

REVIEW

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A Review on Sustainable Fabrication of Futuristic Cementitious Binders Based on Application of Waste Concrete Powder, Steel Slags, and Coal Bottom Ash

Prabhat Vashistha, Sungwoo Park and Sukhoon Pyo*

Abstract

The amendment of cementitious binders with waste materials aids as a path to reduce the volume of waste and carbon emission. This review summarizes the current state of practice for cementitious binder fabrication in favor to the utilization of waste materials such as waste concrete powder (WCP), coal bottom ash (CBA) and steel slags. These materials have the potential to be employed as cementitious material, however much of the application is still up to the laboratory scale. This manuscript will serve as the support to understand the utilization of mentioned waste as nontraditional cementitious products. The highlighted areas likely need more refinement and research with indication on possible negative impact on application of wastes. The use of the aforementioned wastes for blending with OPC (ordinary Portland cement) can reduce carbon emissions from cement manufacturing. Additionally, it can also reduce the use of natural resources during clinker production.

Keywords: waste concrete powder, sustainability, steel slag, LD slag, LF slag, EAF slag, coal bottom ash, cementitious binders

1 Introduction

The demand for construction has increased with the increasing population over the years. Cement is one of the main ingredients in construction and the second most used material after water (Diaz-Loya et al., 2019; Duda, 1989; Nidheesh & Kumar, 2019; Singh & Subramaniam, 2019). The cement industry is the second chief source of anthropogenic emission of CO₂ after power plants and has an adverse impact on the environment. Global warming is one of the biggest challenges facing the world, and high CO₂ emissions from the cement

industry add to it. Currently, the total worldwide cement production is over 4 billion tons, which contributes to more than 7% to 8% of total global warming CO₂ emissions (Frías et al., 2021; Maslyk et al., 2022). The majority of this CO₂ (about 95%) is generated in cement clinker production during limestone calcination (Hossain et al., 2019; Huntzinger & Eatmon, 2009; Olivier & Peters, 2017; Zhang et al., 2018). The cement industry is facing a collective burden to decrease CO₂ emissions and energy consumption during cement manufacturing. Therefore, there is an urgent need to find the right technology to substitute cement clinker with other potential materials to reduce the anthropogenic effect of CO₂ emissions. Researchers are continuously working on alternative methods to reduce the carbon emission through the replacement of OPC in construction applications (Alimohammadi, 2021; Alimohammadi et al., 2020, 2021; Eisa, 2014; Zheng et al., 2021). The development of newer

Journal information: ISSN 1976-0485 / eISSN 2234-1315

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sustainable cementitious materials by replacing cement clinker with other industrial by-products having pozzolanic properties and hydraulic activity as supplementary cementitious materials (SCMs)/newer binders (Diaz-Loya et al., 2019; Hajmohammadian Baghban & Mahjoub, 2020). The major industrial by-products that have been studied by various researchers for application as binders in concrete are furnace slags and fly ash, among others (Ampadu & Torii, 2002; Daube & Bakker, 1986; Dermatas & Meng, 2003; Diaz-Loya et al., 2019; Huashan & Yujun, 2021; Kim & Lee, 2017; Patra & Mukharjee, 2017; Yao et al., 2015). Utilization of some industrial by-products in fabrication of cementitious binders could decrease global warming while simultaneously avoiding their disposal as industrial residues in landfills. The application of other possible waste materials, such as waste concrete powder (WCP), steel slags, and coal bottom ash (CBA), in the fabrication of newer cementitious binders can further reduce global warming and offer a meaningful solution to the waste management problems associated with these wastes (Heede & Belie, 2012; Pešta et al., 2021). Globally, a large number of research groups are focusing on utilization of the mentioned waste materials. The current study is focused on the possibilities of these waste materials in the fabrication of cementitious binders.

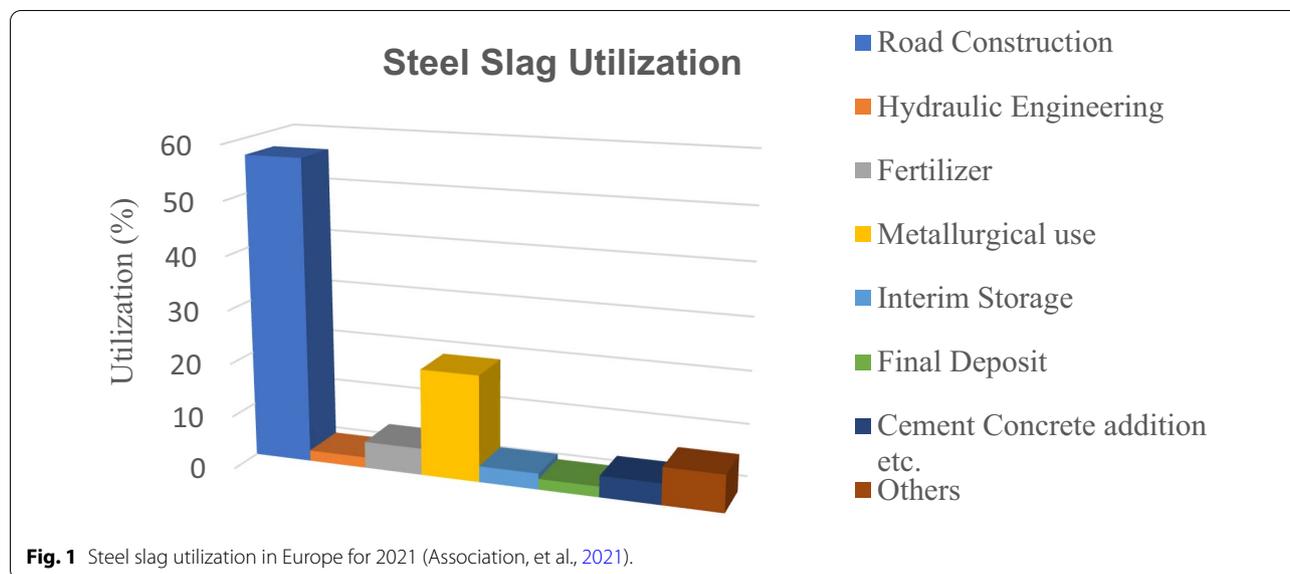
2 Background

Construction and building materials account for half of the solid waste generated every year worldwide (Jain, 2021). According to a report from Transparency Market Research, this volume is expected to increase to 2.2 billion tons every year till 2025 (Jain, 2021). It is estimated that construction and demolition (C&D) activities generated half of the total generated solid wastes (Akhtar & Sarmah, 2018; Yoon, 2012). Therefore, utilization of C&D waste has become a top priority. Production of aggregates from C&D waste is an effective solution; recycling plants that size, sort, and wash C&D waste can produce high-quality aggregates. However, they also produce between 5 and 80 tons of WCP per hour depending on plant size and type of concrete material processes. WCP contains fine (<63 μm) silt particles classified as inert waste and normally landfilled (Lampris et al., 2009; Lee et al., 2020). Other than the disadvantages of WCP production, only reusing the aggregates from old concrete is unsustainable because it is the production of new cement for concrete production that is driving climate change. Therefore, a new cement-free and environmentally friendly approach is needed to help promote the circular economy of concrete (Zhongming et al., 2020).

Steel slags are generated by integrated steel plants in diverse types of metallurgical processes and their

different stages. Steel production around the world reached 1872 million tons in 2020 (Forder, 2020). The production of steel mostly consumes iron ore, limestone, fuel, water, oxygen, and power, and 2 to 4 tons of waste materials are generated in the production of a single ton of steel products (Das et al., 2007). Utilization of these slags is necessary for conservation of the environment and natural resources such as minerals and metals (Chand et al., 2016; Chandrasekhar, 2016; Chinnaraju et al., 2013; Costa Borges, 2012; Grönniger et al., 2015). Slag disposal has become a huge concern because of land consumption and environmental issues. The possibility of deployment of steel slag in Europe in various sectors has been recognized, as shown in Fig. 1. The vast majority of the steel slag is consumed in different applications; however, the interim storage and final landfill deposition remain a concern in view of the environmental impact associated with the steel slag (Guo et al., 2018; Piatak et al., 2015). The land loaded up with waste materials such as slag has become a critical basis for the pollution of water, air, and soil and further unfavorably influences human well-being and the development of flora and plants (Reuter et al., 2004). The use of steel industry slag has not gained confidence in the past because of the presence of heavy metals and the possible hazards to human health and the environment (Gwon et al., 2018; Piatak et al., 2015). The chemical constituents of steel slag including heavy metals such as beryllium, barium, cobalt, nickel, arsenic, and thallium are the major environmental concerns (Piatak et al., 2015; Yildirim & Prezzi, 2009). These hazardous heavy metals could leach into drinkable water from the slag itself (Yüksel, 2017). In addition, pH instabilities and metal percolation to external water sources due to dumped slags could lead to ecological hazards (Piatak et al., 2015; Yüksel, 2017). Other known drawbacks include degradation of the soil due to the presence of leachable components (Gwon, et al., 2018; Pan, et al., 2019). Hence, investigating new roads for slag use and innocuous transfer is of great importance. Therefore, the current review article presents enormous possibilities for the considerate expansion of the application of these wastes.

The potential utilization of WCP, slag, and different types of ash in cementitious binders has been studied and reported in the past (Adolfsson, 2011; Akhtar & Sarmah, 2018; Chen et al., 2021; Frías et al., 2021; Singh & Vashistha, 2021). However, the inactivity of WCP, menial reactivity of the steel slags, and presence of unburned carbon particles and heavy metals in CBA are major hindrance to their effective utilization. There have been past efforts to adopt cited wastes. However, no study has incorporated in totality the characteristics of these wastes, need of their utilization, and all the methods of utilization



with their nuances. The present study providing a holistic insight on binder fabrication from WCP, steel slag, and CBA. Therefore, the authors believe this paper will provide a single document to serve as a reference and potential guide for those who produce industrial waste and for those looking to utilize the waste materials for cementitious material with less clinker factor.

3 Waste Concrete Powder (WCP)

3.1 WCP Generation Process

WCP is the main component that is co-generated during the recycling of C&D waste. In the process of manufacturing aggregates from C&D waste, WCP accounts for almost 20–30% of the total waste. WCP is produced in the size range of fewer than 150 μm (Li et al., 2010). WCP of this size cannot be used directly as SCM for the fabrication of cementitious binders despite the fact that it contains similar compounds to fly ash, with an abundance of silica and alumina (Xiao et al., 2018) (Gupta et al., 2019). Fig. 2 depicts the WCP generation process.

3.2 Utilization Possibilities of WCP as a Cementitious Material

As discussed earlier, the utilization of WCP is a high-priority need. Thus, WCP-based cementitious binders are the subject of recent research focusing on the sustainable application of WCP (Mao et al., 2019). Fig. 3 presents the utilization possibilities of WCP (Chen et al., 2021; Huashan & Yujun, 2021; Kwon et al., 2015; Sui et al., 2020). It can be beneficial on two sides: First, it provides a method for bulk utilization of waste, and second, it reduces greenhouse gas emissions through cement clinker factor reduction.

There are three different strategies of WCP application in cementitious binders:

- Application of as-received WCP.
- Application of WCP after thermal and chemical treatment.
- Application of WCP with other cementitious materials.

