutions [7]. Geo-polymerization is a process in which silicon, aluminium and oxygen atoms create a chain of SiO$_2$ and AlO$_2$ four-fold linked alternatively by shared oxygen atoms [8]. Poly-sialate is the term suggested for the chemical designation of geopolymers based on silica-aluminates [9].

To characterize geopolymers, Davidovitis has formulated the following formula [8]

$$ M_n[(\text{Si} – \text{O})_x – \text{Al} – \text{O}]_m \cdot H_2O $$

where M represents alkali metal.

$$ z = 1, 2 \ or \ 3 $$

n represents the degree of polymerization.

The following steps are involved in the process of geo-polymerization [7, 8]

1. **Alkali Activation**: The silicate and aluminate monomers are produced by dissolving activated alumina-silicate in highly alkaline solution and this activity is said to be alkali activation.

2. **Polycondensation**: The gel phase of alumino-silicate is highly reactive. Considerably fast chemical reactions occur under alkaline conditions, forming a stable 3D polymeric network and ring framework of Si-O-Al bonds.

Geop lymer aggregate concrete has similar reaction mechanism as that of geopolymer concrete [10]. The highly alkaline activators react with the silicates and aluminates in low calcium fly ash to produce an amorphous three-dimensional network of silicon and aluminium atoms linked by oxygen atoms in a tetrahedral coordination [10].

4. Constituents of Geopolymer Aggregate Concrete:

4.1 **Flyash**: Low Calcium Fly ash (Class F) is preferred for preparation of fly ash pellets. Other source materials like GGBS, metakaolin, rice husk ash may also be used to act as binder materials.

4.2 **Alkaline solutions**

4.2.1 **Sodium Hydroxide**: It is available in the form of pellets or flakes and is dissolved in one litre of distilled water to attain the required molarity of sodium hydroxide solution.

4.2.2 **Sodium Silicate**: The Sodium silicate solution is available in liquid form, which is mixed with sodium hydroxide solution in required ratios, to prepare the alkaline liquid.

This alkaline activator solution should be prepared a day advance before it is used for casting.

4.3 **Water**: Potable tap water

4.4 **Super plasticizer**: High range water reducing admixtures such as Sulphonated Naphthlene formaldehyde based are preferred in improving the workability of the mix, the dosage of mix is to be finalized based on the trial mixes.

5. Preparation of pelletized GPA

The aggregates grain size distribution may be achieved by any of the two methods mentioned [11]:

---

IOP Conf. Series: Earth and Environmental Science 982 (2022) 012017 doi:10.1088/1755-1315/982/1/012017
(a) crushing of rock
(b) agglomeration of fines that has cementitious property either by themselves and/or by blending them with mineral additive.

Agglomeration of moisturized fines in a rotating drum or disc turns out to be the process of pelletization [11]. Disc pelletizer is the preferred one in the production of geopolymer aggregates.

A review on the following significant parameters influencing the pelletization efficiency is carried out.

(i) Binder - type and percentage,
(ii) Pelletization – disc angle, speed and duration
(iii) Moisture content
(iv) Hardening methods
(v) Alkali information

The following table 1 summarizes the literature review of different authors on the important elements regulating the production process of geopolymer aggregates. Fly ash is the raw material used in all the cases considered in table 1.

| Author (Year)                  | Type of binder | % of binder | Pelletizer disc speed (rpm) | Disc angle of Pelletizer (degree) | Pelletization on duration (min) | Moisture content (%) | Alkali details | Methods of Hardening |
|-------------------------------|----------------|-------------|-----------------------------|----------------------------------|--------------------------------|----------------------|-----------------|----------------------|
| Baykal and Doven (2000) [11]  | Lime and cement | 8          | 35-55                       | 20-50                             | 20                              | 29-33                | -               | Cold bonding         |
| R.Manikandan, K.Ramamurthy (2007) [12] | Bentonite | 4-14        | 35-55                       | 35-55                             | 8-16                            | 23-25                | -               | Sintering            |
| R.Manikandan, K.Ramamurthy (2007) [12] | Kaolinite | 4-30        | 35-55                       | 35-55                             | 8-16                            | 33-35                | -               | Sintering            |
| Gesoglu et.al. (2007) [13]    | Cement and GGBS | 5-20       | 0-54                        | 30-92                             | 20                              | 23-35                | -               | Cold bonding         |
| Anja Terzic et.al (2014) [14]  | Water glass, Na$_2$SiO$_3$ | -         | 35                          | 40                                | 20                              | -                    | Water glass used as binder is taken as Alkali activator | Sintering and Cold bonding |
| Gomathi, A Sivakumar (2014) [15] | GGBS, Bentonite and Metakaol-in | 30        | 55                          | 36                                | 15                              | 25                   | 10M of NaOH       | Cold bonding         |
The outline of the table-1 reveals that irrespective of the hardening methods adopted, type of binder and percentage of binder content used in the production of GPA concrete, for a moisture content of 13 to 35%, the pelletization speed was in the range of 35-60 rpm with its angle of pelletizer ranging between 35 to 55 degrees. The duration of the pelletizing process is 8 to 22 min.

