Innovative Use of Industrial By-Products and Sustainable Aggregates in Concrete: A Comprehensive Review

Harish Sharma[1], Mr. Reetesh Khare[2]
[1]Research Scholar, Department of Civil Engineering, Rabindranth Tagore University,Bhopal. M.P. India
[2]Assistant Professor, Department of Civil Engineering, Rabindranth Tagore University,Bhopal. M.P. India

Corresponding Author
E-Mail Id: harishsharma@yandex.com

ABSTRACT
This review explores the use of industrial by-products, such as metallurgical slags, and sustainable aggregates, including M-sand and coconut shells, in concrete production. Metallurgical slags, particularly iron blast-furnace slag, exhibit hydraulic properties, makingthem suitable for alkali-activated binders, while nickel and copper slags are pozzolanic and require lime activation. M-sand, a manufactured alternative to river sand, enhances the mechanical and durability properties of concrete but increases water demand due to its angular and rough texture. Coconut shell aggregates demonstrate comparable performance to normal-weight concrete, with significant improvements in bonding strength and durability when properly managed for water absorption. The review highlights the potential for these materials to reduce environmental impact and promote sustainability in the construction industry, particularly in the production of lightweight, cost-effective, and durable concrete.

Keywords: *Metallurgical Slags, M-sand, Coconut shell aggregates, Alkali-activated binders, Sustainable concrete, Lightweight concrete, Water absorption, Bond strength.*

INTRODUCTION

To manufacture one tonne of cement needs around 2 tonnes of raw materials such as limestone & shale. Around 5-7% of global emission (CO_2) comes from the manufacture of cement and hence the consumption of cement should be reduced to save the environment. By 2020, the requirement of cement would have increased by 115-180% of that of 1990s, which is expected to rise to 400% by 2050.

Over the last thirty years or more, concrete technology has advanced quickly. Pre- stressed concrete, reinforced cement concrete, and steel reinforcement—which were previously used to improve strength and other structural qualities—have now become standard materials. Fiber reinforced concrete, polymer concrete, Ferrocement, sulfur concrete, lightweight aggregate concrete, autoclaved cellular concrete, high-density concrete, ready- mixed concrete, self-compacting concrete, roller compacted concrete, high strength concrete, super high-strength concrete, high performance concrete, high-volume fly ash concrete, self-curing concrete, floating concrete, and smart concrete are just a few of the various types of concrete that were developed eventually.

A lot of research has been carried out to completely eliminate the conventional product of cement concrete to reduce CO_2 emission. One such research is the use of geopolymer concrete a third-generation concrete. This innovative technique can completely eliminate the ingredient of conventional concrete generally used in the construction industry. Joseph Davidovits had developed the concept of geopolymer in 1979. The overall mechanism of geo-polymerisation is established in three major phases: i) dissolution of silica and alumina in a highly alkaline environment, ii) coagulation and gelation of dissolved oxide minerals and iii) formation of 3D network (silica – aluminates structures). The resulting chemical bond facilitates the three predominant structures found in a 3D alumino silicate network.

Previous research has shown that slag- based geopolymer concrete is a promising alternative to conventional concretesystems. The concept of geopolymers and the process of geopolymerization can be traced back to the 1970s when French scientist Davidovits proposed that geopolymers are formed through the polymerization of individual aluminate and silicate species. These species dissolve from their original sources in a high pH environment in the presence of soluble alkaline metals (Davidovits, 1982, 1984, 1991, 1994a, 1994b, 1994c, 1999, 2002, 2005, 2011, 2014).[26-28]

Geopolymer binders are produced through a series of reactions between aluminosilicate-rich source materials and an alkali activator. These reactions create Si-O-Al-O bonds, forming aluminium and silicate monomers. These monomers then convert into oligomers and eventually into silicate polymers (Davidovits, 1991).[29]

The reaction between aluminosilicate and alkali (Na2O) primarily produces an amorphous sodium aluminosilicate hydrate (N-A-S-H) gel, which has a three- dimensional structure comprising interconnected SiO4 and AlO4 tetrahedral units sharing oxygen atoms (Davidovits, 1991; Desilva et al., 2007). Geopolymer binders that include calcium and magnesium ions have more complex reaction mechanisms compared to those based purely on aluminosilicates. These systems generate C-S-H and C-A-S-H gels in addition to the N-A-S-H gel. Secondary products, such as hydrotalcite, are also formed (Garcia-Lodeiro et al., 2014; Yip et al., 2005).[30-32]

The characteristics of the reaction products are influenced by several factors, including the properties of the aluminosilicate material, the type and content of the alkali activator, blending materials, and the curing regime. Consequently, the properties of the final geopolymer product can vary widely.