This study offers a detailed discussion on the utilization possibilities of WCP as a cementitious material. The above-mentioned methods of WCP application are discussed below:

- Application of as-received WCP

In the initial efforts of WCP utilization as a cementitious material, Kamon et al. (1988) worked on figuring out the potential of WCP utilization for practical uses in cement. A cementitious binder was prepared by mixing WCP and ordinary Portland cement (OPC). The study concluded that WCP-based binder can be applied as a grouting material and soil stabilizer due to its fast hardening properties. Moon et al. (2008) used the WCP as a cementitious material. The study reveals that WCP is constituted with calcium, silica, and alumina-based reactive phases and develop better compressive strength. WCP was recommended to use as cementitious material for application in compacting concrete, pavement concrete, and roller compacting concrete. Kim and Choi (2012) also utilized WCP as a replacement for OPC in mortar blocks to check the feasibility of WCP. However, only 15% usage of WCP in cementitious binder fabrication is

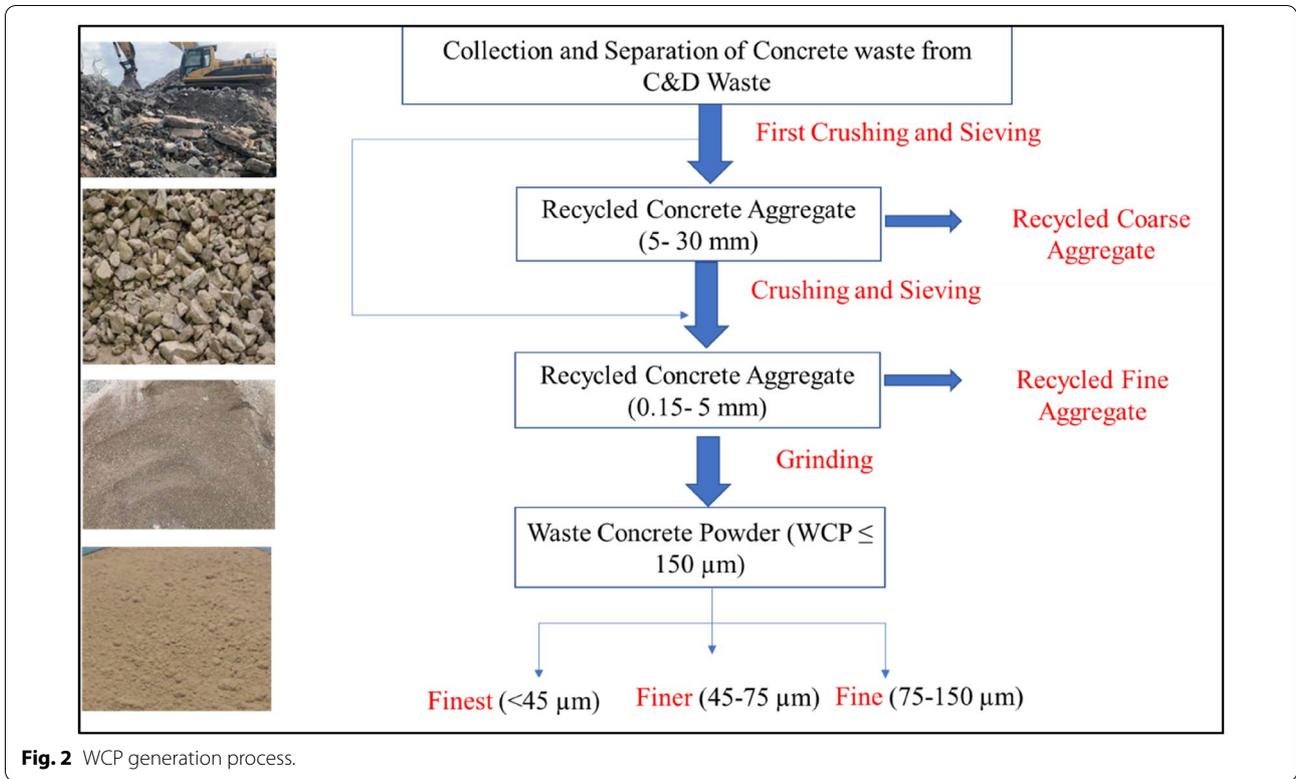


Fig. 2 WCP generation process.

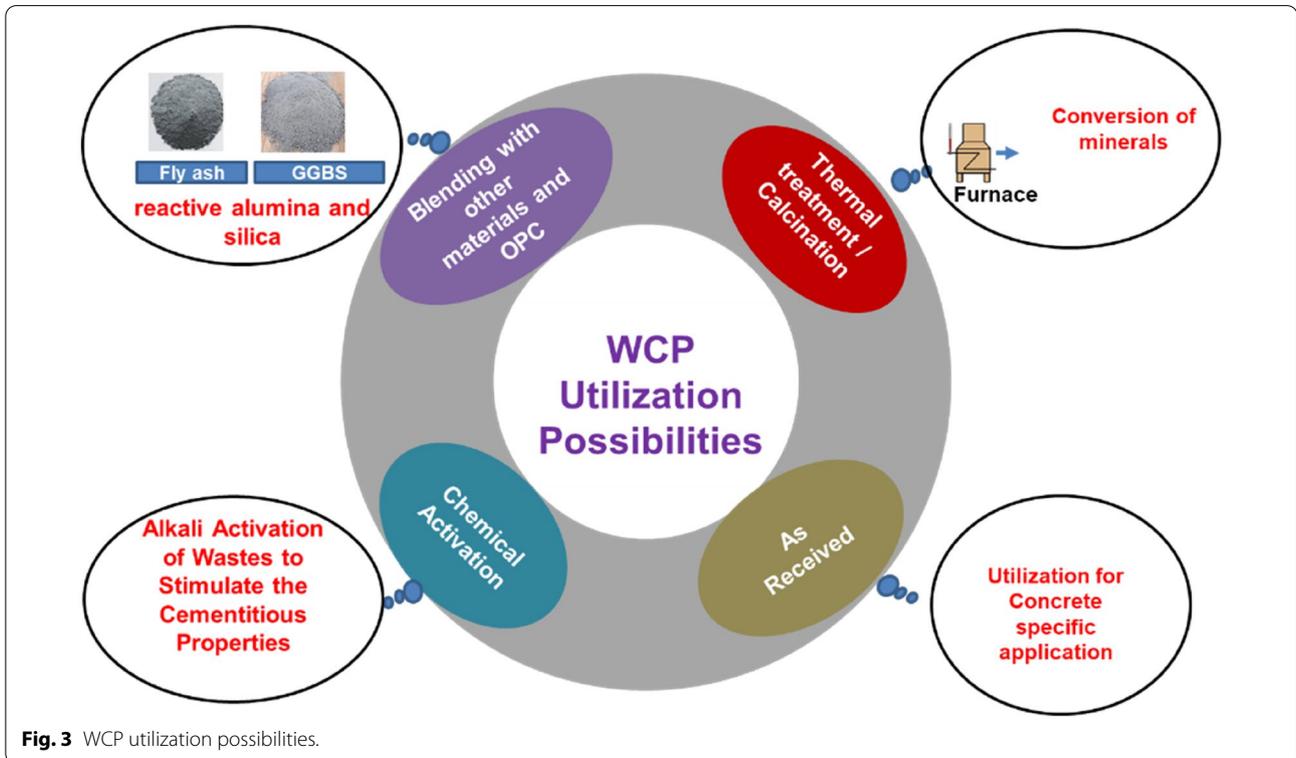


Fig. 3 WCP utilization possibilities.

recommended due to nonperformance on mortar application. The viscosity decreased up to 62%, final set time delayed by 2 h, and compressive strength decreased by 73% in comparison to the reference mortar samples. Ma and Wang (2013) used WCP with OPC for binder fabrication, and also used red clay brick (RCB) waste to replace 20% of river sand for the preparation of C20 class concrete. As-prepared concrete was tested for different mechanical and physical properties. It was observed that the compressive strength of the concrete prepared with 20% WCP and 20% RCB increased by 17% compared with the concrete prepared without application of RCB. The effect of RCB application was prominent in the concrete, which might be due to the better pozzolanic nature of it in comparison to the WCP. Topic et al. (2017c) used WCP as a cementitious material with OPC to test its impact on mechanical properties and durability aspects. The researchers concluded that WCP can work as a micro filler in concrete systems and hence can improve the compressive strength. Thirty percent WCP can be used to replace the OPC; the results of compressive strength were comparable to the reference results. However, the study also suggested abnormalities in the long-term strength development and recommended future research on the same. In another study, Topič et al. (2017a) extended the previous research and defined the critical limit of WCP application in concrete. With the application of 65–70% of the WCP, the compressive strength reduced by about 65%. After testing the different blends of WCP and OPC, the researchers concluded that when the critical proportion of WCP application lies between 30 and 50%, it does not affect the compressive strength. Topič et al. (2017b) published yet another work on WCP utilization. In this study, WCP was applied for use as a micro filler and binder. The binding properties were assumed supposed to function due to the presence of non-hydrated particles in grounded WCP. These non-hydrated particles can rehydrate and hence contribute to the strength development. In addition, application of 20–30% of WCP improves the flexural strength and Young's modulus and shrinkage in comparison to the reference. However, the compressive strength was affected negatively with the WCP application; it reduced almost 25% with the replacement of just 10% of the cement, and further replacement resulted in a linear decrement in compressive strength. On application of WCP for OPC replacement, the strength properties started to deteriorate. This trend refers to the non-hydraulic nature of WCP, which limited the application of it upto 30% in as-received conditions.

In addition to the optimization of WCP proportion in mortar and concrete applications, the outcome of WCP has been researched using predictive artificial models.

Lin et al. (2020) used an artificial predictive model for WCP utilization in mortar. The OPC was replaced by WCP in the proportion of up to 30%. The predictive model was applied for the compressive strength prediction with respect to the different WCP dosages. The compressive strength of the mortar was first tested physically, and then quantitative values were applied to the artificial neural network to establish the predictive model. Time was taken as the variable which was represented as 28 days and 3 days of compressive strength; on this basis, the feasibility and best dosage of WCP application were optimized. The model was applied to reduce physical test cycles, improve efficiency of work, and, importantly, achieve the maximum possible utilization of WCP in construction applications. Pešta et al. (2021) used another kind of predictive model for the environmental perspective of WCP application in construction material. The model includes all the factors of WCP generation, from the concrete recycling process to its utilization as a construction material. In the first phase of the study, all the physical properties of the concrete such as density, workability, and compressive strength were measured. The WCP was applied in the range of 0–50% for OPC replacement. As downstream research, life cycle analysis was performed for the environmental assessment of concrete. The analysis was conducted on the basis of the environmental footprint methodology. The life cycle analysis outcome suggested the use of WCP for cement replacement. Moreover, the outcome confirms the positive impact of WCP application in concrete through reduction of climate change, as well as in other categories.

A few studies also focused on the WCP properties that can impact its response in cement replacement application. Mehdizadeh et al. (2021) published a study on the role of CO₂ treatment and the particle size range impact of WCP on cement replacement application. The cement paste was blended with the application of the CO₂-treated WCP in the proportions of 0%, 5%, 10%, 15%, 20%, 25%, and 30%. It was observed that treatment of WCP with CO₂ was very effective. The carbonation of the WCP leads to a drastic decrease in the porosity of the cement paste microstructure with formation of calcite crystals. Simultaneously the water demand to achieve the desired workability decreased with larger particle size. Carbonation of WCP decreased the 28-day compressive strength due to the formation of excessive calcite.

Li et al. (2021) also investigated the impact of WCP on the basis of particle size. They compared the WCP results with the results of another waste brick powder. The impact of their fineness on the properties of mortar was compared. The waste brick powder had better workability compared with WCP due to its lower surface area and

Table 1 Effect of WCP on compressive strength.

References	Compressive strength (MPa @ Age (% to the Ref.))	Effect on other properties	W/C	application type	Recommended amount of WCP in binder	Remarks
Kamon et al., (1988)	12 @ 3 (– 40%) 18 @ 7 (– 25%) 24 @ 28 (–20%)	Not mentioned	0.4	Cement paste	WCP (60%) + 40% OPC	Hardening agent was also used with WCP
Moon et al., (2008)	15.7 @ 3 (– 3.1%) 27.2 @ 7 (– 4.2%) 36.7 @ 28 (–2.4%)	Flow value— decreased Porosity— increased	0.45	Mortar	WCP (10%) + 90% OPC	Comparison b/w matrix WCP and demolished WCP
Kim and Choi (2012)	17 @ 7 (– 38.88%) 26 @ 28 (– 34.6%) 28 @ 56 (– 33.33%) 17.5 @ 7 (– 2.7%) 25.5 @ 28 (– 3.3%) 30 @ 56 (– 33.33%)	Flow value— decreased Viscosity— decreased Yield stress— decreased Setting time— increased	0.55	Mortar	15% WCP I with fineness of 928 cm ² /g + 85% OPC 15% WCP II with fineness of 1360 cm ² /g + 85% OPC	WCP only acted as a nonreactive material
Topič et al.(2017c)	50.4 @ 28 (3.04%) 63.7 @ 287 (– 64%) 58.7 @ 409 (– 11%)	Flexural strength— decreased Dynamic Young's modulus— decreased	0.38	Cement paste	33% WCP + 67% OPC	Later age degradation in compressive strength due to presence of fewer pozzolans
Topič et al., 2017a)	66.7 @ 28 (– 13.04%)	Flexural strength— increased	0.36	Cement paste	10% WCP + 90% OPC	Nonreactivity of WCP affected the compressive strength significantly
Topič, et al., 2017b)	56.9 @ 28 (– 25%)	Flexural strength— increased Dynamic Young's modulus— decreased	0.37	Cement paste	20% WCP + 80% OPC	Micro-filler effect of WCP improves the performance
Lin et al., (2020)	5.43 @ 3 (– 9.35%) 6.84 @ 7 (– 20.87%) 81.03 @ 28 (736%)	Apparent Density— decreased Setting time— decreased	–	Mortar	30% WCP + 70% OPC	Effect of cellulose ether and latex powder influenced the compressive strength and other properties
Mehdizadeh et al., (2021)	65.8 @ 28 (5.8%)	Flowability— decreased	0.3	Cement paste	15% WCP (carbonated) + 85% OPC	Carbonation of the WCP reduced the water demand with flowability improvement
Pešta et al., (2021)	65.8 @ 28 (– 20%)	Density— decreased Workability— increased	0.61	Mortar	10% WCP + 90% OPC	Loss of compressive strength is caused by the organic impurities present in the WCP
Li et al., (2021)	34.2 @ 28 (– 28%) 39 @ 28 (– 23.5%)	Workability— decreased	0.5	Mortar	30% WCP + 70% OPC	Strength properties deteriorate with WCP application

porosity. At different levels of fineness, WCP had water requirement ratios from 110 to 114%, while at the same level of fineness, it was from 103 to 105% for the waste brick powder. The activity index was also much better in the case of the waste brick powder, with 82% to 87% compared with 72% to 78% for WCP at 90 days. Table 1 summarizes the effect of WCP application on compressive strength.