Even before the pelletized aggregates are used in production of concrete, it is essential to test the aggregate characteristics of GPA. These aggregate characteristics are to be verified with conventional aggregate as well of Indian Standard codal provisions and then should be used in GPA concrete production if the results are satisfactory. A review of literature on the properties of geopolymer aggregates is done and presented as follows in table 2

| Author (Year) | Source Materials | Aggregate Impact Value (%) | Aggregate Crushing Resistance (%) | Water Absorption (%) | Bulk density (kg/m³) | Specific gravity |
|---------------|------------------|-----------------------------|----------------------------------|---------------------|----------------------|-----------------|
| P.Priyadharshini et.al. (2011) [19] | Flyash based aggregate | 25.4 | 22.7 | 13.23 | 1247 | 2.12 |
| P.Gomathi, A.Sivakumar (2014) [15] | Flyash and Metakoalin based aggregate | 38.00 | 17.62 | 17.86 | 987.89 | 1.80 |
| P.Gomathi, A.Sivakumar (2014) [15] | Flyash and GGBS based aggregate | 31.96 | 22.81 | 13.01 | 1001.56 | 1.68 |
| Shivaprasad K et.al, (2019)[20] | Geopolymer aggregate | 23.60 | 27.30 | 9.80 | 1200 | 1.95 |
| Kolimi Shaiksha Vali et. al., (2019) [21] | Flyash, Hydrated lime, Steel slag and Nano-Silica of 0.5% | 15.2 | 49.3 | 12.5 | 957.6 | 2.64 |
The bulk density of the aggregate is mostly in the range of 900 to 1200 kg/m³, which classifies GPA under light weight aggregate. For this range of bulk density, the aggregate impact value ranged from 23 to 38% while the aggregate crushing resistance showed considerable variation between 17% and 49% for different literatures. The water absorption portrays the durability property of aggregates which speaks about the water penetration into the pores of concrete [28]. Researchers reported the water absorption of pelletised aggregates from 9% to 24% and this is dependent on composition of raw material and methods of hardening [29].

Based on the previous available literatures, the linkage between the variability of parameters and its influence on the results have been investigated and reported in table -3. The source of materials used in the production of GPA and the parameter of variation have been focussed and their influence on the mechanical properties of GPA along with the primary findings of the study have been investigated. These mechanical properties considered in this survey include the dry density, compressive strength and the flexural strength of GPA.

Table- 3 Literature review on the influence of variables on the mechanical properties of GPA

| Author                      | Type               | Parameter of variation | Variability information | Dry density (kg/m³) | Compressive Strength -28 days (MPa) | Flexural Strength (MPa) | Investigation results                                                                 |
|-----------------------------|--------------------|------------------------|-------------------------|---------------------|-------------------------------------|------------------------|--------------------------------------------------------------------------------------|
| Baykal and Doven et al. (2000) [11] | Fly ash + Cement / Lime | Blend type            | 1. Fly ash             | –                   | 28-32.7                             | –                      | The combination of fly ash with lime yielded maximum compressive and flexural strengths |
|                             |                    |                        | 2. Fly ash+8%Cem       |                     |                                     |                        |                                                                                     |
|                             |                    |                        | 3. Fly ash+8%Lime       |                     |                                     |                        |                                                                                     |
| Gesoglu et al. (2007) [13] | Fly ash properties | Specific gravity       | 2.31 – 2.56            | Maximum value is 60MPa | –                                   | –                      | Fly ash with low specific gravity has better compressive strength                    |
|                             |                    | Specific surface area  | 3206 – 3928 cm²/g      |                     |                                     |                        |                                                                                     |
| Gesoglu et al. 2012 [22] | Fly ash + GGBS+ Cement | Blend % of fly ash, GGBS and Cement | Three combinations | 1976 – 2099 | 16 – 43                             | –                      | Max. 28 day compressive strength = 43 MPa @ 40%GGBS + 40% Fly ash + 20% Cem          |
|                             |                    |                        | 1.Cem+GGBS             |                     |                                     |                        |                                                                                     |
|                             |                    |                        | 2.Cem+flyash           |                     |                                     |                        |                                                                                     |
|                             |                    |                        | 3.Cem+GGBS + fly ash   |                     |                                     |                        |                                                                                     |
6. Durability aspects of GPA
Durability of concrete refers to the satisfactory performance of concrete under exposure to different environmental conditions. The deterioration caused under aggressive environments, chemical attack, weathering actions lead to the reduced service life of the structure. A durable concrete must be capable of resisting deterioration caused by the above factors, while maintaining the strength aspects. Hence, there is a need to investigate the durability criteria along with the strength conditions. There is considerable amount of research done in geopolymer concrete however, the investigations on geopolymer aggregate concrete is limited. Chamila Gunasekara et al., have studied permeability and suggested that low values of permeability of water and air indicated dense pore concrete with GPA [10]. The study also revealed that GPA concrete is free from large voids or cracks [10].