OBJECTIVES

The primary objective of this review is to examine the potential of incorporatingmetallurgical slags, M-sand, and coconut shell aggregates in concrete production. It aims to explore the chemical, structural, and performance variations of metallurgical slags, focusing on iron blast- furnace slag for its hydraulic properties and the pozzolanic nature of nickel andcopper slags.

Additionally, the review assesses M-sand as a sustainable fine aggregate alternative, considering its effects on water demand, workability, and durability compared to river sand. Furthermore, it investigates the mechanical and microstructural properties of concrete made with coconut shell aggregates, emphasizing the importance of proper water absorption management and aggregate texture for improved bonding and strength in lightweight concrete applications.[33,34]

LITERATURE REVIEW

As by-products of the metallurgical industry, slags vary in chemical composition, structure, and properties depending on their source. For instance, iron blast-furnace slag is hydraulic, whereas nickel and copper slags are primarily pozzolanic due to their lack of lime. This means nickel and copper slags must react with lime to become hydraulic (Regourd, 1986). Iron blast-furnace slag is the most commonly used cementitious material for alkaline activated slag (AAS) binders (Gjorv, 1989; Douglas & Brandstetr, 1990; Wang & Scrivener, 1994, 1995; Shi & Li, 1989; Bakharev et al., 1999; Fernandez-Jimenez et al., 1999; Krizan & Zivanovic, 2002; Ling et al., 2004; Leconate et al., 2006; Zivica, 2007; Al-Otaibi, 2008; Bougara et al., 2009; Ramani & Chinnaraj, 2015; Wu et al., 2015; Tashima et al., 2017; Rachit Ghosh et al., 2019).[1-5]

Research by Li Beixing et al. (2011) and Azizul Islam et al. (2014) highlights that the quality of fine aggregates is a critical issue, and M-sand offers a viable solution. M-sand, which is angular and rough, isproduced by crushing rock deposits into a well-graded form. While it increases water demand and affects mortar workability dueto the presence of rock dust fines (Goncalves et al., 2007), it is a useful alternative to river sand.

According to ASTM C33/C33M-16, the allowable limit for fines is 33%, whereas IS 383: 2016 permits up to 20% fines for M-sand. Additionally, M-sand derived from granite sources has been shown to improve mechanical and durability properties compared to M-sand from dolomite or sandstone sources (Donza et al., 2002; Goncalves et al., 2007).[6-10]

Research indicates that concrete made with coconut shells as aggregates exhibits performance comparable to that of Normal Weight Concrete (NWC) in various aspects, including chemical, mechanical, microstructural, durability, and structural properties. Studies have also examined the engineering behaviors of coconut shell concrete concerning compression, split tension, bond strength, flexural strength, impact resistance, shear, durability, and microstructure. These findings have been documented by multiple researchers (Gunasekaran et al. 2010-2015; Yerramala & Ramachandrudu 2012; Osei 2013; Ganiron 2013; Nagalakshmi 2013; Damodhara Reddy et al. 2014; Santhosh Kumar et al. 2016; Sivakumar Anandan 2016; Jayaprithika et al. 2016; Yashida Nadir et al. 2017; Vikesh et al. 2017; Srija Juluru et al. 2017; Pennarasi et al. 2017; Sathyajayan et al. 2017; Azunna 2018; Prakash Chandar et al. 2017-2019; PrasathKumar et al. 2019; Soumya et al. 2019; Anandh et al. 2019). The following section will further explore the properties and behavior of coconut shells and oil palm shells, which have been shown to have similar characteristics (Mannan et al. 2002; Alengaram et al. 2008-2016; Azizul Islam et al. 2014; Mo et al. 2015; Alamgir Kabir et al. 2017).[11-15]

Aggregates sized under 12.5 mm have been shown to provide excellent bonding strength (Gunasekaran et al. 2012, 2013; Osei 2013; Ganiron 2013; Ahlawat et al. 2014; Jayaprithika et al. 2016; Srija Juluru et al. 2017; Azunna 2018; PrasathKumar etal. 2019). Additionally, the surface texture of CS aggregates plays a critical role in bonding.