The application of as-received WCP for OPC replacement in cement paste, mortar, and concrete can be effective up to the proportion of 10% to 30%. The mechanical strength, workability, shrinkage, and density are negatively impacted by WCP when it is applied at a proportion higher than the upper mentioned range. This impact of WCP application is due to its poor binding properties and high water absorption (Mehdizadeh et al., 2021;

Pešta, et al., 2021; Topič et al. 2017b). Therefore, alternate methods of effective and bulk utilization of WCP are required.

(b) Application of WCP after thermal and chemical treatment

The primary obstacle to WCP's bulk utilization as a cementitious material is the fact that it does not have a high reactivity level, as discussed in section (a). As a result, various investigations on the activation of WCP to achieve bulk application in the production of cementitious binders have been published. Thermal and chemical WCP treatments were hypothesized to increase its reactivity. Mehdizadeh et al., (2021) investigated the use of WCP after it had been chemically treated. To promote the hydration process in WCP, sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were utilized as stimulating agents. The mixture was tested for strength and permeability after the excited WCP was employed to partially replace OPC. However, it was discovered that merely 10% application of excited WCP could greatly increase compressive strength over the reference, and that additional increases resulted in a severe drop in strength attributes. According to the studies, several factors can influence the strength development following WCP application. The WCP content has a significant impact on strength development. Strength growth is also influenced by the substance and activator. The appropriate activator application content was found to be 1% of the cement used. However, studies have revealed that additional research is needed to establish the chemical activator's mode of action. Liu et al. (2016) tried to use chemically activated WCP as a mine backfilling cementitious material. The pozzolanic activity of WCP was investigated. The combination of alkali-calcium and sulfur was used to serve as the activation chemical, and an orthogonal test was performed to measure the impact of the activators as early strength agents. The study results suggest that chemical activators worked in the descending order of alkali > lime > sulfur in the case of early strength development, whereas for the late age strength development, the descending order was lime > sulfur > alkali. The early strength development and setting time were used for the analysis index and extreme index analysis, and it was concluded that the optimal ratio for WCP and chemicals for mine backfilling paste was 78%:10%:8%:4% for WCP:lime:sulfur:alkali. The early age hydration products of activated WCP paste were also tested through XRD analysis and SEM. It was found that calcium hydroxide and ettringite were the main compounds formed in the hydration products at an early age. As the age of hydration increased, the compounds of WCP activated and

formed more calcium silicate hydrate (CSH) and calcium aluminum hydrates. This was attributed as the sole reason for the late age strength development with activated WCP. However, possible chemical reactions and the mechanism of chemical activators' function in the WCP matrix is a topic of interest and requires much clarification.

In addition to the chemical treatment, a few studies attempted thermal treatment for the activation of WCP. Sui et al. (2020) worked on WCP activation by means of thermal activation. They observed that the WCP particle size tended to change from 400 °C to 800 °C. The thermal treatment at 600 °C increased the particle size of WCP, whereas treatment at 700 °C decreased the particle size. However, the reason for the particle size fluctuation is not discussed in the research. The WCP reactivity increased with the treatment at 800 °C due to the formation of more reactive oxides. The authors concluded that WCP treated at 700 °C had the optimum activity index when considering all the factors. The treated WCP was used to replace the cement in mortar. In comparison with mortar without WCP, it was found that 30% replacement of the cement is possible with thermally treated WCP for mortar and concrete applications.

Following several publications on WCP application in mortar and concrete, Qian et al. (2020) took the next step and worked on the application of thermally activated WCP in ultra-high performance concrete (UHPC) as a sustainable and green method. The dehydrated WCP was obtained through the thermal treatment of WCP as shown in Fig. 4. The dehydrated WCP was used to partially replace the OPC in UHPC development. Fig. 5 exhibits the XRD analysis of the dehydrated WCP with treatment at different temperatures. It was seen that CSH was dehydrated to calcium silicate at temperatures above 650 °C, and calcium hydroxide was converted to calcium oxide in a similar temperature range. Dehydrated WCP was applied in the range from 10 to 40%, and the modified Andreasen and Andersen particle packing model was used to design the UHPC. The physical and chemical properties of the developed UHPC were evaluated. It was concluded that application of 25% of thermally treated WCP is possible to develop UHPC without any significant effects on the physical and mechanical properties. The microstructure and durability aspects of the developed UHPC also supported the optimum application of WCP up to 25%. Additionally, the ecological assessment shows that the UHPC incorporating WCP has a relatively small impact on the environment, which provides a broad prospect for the future sustainable development of UHPC.

Table 2 summarizes the effect of treated WCP application on compressive strength. According to the

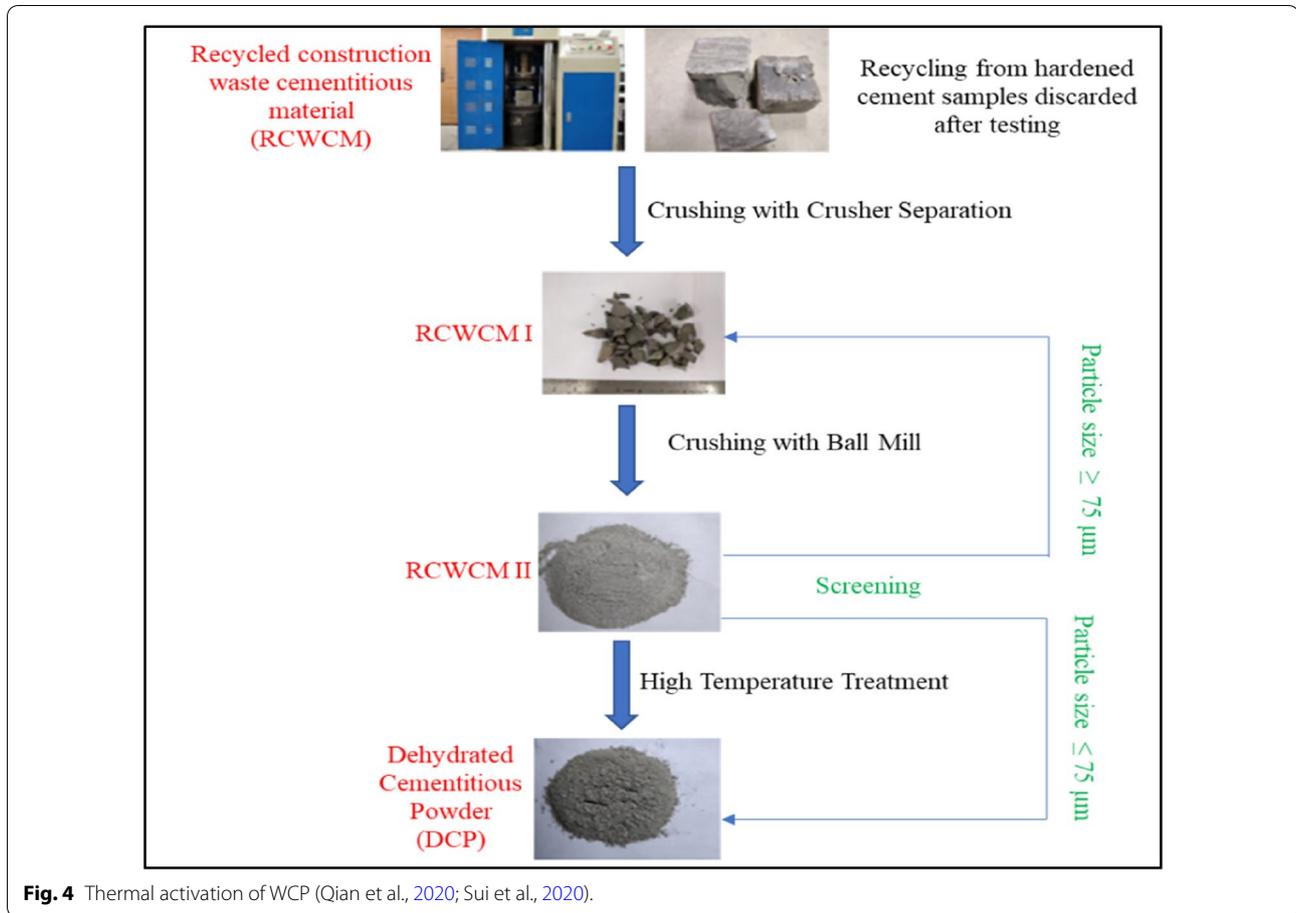


Fig. 4 Thermal activation of WCP (Qian et al., 2020; Sui et al., 2020).

mentioned studies, it can be concluded that chemically and thermally treated WCP can be used in construction applications in the proportion of 10% to 78%. However, more research is needed to optimize the standard process of WCP activation. The changes in the chemistry of activated WCP also need to be addressed in future studies. In addition, sustainable combination of chemical and thermal activation WCP is necessary, as recommended in the current study.

(c) Application of WCP with other cementitious materials

Chemical and thermal treatments can be environmentally harmful and expensive ways to utilize WCP due to the consumption of energy during the treatments, which renders them less sustainable. In view of this, researchers have started to look for alternative methods, and several studies have been published on the co-application of SCM with WCP. In initial efforts for WCP utilization in this manner, Aghili et al. (1970) observed that the utilization of WCP in masonry mortars seems more practical

with co-application of silica fume. The silica fume was used with WCP with the idea of enhancing early age and overall strength properties due to the presence of reactive silica. Three different groups of mortar mixes were designed. The first group consisted of mixes in which 25%, 50%, and 75% of the total OPC were replaced with WCP. In the second group, 10% and 15% silica fume were replaced with OPC, and finally, in the third mix, 10% and 15% silica fume were used in mixes containing 25% WCP. The results of physical (both fresh and hardened states) and mechanical tests showed that utilizing 10% or 15% silica fume in mortar containing 25% WCP can lead to similar or even better physical and mechanical performance compared with the reference mixture without WCP and silica fume. However, application of 10–15% silica fume rendered the application unsustainable from an economic standpoint. In view of this, Kasami et al. (2001) used ground granulated blast furnace slag (GGBS) as an SCM with WCP to investigate its effect. GGBS is generated in bulk as a coproduct of the steel industry, which makes it sustainable for application with WCP as a cementitious binder. Limestone was also used with