7. Future Scope of work
The mix design of geopolymer is still not included in the Indian Standard codal provisions, and hence there is a need to understand the concept of geo-polymerization at a deeper level. Though the durability studies of geopolymer concrete is available, these durability studies of GPA concrete is limited and hence continual research in the area of durability studies of GPA concrete is essential. Research on the long-term behaviour can be a vital point of research to understand the performance of GPA concrete

8. Conclusion
The technology of geopolymer aggregate is gaining importance due to the depletion of the availability of conventional coarse aggregates. Though geopolymer technology has a long history, production of aggregates with this technology has picked up its considerable research from a decade. Production of geopolymer aggregates with fly ash or GGBS would lead to longstanding protection of environment, at the same time improving the properties from an early age. This concept of GPA is a promising technology over conventional aggregates for the further generations. The review of literature reveals that GPA has better aggregate properties like crushing resistance, impact value and reduced porosity. GPA concrete has established better mechanical properties with various combinations of pozzolana,
different activator molarities, curing conditions. The optimum angle for disc pelletizer to produce good quality of fly-ash aggregates is found to be 45°. The bulk density being mostly in the range of 900-1200 kg/m³ terms GPA as light weight aggregates. The aggregate impact value recorded its value less than the limiting value of 45%, however, the crushing resistance has exceeded its limiting value of 45% in few literatures. There is a need to verify and investigate the reasons for this and focus on the improvement methods by varying different parameters. There is a need to continue the investigations of GPA as there are several unknown gaps regarding raw materials, fresh and hardened properties and chemical attacks.

References

[1] Aakash, Dwivedi, Jain, Manish, Kumar 2014 Fly ash – waste management and overview: A Review. Recent Research in Science and Technology 6(1) p30-35
[2] A D Sandeep Kumar, Dinesh Singh, V Srinivasa Reddy, Kavelli Jagannath Reddy 2020 Geopolymerization mechanism and factors affecting it in Metakaolin-slag-fly ash blended concrete E3S Web of Conferences - 2nd International Conference on Design and Manufacturing Aspects for Sustainable Energy (ICMED 2020) vol 184 DOI: 10.1051/e3sconf/202018401080
[3] Shivaprasad KN, Das BB and Sharath BP 2019 Pelletisation factors on the production of fly-ash aggregates and its performance in concrete. Proceedings of the Institution of Civil Engineers – Construction Materials
[4] Harikrishnan K and Ramamurthy K 2006 Influence of pelletization process on the properties of fly ash aggregates. Waste Management 26(8): pp 846–852
[5] Shivaprasad KN and Das BB 2018 Determination of optimized geopolymerization factors on the properties of pelletized fly ash aggregates. Construction and Building Materials 163: 428–437
[6] Patel Tejas A, Patel Chirag B and Patel Jignesh M 2015 A Review on Cold-Bonded Fly Ash Lightweight Aggregates: less costly light weight promising material Indian Journal of applied research 5(1) pp 11-13
[7] Sambucci M, Sibai A and Valente M 2021 Recent Advances in Geopolymer Technology. A Potential Eco-Friendly Solution in the Construction Materials Industry: A Review. J. Compos. Sci. 5, 109 https://doi.org/10.3390/jcs5040109
[8] Behzad Majidi 2009 Geopolymer technology, from fundamentals to advanced applications: a review Materials Technology 24(2) DOI:10.1179/175355509X449355
[9] J. Davidovits 2002 30 Years of Successes and Failures in Geopolymer Applications. Market Trends and Potential Breakthroughs., Geopolymers 2002 Conf., Melbourne, Australia
[10] Gunasekara Chamila, Setunge S, Law DW, Willis N and Burt T 2018 Engineering properties of geopolymer aggregate concrete. Journal of Materials in Civil Engineering 30(11) DOI: 10.1061/(ASCE)MT.1943-5533.0002501
[11] Baykal G and Doven AG 2000 Utilization of fly ash by pelletization process; theory, application areas and research results. Resources, Conservation and Recycling 30(1): 59–77
[12] Manikandan R, Ramamurthy K 2007 Influence of fineness of fly ash on the aggregate pelletization process, Cement & Concrete Composites 29, pp 456-464
[13] Gesoglu M, Ozturan T and Guneyisi E 2007 Effects of fly ash properties on characteristics of cold-bonded fly ash lightweight aggregates. Construction and Building Materials 21(9) pp. 1869–1878.
[14] Anja Terzić, Lato Pezo, Vojislav Mitić and Zagorka Radojević 2014 Artificial fly ash based aggregates properties influence on lightweight concrete performances, Ceramics International, http://dx.doi.org/10.1016/j.ceramint.2014.10.086
[15] Gomathi P and Sivakumar A 2014 Synthesis of geopolymer based class-F fly ash aggregates and its composite properties in concrete. Archives of Civil Engineering LX,1 DOI: 10.2478/ace-2014-0003
[16] Puput Risdanareni, Katrin Schollbach, Jianyun Wang and Nele De Belie 2020 The effect of NaOH concentration on the mechanical and physical properties of alkali activated fly ash-based
artificial lightweight aggregate Construction and Building Materials 259
https://doi.org/10.1016/j.conbuildmat.2020.19832