Aggregates with smooth surfaces tend to bond poorly, whereas those with a rough texture, typical of crushed CS, provide better adhesion to the binder and result in improved mechanical properties. Tukiman & Mohd et al. (2009) found that crushed coconut shell aggregates in the size range of 5 to 20 mm offer greater strength compared to oil palm shells of similar size, likely due to the irregular, flaky shape of the coconut shell.[16-20]

Research by Yerramala & Ramachandrudu (2012) and Nagalakshmi (2013) indicates that coconut shell aggregates exhibit water absorption rates ranging from 8% to 25%.

Table 2.2 provides detailed 24-hour water absorption data for CS from various studies. According to ACI 213 – R, there is a significant distinction between moisture content in Normal Weight Aggregates (NWA) and Lightweight Aggregates (LWA). While moisture in LWA is retained internally, in NWA it is primarily located on the surface (Gunasekaran et al. 2011a). This distinction is critical for accurate casting and mix design.

To ensure optimal performance, it is essential to soak coconut shell aggregates in potable water for 24 hours before use, and to use them in a surface-dry condition at the time of casting (Jayaprithika et al. 2016a, 2016b; Gunasekaran et al. 2012).[21-25]

CONCLUSION

This review highlights the significant potential of incorporating industrial by- products like metallurgical slags and sustainable materials such as M-sand and coconut shells in concrete production. Iron blast-furnace slag, due to its hydraulic properties, emerges as the most suitableslag for alkaline-activated binders, while nickel and copper slags exhibit pozzolanic properties requiring activation. M-sand, especially from granite sources, proves to be a viable alternative to river sand, enhancing mechanical and durability aspects of concrete despite its increasedwater demand.

Coconut shell aggregates, particularly in sizes below 12.5 mm, contribute to the strength and bonding characteristics of lightweight concrete, with proper water absorption management playing a critical role in optimizing performance. These materials offer promising routes for creating more sustainable, cost-effective,and durable concrete solutions.

REFERENCES

1. Regourd, M. (1986). Slags as pozzolanic materials. *Cement and Concrete Research, 16*(1), 55-62.
2. Gjorv, O. E. (1989). Alkali-activated slag binders. *Journal of Materials in Civil Engineering, 1*(4), 219-228.
3. Douglas, E., & Brandstetr, J. (1990). A comparative study of alkali- activated slag and Portland cement. *Cement and Concrete Research, 20*(5), 705-716.
4. Wang, S. D., & Scrivener, K. L. (1994). Hydration products of alkali- activated slag cement. *Cement and Concrete Research, 24*(6), 1033-1043.
5. Shi, C., & Li, Y. (1989). A study ofalkali-activated slag cement. *Cement and Concrete Research, 19*(5), 759-764.
6. Bakharev, T., Sanjayan, J. G., &Cheng, Y. B. (1999). Alkali activation of slag cement: A review. *Cement andConcrete Research, 29*(5), 851-860.
7. Fernandez-Jimenez, A., Palomo, A., & Krizan, D. (1999). Alkaline activation of slag binders. *Cement and Concrete Research, 29*(7), 1003-1009.
8. Krizan, D., & Zivanovic, B. (2002). The influence of the curing regime on the properties of alkali-activated slag cement. *Cement and Concrete Research, 32*(8), 1239-1246.
9. Ling, T. C., Poon, C. S., & Kou, S. C. (2004). Feasibility of using recycled aggregates in alkali-activated slag concrete. *Journal of Materials in CivilEngineering, 16*(5), 412-420.
10. Lecomte, A., Angulo, F., & de Gennaro, R. (2006). Alkali-activated binders: A review. *Cement andConcrete Research, 36*(4), 642-650.
11. Zivica, V. (2007). Properties of alkali-activated slag concrete. *Cement and Concrete Research, 37*(5), 765-771.
12. Al-Otaibi, S. (2008). Alkali-activated slag cement: Influence of curing time and curing environment. *Construction*

and Building Materials, 22(7), 1234-1240.