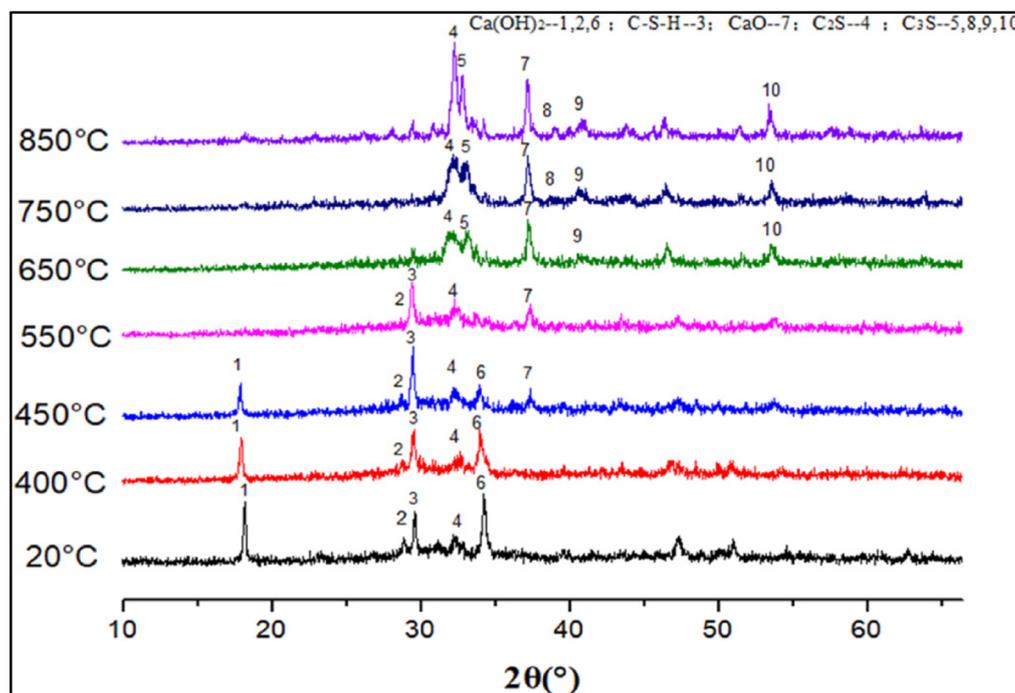


Fig. 5 XRD analysis of thermally treated WCP (Qian et al., 2020)

WCP and GGBS. The purpose of GGBS and limestone application with WCP was to provide a sufficient proportion of reactive silica and calcium for the development of strength properties. It was concluded that WCP with GGBS and limestone is usable in self-compacting concrete without making further changes. However, the water-reducing plasticizer dosage was increased for the given slump flow and drying shrinkage. In addition, if GGBS is added with WCP, it can improve the performance of superplasticizers in self-compacting concrete. Quan and Kasami (2018) worked on self-compacting concrete by applying the WCP with GGBS and limestone. Different properties of self-compacting concrete were also tested and it was noticed that WCP application in concrete reduced the super-plasticizing effect of the water-reducing agent. The concrete with WCP resulted in similar compressive strength as the concrete with limestone, however in comparison with concrete with GGBS it found lesser. In terms of drying shrinkage and elasticity, WCP reflects negative impact on concrete than GGBS and limestone. In conclusion, it was recommended to use WCP in concrete applications with increased proportion of plasticizer to overcome the water demand. In addition to that WCP application with GGBS is recommended to decrease the water demand, because GGBS also provides the superplasticizer effect in concrete.

In addition to the development of self-compacting concrete, Kwon et al. (2015) worked on cementitious powder for the development of carbonic cement. WCP, converter slag, and limestone were used as the mineral waste materials for the fabrication of the cementitious binder. The converter slag was used due to its abundance of calcium, silica, and iron compounds, whereas limestone was used to balance calcium and silica compounds in the mix proportion. A multi-objective optimization method, namely Non-dominated Sorted Genetic Algorithm-II, was used to optimize the mix proportion for the clinker using the materials used in the study. To evaluate the clinker performance, several tests, such as free lime measurement, XRD analysis, thermogravimetric analysis (TGA), mechanical tests, and flowability tests, were performed. The analysis indicated that the fabricated binder was 80% efficient in comparison with OPC. As a more advantageous point from the study, it was evaluated that application of cement paste in the place of limestone reduced the carbon emissions up to 46%. However, the cementitious powder used in the study contained imbedded fine aggregates, which reduced the plasticity and carbon emission reduction. The study recommends utilizing WCP as cementitious material; however, development of better fine aggregate separation techniques is suggested.

In addition, materials other than GGBS and limestone were used with WCP to enhance the properties

Table 2 Effect of treated WCP on compressive strength.

Ref	Treatment method	Compressive strength (MPa @ Age (% to the Ref.))	Effect on other properties	W/C	Application type	Recommended amount of WCP in Binder	Remarks
Tian, F., X.S. Xie, & W.X. Hu. Research, 2011)	Chemical treatment/1% application of activator	12 @ 3 (−40%) 18 @ 7 (−25%) 24 @ 28 (−20%)	Flexural strength— Decreased	0.4	Cement paste	WCP (60%) + 40% OPC	Hardening agent was also used with WCP
Liu et al., 2016)	Chemical treatment/4% alkali activator	4.7 @ 7 (280%) 12.45 @ 28 (122%)	Effect on mineralogy—SiO ₂ and Ca (OH) ₂ diffract peaks significantly decreased	—	Mixture paste	WCP (78%) + 10% quick lime + 8% gypsum	Use of WCP without the use of OPC
Sui et al., 2020)	Thermal treatment from 400 °C to 800 °C	23.71 @ 3 (−19.38%) 33.46 @ 7 (−27.74%) 47.71 @ 28 (−13.78%)	Effect on mineralogy—heat treated WCP added more larnite and calcium silicates in hydration reactions	0.5	Mortar	30% WCP (treated at 700 °C) + 70% OPC	Treatment of WCP at 700 °C decreased the particle size by 55%
Qian et al., 2020)	Thermal treatment from 400 °C to 850 °C	45.15 @ 3 (−6.25%) 61.37 @ 7 (−7.57%) 100.75 @ 28 (−4.76%)	Flowability: decreased Shrinkage: spontaneous shrinkage rate gradually increases	0.5	UHPC	25% (dehydrated cement paste treated at 750 °C) + 75% OPC	Workability, autogenous shrinkage, and durability also had negative effects with more than 25% dehydrated cement paste application

of the cementitious binder. Cong et al. (2019) studied concrete preparation using a blend of WCP, fly ash, and recycled brick powder as cementitious material. The results showed that the addition of the SCMs with WCP increased the water demand, and it could not be fulfilled even after addition of the water-reducing additive. However, it was also concluded that addition of WCP and recycled brick powder with certain fineness can improve the workability and mechanical strength of the concrete. Mao et al. (2019) studied the optimization of different supplementary materials and WCP for application as sustainable and green high-performance binders. The study was based on designing different experimental proportions on the basis of factors such as proportion of WCP, silica fume, steel fibers, and superplasticizer in the binder; water-to-cement ratio; and type of fine aggregate used. The other factors, developed compressive strength and workability of the concrete, were also considered for determination of the optimal ingredient proportions. The sustainability of the binder was the ultimate factor, and in view of that, application of 30% WCP, 1% superplasticizer, 15% silica fume, and 2% steel fiber with a water-to-cement ratio of 0.16 was optimized.

Huashan and Yujun (2021) worked on the utilization of WCP with fly ash as an SCM. The fly ash was used to

provide pozzolanic activity to the binder. The researchers also investigated the effects of the WCP-based binder on the mortar's hydration properties. The study used two different kinds of waste powder: The first was from the mortar prepared from OPC, and the second was derived from the same type of mortar. The OPC was replaced by a blend of WCP and fly ash in the proportion of 40% to 70%, while up to 20% WCP was used in the blend with fly ash. Different properties such as workability, setting time, mechanical strength, flow index, hydration products, and microstructural properties were evaluated for the prepared mortars. It was concluded that 10% application of WCP with 40% fly ash and 50% OPC developed similar properties to those of the mortar prepared only with OPC. Chen et al. (2021) used fly ash and silica fume as SCMs to provide enhanced strength properties to the WCP-based binder. The heat of hydration for the WCP-based binder and binder without WCP was measured and compared for better understanding. The XRD and TGA tools were used to determine the hydration products in the cement paste, and a mercury intrusion porosity meter was used to measure the porosity of the cement paste. The WCP was used in proportions of 10%, 20%, 30%, and 40% in cement paste and mortar. Different blends of different proportions of fly ash and silica

fume were also applied to measure the impact on hydration. It was observed that in the case of WCP-only application, the hydration and strength decreased with the increasing proportion, whereas the blend with 15% WCP and 15% additive (fly ash:silica fume = 3:2) developed the highest heat of hydration and strength. Frías et al., (2021) applied WCP with glass generated from C&D waste. The OPC were replaced by WCP and glass upto 10%. The study compared the waste-based binder and OPC on the basis of hydration and microstructure. The WCP and glass-based binder developed same hydration products, CSH gel, CASH gel, ettringite and portlandite as developed with OPC. Table 3 summarizes the effect of WCP and SCM application on compressive strength. The application of the supplementary cementitious binder with WCP can enhance the cementitious properties and decrease the water demand. SCM is supplementation in the form of reactive silica and calcium. Fly ash provides reactive silica for the pozzolanic reactions, whereas silica fume addition provides reactive silica and fills the voids in the matrix. WCP lacks reactive silica and calcium in its composition. Hence, addition of fly ash, silica fume, GGBS, and other SCMs is recommended for improvement of WCP application.

4 Steel Slags

4.1 Generation Process and Characteristics of Steel Slags

The metallurgical operations of steel plants generate many kinds of wastes in large quantities at different stages of processing. These wastes include blast furnace (BF) slag, Linz–Donawitz (LD) slag, coke-bridge, tar sludge, iron fines, iron tailings/lime mill sludge, acetylene sludge, and more depending on the quality of raw resources and their processing (Kim & Kang, 2020; Proctor et al., 2000; Sezer & Güldereren, 2015; Shi, 2004; Shumuye et al., 2021; Singh et al., 2015). Of these different waste materials, several can be applied as raw material in other manufacturing industrial processes on the basis of their chemical composition. Table 4 illustrates typical chemical compositions of different types of slag generated from steel plants.

Cementitious properties have been observed and reported in steel slags because of the availability of different silicates, ferrate, and a bit of aluminate (Kourounis et al., 2007; Shi, 2002). Tricalcium silicate and dicalcium silicate are present in considerably lower amounts in steel slags as compared with OPC and may be viewed as a meager OPC clinker (Shi, 2002). Steel slags generally show excellent cementitious properties when treated with chemical activators such as sodium hydroxide, sodium silicate, and sodium carbonate (Shi & Qian, 2000). The corrosion resistance of the steel slags was

better than that of OPC (Shi, 1999). However, a major issue arises with low reactivity of steel slags in comparison with OPC (Murphy et al., 1997; Shi et al., 2003; Wang & Yan, 2010). Minerals containing cementitious properties in steel slags are present in nonreactive form (i.e., in the crystalline phase). Other drawbacks include the relatively high content of free CaO and MgO based on which volume growth matters (Yildirim & Prezzi, 2011).

In the process of iron production, iron ore is charged with limestone and coke in a BF. Carbon monoxide is formed due to the combustion of coke, which reduces the ore iron to molten iron and a nonmetallic coproduct called GGBS. The presence of high silica (SiO_2) and calcium oxide (CaO) along with a glassy phase above 90% and low iron content is effective in the production of cementitious binders, along with the gypsum and clinker (Das et al., 2007; Özbay et al., 2016).

As steel demand is increasing, new methods for steel production have also developed. Steel production by electric arc furnaces (EAFs) and ladle furnaces (LFs) are among them. These methods are advantageous in comparison with the conventionally used BF and converter pathway. The EAF and LF application mainly involves lower energy demand and capital cost in the production per ton of steel with the utility of scraped steel. They also involve better regulation of the chemistry and thermal properties of the steel, with another advantage of furnace size flexibility (very small furnace size application in the case of some alloys). In the case of EAF, a high temperature range can be achieved by arcing (Sarkar et al., 2010). Slag produced by an EAF in the initial stage of steelmaking is known as EAF slag. It is shaped like stones, black in appearance, and easy to crush. It is composed of a high percentage of ferric oxide and low percentage of amorphous silica and leads to small pozzolanic activity in comparison with BF slag (Chen et al., 2011). The steel-refining process generates two types of LF slag, which are high or low in alumina and silica depending on the processes involved (Herrero et al., 2016). The use of LF slag, which is high in silica, is successful as a cementitious material, as an aggregate material, or even as feed for clinker synthesis (Vilaplana et al., 2015).

Several research studies have published the features of EAF slag with regard to its valorization in construction materials. It has excellent resistance to fragmentation with a high abrasion value, which might make it an appropriate raw material for application in conventional as well as high-performance concrete (Faleschini et al., 2016). EAF slag is applied with low volumes in various construction activities, such as for tunnel structures, sealing aggregates, asphalt concrete, unpaved roads, asphalt mixture in road construction, and in roads (Chen et al., 2013; Dippenaar, 2005; Geiseler, 1996; Motz & Geiseler,

Table 3 Effect of WCP and SCMs on compressive strength.