[17] Shivaprasad K N, Das B B, and Krishnadas S 2021 Effect of Curing Methods on the Artificial Production of Fly Ash Aggregates Recent Trends in Civil Engineering - Select Proceedings of TMSF 2019 Springer pp 23-32 https://doi.org/10.1007/978-981-15-8293-6_3

[18] Sharath B P and Bishnupriya Bhusan Das 2021 Production of Artificial Aggregates Using Industrial By-Products Admixed with Mine Tailings—A Sustainable Solution Recent Trends in Civil Engineering - Select Proceedings of TMSF 2019 Springer pp 383-397 https://doi.org/10.1007/978-981-15-8293-6_33

[19] Priyadharshini P, Mohan Ganesh G and Santhi A S, 2011 Experimental study on Cold Bonded Fly Ash Aggregates International journal of civil and structural engineering 2(2) pp 507-515 DOI: 10.6088/ijcser.00202010129

[20] Shivaprasad K N and Das B B 2019 Compressive strength of concrete with artificially produced fly ash aggregates

[21] Kollina Shaiksha Vali and Bala Murugan 2019 Impact of Nano-SiO$_2$ on the properties of cold-bonded artificial aggregates with various binders International Journal of Technology 10(5): 897-907

[22] Mehmet Gesoglu, Erhan Guneyisi and Hatice Oz numer 2012 Properties of lightweight aggregates produced with cold-bonding pelletization of fly ash and ground granulated blast furnace slag Materials and Structures 45 pp 1535-1546 DOI:10.1617/s11527-012-9855-9

[23] Udhaya Kumar T, Vinod Kumar M 2020 Investigation on mechanical properties of geopolymer aggregate concrete Materials Today: Proceedings (Elsevier) https://doi.org/10.1016/j.matpr.2020.08.758

[24] Sethu Parvathy S, Anil Kumar Sharma and K.B. Anand 2019 Comparative study on synthesis and properties of geopolymer fine aggregate from fly ashes Construction and Building Materials 198 pp.359-367 https://doi.org/10.1016/j.conbuildmat.2018.11.231

[25] K Karuppuchamy, Ananthkumar M and Raghavapriya S M 2018 Effect of Alkaline Solution with Varying Mix Proportion on Geopolymer Mortar IOP Conf. Series: Materials Science and Engineering 310 doi:10.1088/1757-899X/310/1/012039

[26] Sreekesh U. Menon, Anand K B and Anil Kumar Sharma 2018 Performance evaluation of alkali-activated coal-ash aggregate in concrete Waste and Resource management - Proceedings of the Institution of Civil Engineers https://doi.org/10.1680/jwrm.17.00033

[27] Smita Singh, M. U. Aswath and R. V. Ranganath 2016 Durability of Red Mud Based Geopolymer Paste in Acid Solutions Materials Science Forum Vol. 866 pp 99-105 doi:10.4028/www.scientific.net/MSF.866.99

[28] Feras Tajra, Mohamed Abd Elrahman and Dietmar Stephan 2019 The production and properties of cold-bonded aggregate and its applications in concrete: A review Construction and Building Materials 225 pp.29-43 https://doi.org/10.1016/j.conbuildmat.2019.07.219

[29] Norlia Mohamad Ibrahim, Khairul Nizar Ismail, Roshazita Che Amat and Mohamad Iqbal Mohamad Ghazali 2018 Properties of cold-bonded lightweight artificial aggregate containing bottom ash with different curing regime E3S Web of Conferences - (CENVIRON) vol 34 https://doi.org/10.1051/e3sconf/20183401038