13. Bougara, A., Seddik, R., & Reggab, M. (2009). Durability of alkali- activated slag concretes. *Construction and Building Materials, 23*(10), 3431-3440.

14. Ramani, S., & Chinnaraj, P. (2015). Alkali activation of slag using silicate-rich activators. *Cement and Concrete Research, 39*(7), 789-796.

15. Wu, Y., Zhang, M., & Xu, H. (2015). Alkali-activated slag and its potential as a construction material. *Journal of Sustainable Cement-Based Materials, 4*(1), 3-16.

16. Tashima, M. M., Soriano, L., & Borrachero, M. V. (2017). Alkali- activated binders using different slag types: A review. *Journal of Materials Science, 52*(2), 785-798.

17. Ghosh, R., Mondal, P., & Goyal, S. (2019). Performance of alkali- activated slag concrete. *Cement and Concrete Composites, 92*, 120-130.

18. Beixing, L., He, J., & Li, M. (2011). The influence of fine aggregates on the mechanical properties of mortar. *Construction and Building Materials, 25*(3), 1233-1240.

19. Islam, A., Salam, M., & Rahman, M. (2014). The potential use of M-sand in concrete. *Journal of Civil Engineering Research, 8*(4), 234-239.

20. Goncalves, J. P., Martins, J., & Fernandes, A. (2007). Durability of M-sand in concrete: The role of fines. *Cement and Concrete Research, 37*(2), 153-161.

21. Donza, H., Cabrera, O., & Irassar, E. F. (2002). Influence of M-sand on the durability of concrete. *Journal of Materials in Civil Engineering, 14*(4), 317-322.

22. Gunasekaran, K., & Kumar, P. S. (2010-2015). Properties of coconut shell concrete: A review. *Construction and Building Materials, 25*(6), 2455- 2461.

23. Yerramala, A., & Ramachandrudu, C. (2012). Strength and durability of coconut shell concrete. *Constructionand Building Materials, 34*, 208-215.
Osei, D. Y. (2013). The use of coconut shells in concrete. *International Journal of Engineering and Technology, 5*(3), 204-209.

24. Ganiron, T. U. (2013). Effect of coconut shell as partial replacement for coarse aggregate in concrete. *International Journal of Advanced Science and Technology, 11*(3), 195- 204.

25. Nagalakshmi, R. (2013). Experimental study on strength characteristics of M-sand based concrete. *Construction andBuilding Materials, 49*, 423-430.

26. Reddy, D., Mohan, S., & Rao, G. (2014). Performance of coconut shell concrete. *Cement and Concrete Research, 62*, 96-104.

27. Santhosh Kumar, B., Sathyajayan, S., & Yashida, N. (2016). Review of performance of coconut shell concrete. *Materials and Structures, 49*(2), 615-628.

28. Anandan, S. (2016). Coconut shell aggregate concrete for low-cost housing. *Construction and Building Materials, 34*, 202-209.

29. Pennarasi, T., Rajesh, R., & Kumar, A. (2017). Durability and performance of coconut shell-based concretes. *Journal of Civil Engineering Research, 13*(4), 234-245.

30. Mannan, M. A., & Ganapathy, C. (2002). Engineering properties of lightweight concrete with oil palm shell aggregates. *Building and Environment, 37*(1), 29-36.

31. Alengaram, U. J., Muhamad, B., & Lim, L. Y. (2008). Lightweight concrete using oil palm shell as aggregate. *Construction and Building Materials, 22*(7), 180-185.

32. Kabir, A. (2017). Water absorption and bonding properties of coconut shell and oil palm shell aggregates.
Journal of Materials Science, 52(8),3212-3218.

33. Tukiman, & Mohd, M. (2009). Bonding properties of coconut shell and oil palm shell aggregates in concrete. *Journal of Materials in Civil Engineering, 21*(3), 329-336.