Refs.	Cementitious material used	Compressive strength (MPa @ Age (% to the Ref.))	Effect on other properties	W/C	Application type	Recommended amount of WCP in Binder	Remarks
Aghili Lotf et al., (1970)	Silica fume	115 @ 28 (+ 6.48%)	Flowability: Decreased	0.5	Mortar	25% WCP + 10% silica fume + 65% OPC	10% and 20% application of silica fume worked equally
Quan and Kasami (2018)	GGBS, limestone	37.46 @ 7 (10%) 42.71 @ 28 (2.43%)	Drying Shrinkage—increased Modulus of elasticity—decreased	0.5	Concrete	50–60% WCP + 2% GGBS and limestone + 40–50% OPC	Addition of GGBS with WCP reduces water demand
Kwon et al., (2015)	Converter slag, limestone	36.5 @ 28 (– 24%)	Flowability—decreased	0.5	Cement paste	20% WCP (thermally treated at 750 °C) + 10% slag + 10% lime-stone + 60% OPC	WCP also used as a fine aggregate
Cong et al., (2019)	Waste brick powder	23.1 @ 7 days (– 3.5%) 37 @ 28 days (– 11.32%)	Workability—decreased Activity Index—increased with increasing surface area of WCP	0.5	Concrete	20% WCP + 2.2% water reducer	With the addition of water reducer, workability and strength properties could be enhanced
Mao et al., (2019)	Silica fume, steel fiber	68.5 @ 3 days (– 26.5%) 93 @ 7 days (– 19%) 114 @ 28 (– 15%)	Flexural strength—increased Flow—decreased	0.16	Green reactive powder concrete	30% WCP + 15% silica fume + 2% steel fiber	Steel fiber did not show significant impact on flow of the mixture
Huashan and Yujun (2021)	Fly ash	20 @ 7 days (static) 39 @ 28 days (+ 1%) 55 @ 90 days (– 2%)	Water absorption—increased Initial setting time—decreased Final setting time—decreased Flowability—decreased	0.5	Mortar	10% WCP + 40% fly ash + 50% OPC	Increasing the proportion of WCP increased the water demand
Chen et al., (2021)	Fly ash and silica fume	4.0 @ 3 days (– 2.2%) 5.1 @ 7 days (– 2.8%) 8.3 @ 28 days (+ 0.7%)	Flowability—decreased Porosity—decreased	0.45	Paste, mortar	15% WCP + 15% fly ash and silica fume + 70% OPC	Fly ash and silica fume application decreased the unwanted pores by 9.67%
Frias et al., (2021)	Glass from C&D waste	–	Effect on mineralogy—after 28 d the pozzolanic reaction develop more CSH gel and Ettringite	–	Paste	5–10% OPC replacement	Microstructural analysis

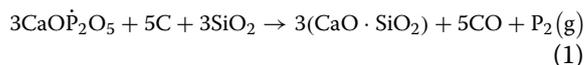
2000; Oluwasola et al., 2015; Pasetto & Baldo, 2010; Rohde et al., 2003; Wu et al., 2015). However, the application of EAF slag in these activities resulted in lower structure durability. The free lime and periclase (MgO) content cause volumetric variability due to expansion and lead to lower durability of the material. Therefore, in light of this, several research studies focused on the pretreatment of EAF slag and its application in cementitious binder fabrication. Mechanical pretreatment of EAF slag is conducted for the activation; due to reduction in particle size, slag reactivity increases (Amin et al., 2017).

Around 150–200 kg of LD slag is created in the production of one ton of steel (Chand et al., 2016) (Reuter et al., 2004; Yi et al., 2012). It is generated in an LD furnace during the steelmaking process. In this process, hot metal is transferred from a BF to an LD converter, where it undergoes an oxidation process to remove impurities such as carbon, silicon, and phosphorous, which are present in hot metal. Lime is added to the furnace, and slag is skimmed out, composed of oxide impurities such as calcium silicate and others. This slag material is collected in a cast iron ladle for quenching, and cooling down is performed with air or water. The cooling rate of slag is slow, which is responsible for its crystalline phase. Due to efficient mechanical properties, application of this slag is possible as a substitution material for natural aggregates in road construction. This application is beneficial due to the conservation of natural resource materials (Xue et al., 2006). However, due to the presence of magnesia and lime, an insignificant ratio of the slag can actually be utilized in structural materials application. Lime and magnesia engage moisture and carbon dioxide from the air and form hydroxides and carbonates, respectively. This causes volume enlargement in the application of LD slag in concrete, which results in crack formation. To overcome this instability issue and ensure gainful utilization of LD slag, different physical methods similar to accelerated aging, magnetic separation, flotation, dual phase separation, and so on have been reported in previous studies (Gawwad et al., 2015; Shiomi, et al., 1977).

The main purpose of accelerated aging is to remove the free lime and magnesia present in LD slag.

LD slag has several limitations to apply it as building material. The high proportion of phosphorus (1–7%) and presence of heavy metals like (P₂O₅) reduces LD slag chances to utilize in building material. However, several studies focused on the LD slag pretreatment for making it suitable have been published. Dephosphorization of LD slag through biological and chemical method has been applied for the removal of phosphorous (Panda et al., 2013). Takeuchi et al. used iron–silica as reducing agent instead of carbon which reduced the phosphorous to P₂. The alloy targeted in the LD slag was Fe–P–C_{satd} which was dephosphorization at the temperature of 1200 °C (Morita et al., 2002; Takeuchi et al., 1980). Marhual et al. (2011) used biological method for the dephosphorization of LD slag. The microorganisms which are able to solubilize phosphorus in LD slag removed were used. The bacteria from the family of Pseudomonas and bacillus were used in the study. The recovered phosphorus was found suitable for the application in fertilizer making.

To overcome the issue of P₂O₅, reduction method was applied. LD slag contains the P₂O₅ in the form of (3CaO·P₂O₅), it is reducible to metallic (Fe–P–C) and nonmetallic (3(CaO·SiO₂)) forms with carbon application. Equation 1 represents the reduction of the phases:

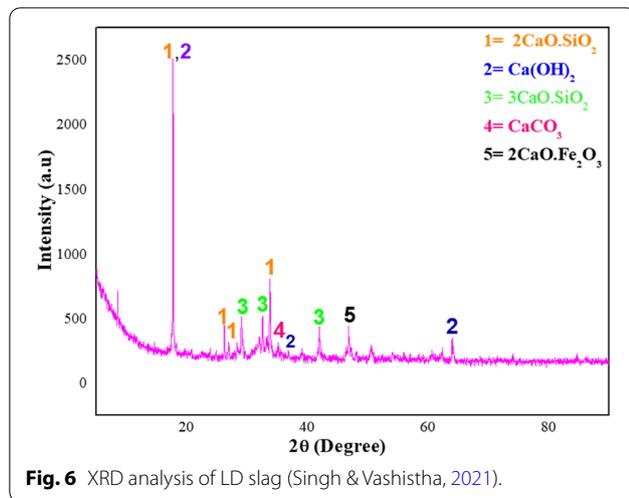


The drawback of the above-mentioned method is that it requires a significantly high temperature of 1500 °C, however hence produced nonmetallic phases are reactive and can be utilized in cement production.

In addition to this, the metals like Al, Fe, Zn, Pb, Ni, Ta, Ag and Au have also recovered from LD slag, with the application of different separation methods like magnetic, flotation, grinding, leaching, etc. (Chand et al., 2017; Menad et al., 2014; Mirazimi et al., 2013, 2015; Shen & Forssberg, 2003; Xiang et al., 2017). The natural resources of these metals can be conserved through recovery of them from LD slag. Mirazimi et al. (2015) applied one of upper mentioned method for the recovery of vanadium.

Table 4 Typical chemical compositions of BF, electric arc furnace (EAF), ladle furnace (LF), and LD slag (Ashrit et al., 2015; Faleschini et al., 2016; Haha et al., 2011; Luxán et al., 2000; Radenović et al., 2003).

Slag type	Chemical composition (%)									
	CaO	SiO ₂	FeO	Fe ₂ O ₃	MnO	MgO	P ₂ O ₅	Al ₂ O ₃	TiO ₂	SO ₂
BF slag	35–50	30–40	–	0.1–1.6	0.2–1.5	0–8	0–0.03	7–18	0–0.5	0–2
EAF slag	24–29	13–15	26–34	–	5–15	3–7	1–2	4–14	0–0.5	–
LF slag	48–54	08–15	1–1.5	–	1–2	10–15	2–3	14–22	0–0.2	–
LD slag	42–50	12–26	8–24	0.3–2.2	2–6	1–9	1–7	2–11	1–3	0.1–0.6



The roasting-leaching method was used for the recovery. However, this method consumes significant quantity of thermal energy while other studies could recover the 98% of vanadium by using only leaching with acid.

4.2 Application of Slags as Cementitious Binders

Among all the slags, GGBS has the best properties to be utilized as a cementitious material directly. It is commonly utilized in cement manufacturing with availability in the market as Portland BF slag cement. The inorganic BF slag mainly comprises ingredients such as calcium oxide (29–36%), magnesium oxide (1–7%), silica (30–35%), and $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ (18–25%) (El-Mahllawy, 2008; Haha et al., 2011; Kim & Lee, 2017; Yildirim & Prezzi, 2009). The presence of iron, silicon, and calcium oxide in BF slag makes it a perfect raw substance for production of cement along with the gypsum (Das et al., 2007; Kim & Lee, 2017; Yildirim & Prezzi, 2009). GGBS and Portland clinker-based blended cement is being commercialized and used for various construction applications. Hence, GGBS application as a cementitious binder is not included, and application of steel slags is the focus of the present study.

Regarding the generation of different types of steel slags, CaO, SiO_2 , Al_2O_3 , Fe_2O_3 , MgO, and FeO are the main elemental oxides present (Shi & Qian, 2000; Tüfekçi et al., 1997). In terms of the minerals, merwinite, calcium alumina ferrite (C_4AF), dicalcium silicate (C_2S), olivine, tricalcium silicate (C_3S), tetra dicalcium ferrite (C_2F), and free CaO are those commonly found in the slags (Zhongming, et al., 2020). Different types of steel slags have been covered in the present study, as follows:

- a) Application of LD slag as a cementitious binder

Unlike GGBS, LD slag has limited applications due to possessing less suitable properties. It has been used in various civil engineering applications, but only 25% of total generated LD slag could be utilized in various conceivable applications such as aggregates in road construction, as a liming agent, in manufacturing of cement clinkers, in manufacturing of bricks, and in production of fertilizers. The remaining 75% is disposed of in landfills (Menad et al., 2014; Tiwari et al., 2016). This is due to the difference in composition and properties of the LD slag from GGBS. GGBS is glassy (92–93%) and amorphous in nature, whereas LD slag is mainly crystalline (about 38–40% glass content) (Agarwal, et al., 2017; Conjeaud et al., 1981; Han & Wu, 2019; Pal et al., 2003). Fig. 6 represents the XRD analysis of LD slag. However, the calcium silicate is abundant but it remains in nonreactive state (Singh & Vashistha, 2021). In addition, the particle size of the LD slag remains variable, with almost 42.9% of volume fraction containing $10\ \mu\text{m}$ and only 28.8% having a particle size of $< 60\ \mu\text{m}$, which is almost in the range of OPC in terms of fineness (composed of 32.3% particles $< 10\ \mu\text{m}$ and 4.3% $> 60\ \mu\text{m}$).

Clearly, the proportion of small particles ($< 10\ \mu\text{m}$) in LD slag is slightly higher than in OPC, whereas the proportion of large particles of slag ($> 60\ \mu\text{m}$) is much higher than that of OPC. However, a demerit of LD slag is that it contains far less moderate particle sizes (10–60 μm) than OPC, which is indicative of ordinary particle continuity in particle size distribution of the slag (Aghili Lotf et al., 1970).

The usage of LD slag in fabrication of cementitious binders is also limited due to instability of volume and presence of sulfur, phosphorus, magnesium, and free lime content. In view of this, and as efforts to utilize LD slag as a cementitious material, several studies focused on the stability of LD slag. Various physical processes such as flotation, dual phase separation, magnetic separation, and accelerated aging have been applied for the volume stability of LD slag (Das et al., 2007; Gawwad et al., 2015). In other attempts, magnesium and free lime were removed through the process of accelerated aging. The LD slag was treated in vigorous conditions of heat, sunlight, oxygen, and vibration during its aging. Additionally, methods such as steam aging and pressurized steam aging have been applied to shorten the aging time in comparison with air aging (Gawwad et al., 2015). The dual phase separation method along with crushing, grinding, flotation, and leaching has also been applied for the recovery of fine iron and other trace elements present in LD slag (Das et al., 2007; Menad et al., 2014). Dephosphorization attempts have also been made using biological and chemical methods (Maheswara Rao et al., 2006; Marhual et al., 2011; Pradhan et al., 2004; Shiomi et al., 1977). However,

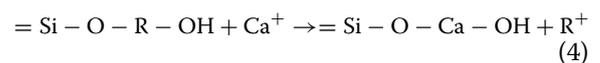
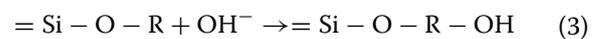
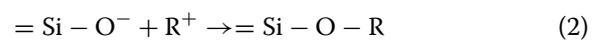
all these studies also concluded that separation methods for these compounds are expensive, which could lead to accumulation of LD slag disposal in landfills (Costa Borges, 2012; Gawwad et al., 2015; Maheswara Rao et al., 2006; Yi et al., 2012). The environmental problems associated with landfilling are space constraint, lowering of moisture, leaching of harmful metals into channels and water pollution in proximate springs, biochemical dilapidation, and deficiency of esthetics.

In this matter, many studies focused on efforts to enhance the cementitious properties of LD slag. It was first studied by Conjeaud et al. (1981). The theoretical and semi-field trials performed proved that the addition of 6–15% of alumina to the LD slag in the oxygen furnace improved the slag's cementitious property. Cements were made with a mixture of LD slag, GGBS cement clinkers, and gypsum (Dongxue et al., 1997; Han & Wu, 2019). In comparison to conventional cement, this slag cement exhibited higher acid resistance, improved strength, and high initial porosity, which reduced after 28 days. Murphy et al. (1997) (Murphy et al., 1997) studied the effect of cooling rate on the mineral structure, crystalline nature, and amorphous nature of LD slag. The study revealed that granulation of the LD slag can enhance the slag's cementitious properties, and hence, the produced slag can be utilized up to 20% in slag cement production. The quenching/granulation improved the slag's amorphousness, despite the fact that slag has a high lime-to-silica ratio, which is not conducive to glass formation. However, the quenching rate was maintained sufficiently to inhibit the crystal development through nucleation.

Singh et al. (2013) studied the possibility of using LD slag in place of iron ore in raw feed during clinker manufacturing. The study showed that 2% LD slag can be used as raw mix component for correction of iron content in raw mix. Recently, Agrawal et al. (2017) studied the viability of adding LD slag as a partial replacement of GGBS in Portland slag cement. They found that only 7.5% of LD slag could be recycled as a fractional substitution to GGBS in Portland slag cement due to the crystalline nature and nonreactivity of LD slag. As per IS: 12,089 (Upadhyay & Jamnu, 2014), the glass content in slag should be $\geq 85\%$ for its gainful utilization. However, the glass content in LD slag is only 49%. These studies suggested different utilization methods for LD slag application as a cementitious material. However, none of these studies achieved the bulk utilization of LD slag.

Several studies suggested that LD slag can be utilized in bulk through chemical and mechanical means. The chemical and mechanical stimulation helps in the improvement of hydraulic behavior (Kriskova et al., 2012; Krivenko, 1994). However, alkali activation of LD slag is a significant challenge due to the fact that it is extremely

crystalline and non-hydraulic parts such as merwinite, bredigite, and C_2S restrict its activation (El-Mahllawy, 2008; Tiwari et al., 2016; Tüfekçi et al., 1997). Despite this fact, several studies have been published on LD slag activation in attempts at bulk utilization as cementitious material. Duda (1989) worked on the enhancement of reactivity of crystalline LD slag by milling and blending it with GGBS and through chemical activation with NaOH. The alkali activation of LD slag showed significant improvement in cementitious properties, which improve with the fineness of the material and display hydration reactions. The series of reactions for alkali activation of CaO- and SiO_2 -abundant slag are given in Eqs. (2) to (4) (Glukhovskiy, 1994; Kazi et al., 2005):

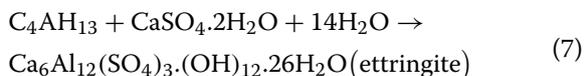
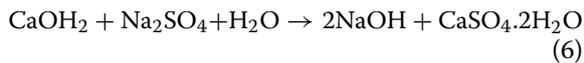
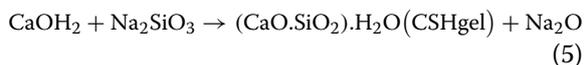


The activation of CaO- and SiO_2 -abundant slag encompasses the dissolution of Ca and break of Si–O–Si bonds to form the reaction outcome of C–S–H type with a low C/S ratio. Table 5 summarizes the recent research results on the usage of LD slag as an addition in cementitious products.

Zhang and Chen (2017) worked on the chemical activation of slag–cement based mixtures. The mixture was treated with different alkali and calcium-based activators, the influence of the activators on the setting time and compressive strength was measured. The outcome of different activators suggests that sulphate-based alkali activator is most suitable for slag–cement mixture activation, while calcium-based activators exhibited better properties with GGBS and cement mixture. However, the activation of LD slag–cement mixture with sodium hydroxide reduced the compressive strength of the cement.

Singh and Vashistha (2021) worked on the mechanochemical activation of LD slag and prepared a composite of 70% OPC and 30% activated LD slag. The LD slag was ball milled for 20 min to reduce the particle size, and sodium hydroxide and sodium silicate were used as the chemical activators for LD slag. The researchers found that the properties of binders prepared with activated slag based on sodium silicate and sodium sulfate showed an increment of 12.63% and 2.59%, respectively, in comparison with the compressive strength of cement. In the case of sodium silicate, the reason for the enhanced strength properties was the development of an extended amount of CSH gel, as mentioned in Eq. (5), whereas

sodium sulfate developed ettringite as per Eqs. (6) and (7):



Guo and Pan (2020) investigate the effects of LD slag on the mechanical properties of the fly ash-based geopolymer. The results reveal that the compressive strength of geopolymers increases with increasing steel slag percentage in the early stages, but when the steel slag level exceeds 10%, the compressive strength of the sample rapidly falls. The fly ash or steel slag-based geopolymer contains both sodium aluminosilicate hydrate (N–A–S–H) gel and calcium aluminosilicate hydrate (C–S–H) gel, according to FT-IR and XRD data. The paste sample containing 30% steel slag had more mesopores and fewer macropores than the control sample (FAP-0), according to BET and FE-SEM measurements (FAP-30). Table 5 summarizes the effect of LD slag application as a cementitious binder. Zhu et al., (2021), presented an experimental investigation targeted at recycling steel slag waste as a supplementary ingredient in metakaolin-based geopolymer composites, resulting in a new form of geopolymer composites. The strength test findings show that adding slag correlates to increased strength at a later age. According to XRD patterns, SEM pictures, and EDS line scanning studies the binder paste accumulates hydrated calcium silicate gel with curing age. Because of the low concentration and activity of steel slag active components, the degree of hydration of the binder remains inferior to the geopolymerization and silica–alumina gel produced by metakaolin.

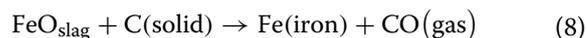
Both aforementioned studies are based on the analysis of slag application in geopolymer. The addition of slag resulted in later age strength development and favor up to 50% application of slag in geopolymer.

b) Application of EAF slag as a cementitious binder

The EAF process generates about 15% of slag, which is characterized as nonhazardous waste on the basis of its properties. A large surface is required for the disposal of this generated slag, which proves economically and environmentally unfavorable. The useful management of EAF slag is a present challenge in the research community. Diverse alternatives have been studied for the reduction or utilization of a large volume of this slag. The

application of the slag as a cementitious binder can provide an alternative for its utilization (Lind et al., 2001). Fig. 7 represents the XRD analysis of EAF slag.

Regarding the composition of EAF slag, provided in Table 4, it has less calcium content and more iron oxide than other slags. Gehlenite and larnite are the major phases present in EAF slag which are less reactive (Singh et al., 2021). However, despite this fact, several research studies have been published with utilization of EAF slag as a cementitious binder. Rojas et al. (Rojas & Rojas, 2004) analyzed EAF slag to check its capability for application as a cementitious material. The slag was found to have low pozzolanic activity and to be crystalline by nature. However, the slag had null or very little free CaO, MgO, Cl^- , and SO_3 content. In addition, several other studies found EAF slag to have low pozzolanic reactivity but with less potential expansivity (Frías et al., 2002; Ramonich & Barra, 2001). The primary reason for the lower reactivity of EAF slag was excess presence of iron oxide and less calcium. In view of this, Kim et al. (2015) worked on modification of EAF slag. FeO was reduced using a two-stage reduction process that included an Al-dross reduction reaction followed by direct carbon reduction. Equation (8) represents the carbon reduction reaction of iron oxide at the second stage:



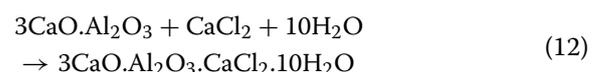
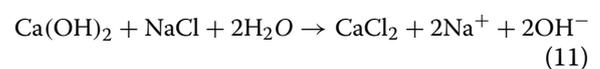
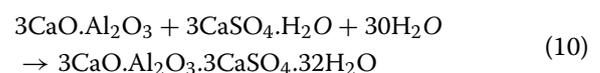
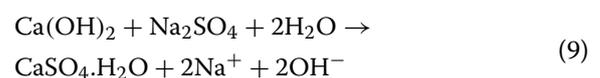
The reduction of FeO in EAF slag was done with rod, after two stages of the reduction the total Fe content in molten slag remained below 5% which is comparable with the composition of Fe in cement clinker composition. Hence produced EAF slag was used in cement applications. It was observed that after mixing with cement, the EAF slag resulted in the compressive strength comparable to the commercial GGBS based cement.

Bernardo et al. (2007) studied the utilization of EAF slag to replace limestone and clay in the mix proportion of raw feed for Portland clinker production. The ratio of $\text{CaO}/(\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3)$ was kept constant, and 20% application of EAF slag was achieved. The primary purpose of EAF application in this study was to utilize the noncarbonated calcium content of EAF slag for limestone replacement. However, besides EAF slag application as raw feed for Portland clinker manufacturing, it is also utilized as partial replacement material for cement in different cementitious applications. Lee et al., (2019) utilized EAF slag for the partial replacement of OPC in concrete application. The 15% substitution of OPC with EAF slag developed significant compressive strength and tensile strength in comparison with the control concrete. The early age strength remained a concern with EAF slag application as it developed 16% less compressive strength

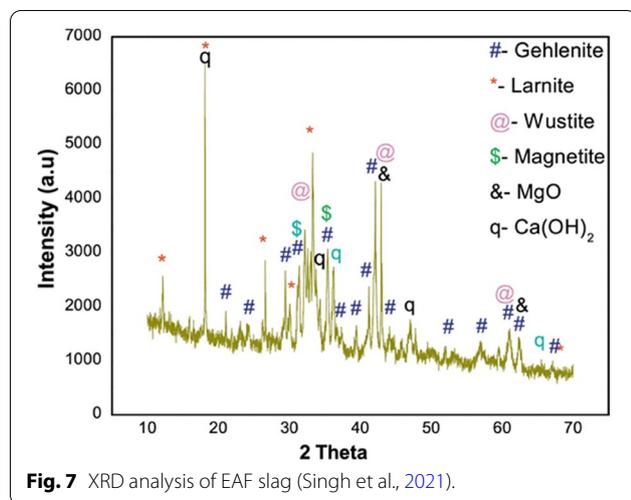
Table 5 LD slag application as a cementitious binder.

Ref	Treatment	Compressive strength (MPa @ Age (% to the Ref.))	Effect on other properties	Recommended limit of LD slag application	Remarks
Conjeaud et al., (1981)	Modification during generation process through 6–15% alumina addition	31 @ 7 (93.5%) 41 @ 28 (41.71%)	Quenching of LD slag—no impact on hydraulic properties	–	Free lime reduced to 4%
Dongxue et al., (1997)	As-received LD slag	38.1 @ 3 (2.97%) 50.2 @ 7 (0%) 66.2 @ 28 (– 4.19%)	Flexural strength—increased Porosity—increased	30%	Slight expansion with carbonate and sulfate resistance
Duda (1989)	NaOH treatment of ground LD slag	25 @ 7 (–34.21%) 45 @ 28 (– 18%) 68 @ 182 (1.49%)	Durability—negatively affected	30%	NaOH acts as an accelerator for hydraulic reactions of LD slags
Murphy et al., (1997)	Granulation of LD slag	@ 7 (–5%) @ 4 (30%) @ 35 (19%)	Not mentioned	20%	Quenching improved the hydration of LD slag
Zhang and Chen (2017)	Alkali activation of LD slag	30 @ 7 (–6.21%) 36 @ 14 (– 5.26%) 44 @ 28 (– 4.34%)	Setting time—increased	20%	Ettringite development responsible for early strength
Singh and Vashistha (2021)	Mechano-chemical activation: 20-min ball milling, then sodium silicate and sodium sulfate activation of LD slag	14.78 @ 3 (0.11%) 22.68 @ 7 (0.12%) 34.45 @ 28 (23.51%)	Slag activity index—increased with alkali activation of slag	30%	Free lime content reduced; slag activity index increased from 58 to 73%
Guo and Pan (2020)	Fly ash–slag based Geopolymer	15.0 @3 (130.77%) 21.7 @ 7 (60.74%) 42.0 @ 14(40%)	Flexural strength—increased	50%	Geopolymer mortar developed more strength than geopolymer paste
Zhu et al., (2021)	Steel slag–metakaolinite-based geopolymer	31 @3 (– 18.39%) 33@7 (– 24.7%) 38@ 28 (– 7.32%)	Flexural strength—decreased	10%	Slag contributed to the compressive strength improvement at a later age

in comparison with the control. However, concrete developed late strength almost similar to the control due to the presence of silica in EAF slag, which enhanced pozzolanic reactions. In addition, EAF did not cause shrinkage up to 15% application. However, this method of EAF slag application could not consume a bulk amount due to the nonreactivity of slag in its original form. Hence, to replace a bulk amount of OPC, treatment of EAF slag is needed. Cristelo et al. (2021) worked on an innovative hybrid cement based on the utilization of EAF slag, type F fly ash, and OPC. The one-part geopolymer was prepared with the combination of the mentioned materials and powder alkali elements, namely sodium sulfate and sodium chloride. The prepared geopolymer was tested for strength properties and microstructural properties. A blend of 50% EAF slag + 25% FA + 25% OPC was used to make paste hydrated with no activator included and with an alkali activator. The powder alkali activator increased the mechanical strength of the blend in comparison with the blend without an activator. Sodium sulfate and sodium chloride work as indicated in Eqs. (9) to (12):



Due to the presence of alkali activators and OPC in the binder, it is called “hybrid cement.” Regardless of whether the binder was hydrated with water or activators, the strength remained above 35 MPa after 28 days. In the case of hybrid cement, the first reaction happened between OPC phases and activators, which resulted in the development of calcium sulfate, Friedel’s salt, and



ettringite. Development of all these phases provided density to the matrix, which resulted in improved mechanical strength.

The researchers also used EAF slag for geopolymer applications due to availability of silica and alumina in its composition. Bignozzi et al. (2010) aim to investigate the impact of EAF slag in geopolymer system. The results of mechanical properties and microstructure analysis demonstrate that the optimal weight ratio of metakaolinite/EAF slag for use as starting material should be 40/60. Furthermore, the study concludes that EAF slag, when applied with metakaolinite, directly participates in the production of calcium rich aluminosilicate gels. Khater (2015), used EAF slag with GGBFS and cement kiln dust for geopolymer fabrication. It was concluded that EAF slag enhances mechanical strength of the paste with increasing curing time.

Different methods have been used with the aim of bulk utilization of EAF slag. As mentioned earlier, EAF slag has high iron oxide with less calcium and silica in its composition, so its bulk utilization as the replacement material for OPC is difficult. Fifteen percent replacement of OPC was achieved with the direct application of as-received EAF slag. The modification of EAF slag for better cementitious properties can only be achieved in the generation stage of the slag, which is dependent on the engineering tools and feasibility of the process in the steel industry. Thus, there is a possibility for the bulk utilization of EAF slag with the alkali activation method, but more research is needed for further optimization of the process parameters and sustainable application of EAF slag-based alkali-activated cement. Table 6 summarizes the effect of EAF slag application on compressive strength.

c) Application of LF slag as a cementitious binder

LF slag application as a cementitious binder has been studied predominantly due to the calcium aluminate content in the LF slag being high, which makes it more suitable for application in binder fabrication. Herrero et al. (2016) studied the effect of the high alumina content of LF slag on application as a cement replacement in masonry. The present research focuses mainly on the composition of the high-alumina slag and the reactivity of its compounds such as calcium aluminates, free calcium oxide, and free magnesium oxide when aged at room temperature and at water steam temperature (accelerated aging). Additionally, characterization was performed of pastes and masonry mortars that incorporate high-alumina LF slag as a supplementary cementing material in partial substitution of OPC in amounts of 10% and 20% by weight.

Murri et al. (2013) studied the thermal property of an LF slag and fly ash-based binder made through the chemical activation of both materials. The fly ash and LF slag-based materials displayed greater strength improvements and enhanced thermal stability in comparison with OPC. The alkali activation of LF slag and fly ash (two distinct kinds of waste materials) supports the advancement of an ecologically viable cement-type binder. Adolfsson (2011) characterized the mineralogical phases responsible for the cementitious properties of LF slag. The calcium aluminates and other phases were studied through XRD and crystallographic distribution of LF slag was quantified using Rietveld analysis. The LF slag-based mortar was prepared, and the blend was developed with 50% GGBS and 50% LF slag.

In their study, Wang and Yan (2010) concluded that most of the hydration of silicate and aluminate takes place up to 90 days of reaction and results in the production of gel due to the hydration outcome, producing the gel of C-S-H, C-S-Al-H, and Ca (OH)₂, whereas other phases such as Fe₃O₄, RO phase (continuous solid solution formed by MgO, FeO, and MnO), and C₂F hardly participated in the process of hydration due to their inactivity. The hydration outcome of the LF slag after 360 days is analyzed through its XRD pattern. Due to the amorphous nature of the gel, it is not reflected, which indicates the very small reaction magnitude of phases such as the RO phase, Fe₃O₄, and C₂F even after 360 days of hydration. Fig. 8 depicts the XRD of LF slag hydrated paste after 1, 2, 28, and 90 days.

The micro graphical analysis of the hydration products after 360 days, as illustrated in Fig. 9, is also in line with Wang et al. (2011). The RO phase is inlaid in the gel in non-hydrated form, which does not contribute to the strength properties of the slag. Adversely, it forms

a thin layer between the gel and RO particles due to its smoother surface and relatively bigger particle size. Ultimately, it plays a negative role in the strength properties of the gel.

During the hydration process, water consumed by the reaction to form hydration yields remains comparative to the non-evaporable water present in the product. C_3S and C_2S are the main cementitious constituents of the OPC and LF slag, with C–S–H gel and calcium hydroxide as their hydration products. Thus, it is possible to conduct a comparative study of non-evaporable water formed in both OPC and LF slag (Wang et al., 2011). The rate of hydration for LF slag compared with that of OPC also varies. OPC exhibits early age development of hydration products after which its hydration process slows down, whereas in the case of LF slag, early age development of hydration products is lower. In the combined application of LF slag and OPC as a complex binder, the hydration rate remains lower than that of OPC, and with the increase of LF slag in the complex binder, the hydration rate decreases further (Altun & Yilmaz, 2002). This effect of LF slag occurs because lime present in the slag is not ordinary lime and remains in the form of f-CaO. The conversion of lime to f-CaO happens due to over-burning

of lime during the steel production process. The hydration activity of the lime reduces significantly due to this phenomenon, which has an adverse effect on hydration rate and may take place even long after the hardening of cement paste. This causes cracking in the hardened cement paste due to the expansion of calcium hydroxide up to 1.98 times the volume of reactants. This is a noticeable reason for the bad durability of cement paste with LF slag (Monshi & Asgarani, 1999; Wang et al., 2011). The early age hydration of LF slag can be motivated by the action of mechanical grinding of the slag. The concept behind mechanical grinding is to make the particle size of slag finer through dislocation of the mineral crystal lattice, which can upsurge the interaction zone of the reaction between finer particles and water. As a result, it increases the early age hydration process (Wang & Yan, 2010). The increment in the specific surface area of slag particles is a feasible technique to speed up the hydration rate of steel slag. However, the consumption of intense energy is a drawback of this method.

Therefore, LF slag contributes to cementitious properties from the silicate phases (C_2S , C_3S) and aluminate phases ($C_{12}A$, $Ca_2Al_2Si_3O_{12}$), whereas the RO phases and f-CaO do not make any contribution to the cementitious

Table 6 EAF slag application as a cementitious binder.

Ref	Treatment	Compressive strength (MPa @ Age (% to the Ref.))	Effect on other properties	Recommended limit of EAF slag application	Remarks
Rojas and Rojas (2004)	As received	–	Expansion: presence of excessive free lime	–	Slight pozzolanic activity with high crystallinity
Bernardo et al., (2007)	Used as raw mix in clinker manufacturing	27.5 @ 2 days (10%) 46.80 @ 28 days (4%)	Initial setting time— not effected Final setting time— not effected	20%	Very low free lime in clinker
Lee et al.,(2019)	As-received EAF slag	26.8 @ 3 days (– 13.13%) 31.26 @ 7 days (– 16.14%) 37.93 @ 28 days (– 4.14%)	Slump—decreased Air content— decreased Tensile strength— increased	15%	EAF slag application did not show shrinkage
Cristelo and et al., (2021)	Alkali-activated EAF slag	36 @ 2 days (– 34.54%) 62 @ 28 days (– 11.42%)	Not mentioned	24–25%	EAF slag application with fly ash resulted in late age development
Kim et al., (2015)	Reduction of EAF slag	7.5 @ 3 days (– 6.5%) 12 @ 7 days (– 14.28%) 25 @ 28 days (– 4%)	Viscosity—decreased	50%	Reduction of slag improved the CaO/SiO ₂ ratio
Bignozzi et al., (2010)	EAS slag and MK-based geopolymer	48.2 @ 7 days	Workability—increased Flexural strength— Increased	60%	EAF slag combination with MK is strongly suggested
Khater (2015)	GGBFS, cement kiln dust and EAF slag-based alkali-activated geopolymer	12.5 @ 7 days (66.7%) 14.0 @ 28 days (27.27%) 22.0 @ 90 days (83.33%)	Not mentioned	50%	Use of EAF slag results in growth of amorphous content in N–A–S–H gel and the binding gels C–A–S–H

properties and ultimately the strength development of the slag-based cement paste. It should also be considered that the hydration degree of LF slag is significantly lower and slower than that of the OPC at an early age as well as a late age. Table 7 summarizes the effect of LF slag application as a cementitious binder.

5 Coal Bottom Ash (CBA)

5.1 Generation Process of CBA

CBA is a waste material generated from coal-fired thermal power plants. During the combustion process of the coal, the fine and light particles of coal ash escape along with hot combustion gases. Some of the ash is melted because the kiln temperature is higher than the melting point of fly ash, and it accumulates on the furnace wall, forming clinkers. As the clinkers grow over time, they fall to the bottom of the furnace and are called CBA. Whereas fly ash is commonly used as a commercial pozzolanic material, CBA has not been widely applied to the concrete industry as a binding material because of its low reactivity. Most CBA is disposed of in landfills or ponds, causing environmental problems (Abdulmatin et al., 2018). Because CBA is mainly composed of silica, alumina, and iron, it has been considered waste material feasible for concrete production.

5.2 Application of CBA as a Cementitious Material

The application of CBA as a cementitious material is based on the chemical components of CBA, which comply with the specifications of SCMs in ASTM C618 (ASTM Committee C-09 on Concrete and Concrete

Aggregates, 2013). The sum of SiO_2 , Al_2O_3 , and Fe is generally more than 75% by weight which reflects that CBA is expected to result in a pozzolanic reaction with OPC. Fig. 10 represents the XRD analysis of CBA. According to the minerology, quartz, mullite and calcite are the prominent phases present in the CBA.

Jaturapitakkul and Cheerarot (2003) ground CBA to enhance its pozzolanic reaction and compared its effect on the compressive strength of mortar with that of original CBA. The water demand for the same flow of mortar specimen increases as the amount of CBA increases because of the high porosity of CBA. However, the water demand decreases as the amount of ground CBA decreases because of its smoother surface compared with OPC. The 30% replacement of OPC by weight with ground CBA resulted in a higher compressive strength than the reference specimen after 90-day curing. It was inferred that the lower water demand and the pozzolanic reaction of CBA increased the compressive strength of the mortar. Kurama and Kaya (2008) pretreated CBA to remove some of the unburned carbon. Three methods of heavy medium separation, electrostatic separation, and crushing-screening were conducted. The crushing-screening method was the most effective in reducing the carbon content by 58%. The highest compressive strength at 56 days was achieved by the specimens in which 10% of OPC was replaced by CBA. The pozzolanic reaction of CBA was also confirmed by SEM observation. Abdulmatin et al. (2018) studied the effect of the fineness of CBA on compressive strength. Because the porosity of CBA was high, the finer CBA was able to reduce water

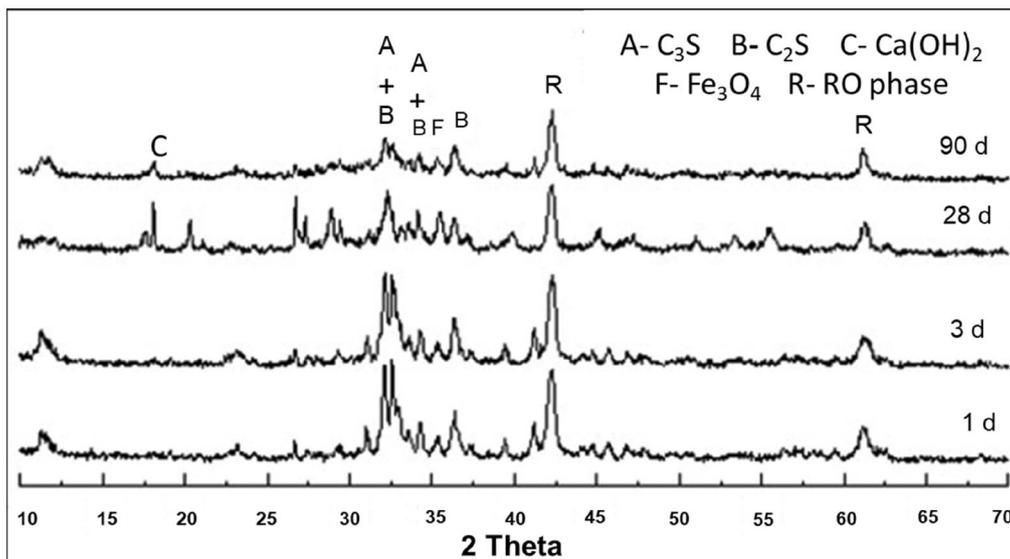


Fig. 8 XRD of LF slag hydrated paste after 1, 2, 28, and 90 days (Wang & Yan, 2010).

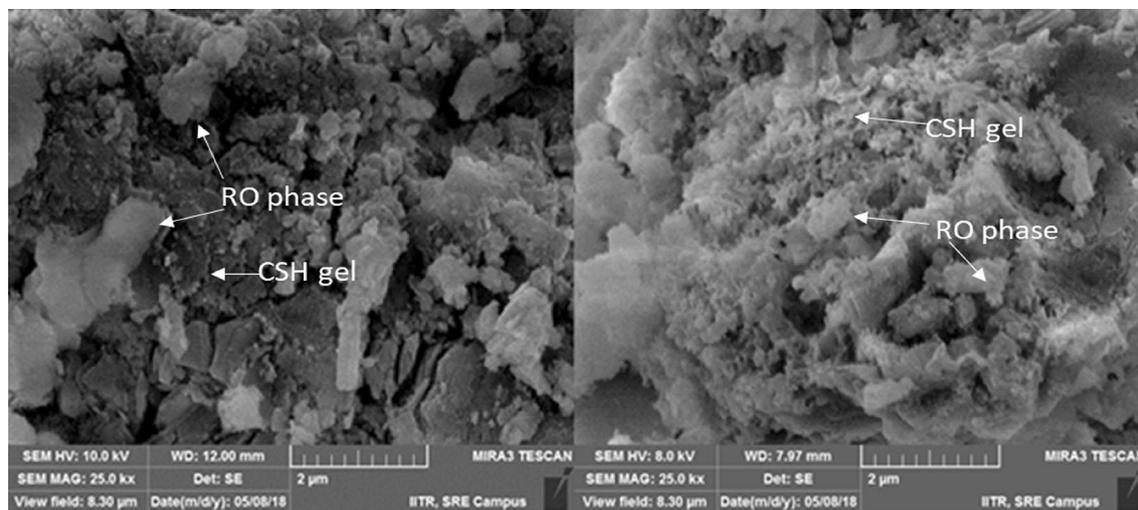


Fig. 9 SEM images of LF slag hydrated paste after 360 days (Wang et al., 2011).

demand. The smaller particle size also decreases the setting time. The highest compressive strength was achieved with the finest CBA, even higher than the reference without CBA. The benefit of CBA on the compressive strength was greater at a later age because of CBA's pozzolanic reaction. Targan et al. (2003) adopted the binary use of CBA and natural pozzolanic (NP) material of volcanic deposits. The binary usage of 10% CBA and 10% NP material increased the compressive strength; however, use of more than 10% NP material resulted in a lower compressive strength than the reference. The researchers insisted that NP material can enhance CBA activity, as the final setting time was accelerated. Wongkeo and Chaipanich (2010) examined the compressive strength of foamed mortar that incorporates CBA and silica fume. The foamed mortar was prepared using aluminum powder. The usage of CBA and silica fume decreased the porosity of the mortar and, thus, increased the density of the material. Therefore, the enhancement of the compressive strength can be affected by the decrease of the porosity. The increase of CSH and gehlenite hydrate with the CBA and silica fume was confirmed through TGA and SEM tests, which indicates the pozzolanic reaction of CBA. Aforementioned studies suggested that CBA can be a suitable material for its use as SCM. Although CBA decreases the early compressive strength, it can be beneficial to the compressive strength after 90-day curing, due to slow pozzolanic reactions. CBA's pozzolanic reaction is slow but produces extra CSH from the reaction with portlandite.

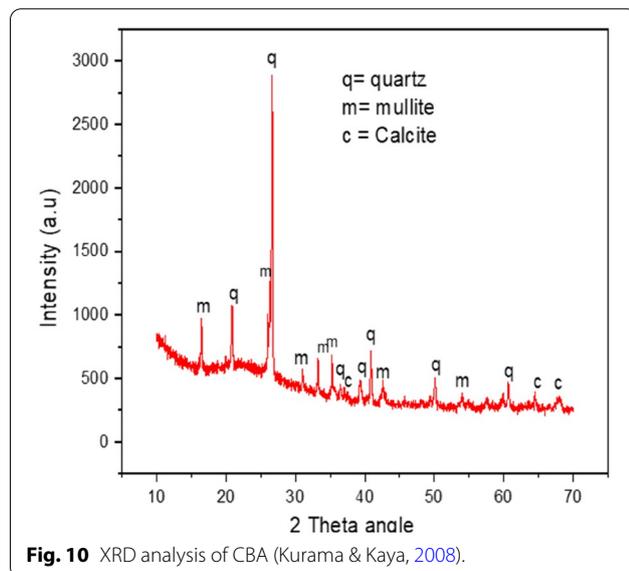
Several studies suggested that CBA also shows cementitious behavior even on its application for fine aggregate replacement. CBA application develops extra CSH

through pozzolanic reaction. Singh and Siddique (2015) found that 30% replacement of fine aggregates with CBA exhibited the highest compressive strength. The compressive strength at 7 days of the concrete with 30% CBA is lower than that of the reference, it became comparable at 28 days, and surpassed at 90 days. The higher compressive strength of the concrete with CBA than the reference specimen was attributed to the extra CSH formed by the pozzolanic reaction. Aggarwal and Siddique (2014) also concluded the pozzolanic effect of CBA as fine aggregate. The CBA was co-utilized with waste foundry to replace natural fine aggregates. The application of CBA and waste foundry reduced the compressive strength significantly up to 90 days, however, the compressive strength of the concrete specimens with CBA and waste foundry became comparable to the reference specimen at one-year age showing slightly higher values. The 30% replacement of fine aggregate with 15% of CBA and 15% of waste foundry resulted in the highest compressive strength. Rafiezonooz (2017) also observed the similar effect of CBA for slow pozzolanic reaction. CBA resulted in a lower compressive strength than reference specimen at early ages, but higher compressive strength after 90 days. Table 8 summarizes the effects of CBA application on compressive strength. CBA is applied as a fine aggregate, it still results in a pozzolanic reaction with cement, resulting in low early compressive strength and high late compressive strength.

CBA was also applied to geopolymer. Hosseini et al. (2021) pretreated the CBA by grinding it with fly ash and sodium silicate for one-part mixing. The grinding treatment enhanced the dissolution rate of fly ash and CBA intensifying the polymerization. However, higher

Table 7 LF slag application as a cementitious binder.

Ref	Treatment	Compressive strength (MPa @ Age (% to the Ref.))	Effect on other properties	Recommended limit of LF slag application	Remarks
Singh et al., (2015)	As-received LF slag	Not mentioned	Flowability—decreased	Not mentioned	Hydration behavior of the LF slag is similar to the cement
Herrero et al., (2016)	As received	15 @ 90 days (−1.87%) 14.6 @ 180 days (−19.78%) 14.4 @ 360 days (−20%)	Flexural strength—decreased	10%	Much less pozzolanic activity
Kim et al., (2015)	LF slag with MgO addition	15.8 @ 2 days (−7.2%) 32.4 @ 7 days (−10.5%) 45.8 @ 28 days (−12.2%)	Workability—decreased	30%	MgO addition improved the mechanical strength
Murri et al., (2013)	Thermo-chemical activation	27.5 @ 2 days (10%) 46.80 @ 28 days (4%)	Porosity—increased	20%	Very low free lime in clinker
Wang et al., (2011)	LF slag with nano-silica	Not mentioned	Amorphousness—increased at temperature more than 900 °C	25%	LF slag application with nano-silica improves the hydration behavior



water demand by CBA eventually lowered the compressive strength. Kumar and Revathi (2016) (2016) applied CBA into metakaolin-based geopolymer. The specimen with CBA exhibited a compressive strength remarkably higher than that of the reference without CBA. The study concluded that the binary usage of metakaolin and CBA can be a promising mix design, however, no concrete evidence of higher compressive strength with CBA was not presented. Therefore, the exact role of CBA in geopolymerization needs to be further examined.

6 Conclusion

Utilization of WCP, steel slags, and CBA has significant potential for application in fabrication of cementitious material. Based on the current review of investigations, the following conclusions were drawn:

- 1) The application of as-received WCP up to 30% replacement of OPC proved sustainable. However, WCP application above this proportion has adverse effects due to its poor binding properties and high water absorption. However, on thermo-chemical activation of WCP the proportion can be increased up to 70%. Alkali-activated WCPs exhibited a more rapid development of strength at an early age, whereas lime-activated WCPs showed a slower development of strength due to the formation of more CSHs and calcium aluminum hydrates. The thermal activation of WCP above 650 °C has degraded the CSH paste and reformed reactive compounds which have contributed to increased strength. The application of SCMs with WCP can prove to be more beneficial with the enhanced cementitious properties and decreased water demand. WCP lacks reactive silica and calcium in its composition; hence, addition of fly ash, silica fume, GGBS, and other SCMs is recommended for improvement of WCP application.
- 2) LD slag contains phases such as portlandite, dicalcium silicate, tricalcium silicate, and so on, which can contribute to cementitious properties. However, due to its crystalline nature, these phases are in non-reactive forms. It is recommended to use LD slag up to 30% application. Additionally, LD slag generation

Table 8 Effects of CBA application on compressive strength.

Refs.	Compressive strength (MPa @ Age (% to the Ref.))	Effect on other properties	W/C	application type	Recommended amount of CBA	Remarks
Jaturapitakkul and Cheerarot (2003)	18.5 @ 3 (− 19%) 25.4 @ 7 (− 17%) 38.3 @ 28 (− 6%) 53.1 @ 90 (12%)	Water requirement—increased	0.68	Mortar	30% of OPC	W/c ratio is different from the reference to produce the same flow
Kurama and Kaya (2008)	28.2 @ 7 (1.5%) 40.2 @ 28 (− 1.6%) 45.1 @ 56 (5.7%)	Flexural strength—decreased	0.5	Mortar	10% of OPC	Carbon particles in CBA were removed by submerging in alcohol
Abdulmatin et al., (2018)	21.1 @ 3 (− 11%) 28.0 @ 7 (− 7%) 40.9 @ 28 (2%) 49.8 @ 90 (6%)	Setting time—decreased Water demand—increased	0.65	Mortar	20% of OPC	Study on the effect of the fineness of CBA
Targan et al., (2003)	35.0 @ 7 (3%) 48.0 @ 28 (4.3%) 52.0 @ 90 (2.0%)	Setting time—increased	0.5	Mortar	10% of OPC	Natural pozzolan 5% of OPC
Wongkeo and Chaipanich (2010)	13.5 @ 7 (22.7%) 16.0 @ 28 (28%)	Permeable void—decreased Thermal conductivity—increased	0.29	Mortar	30% of OPC	5% of silica fume; foamed mortar with aluminum powder
Singh and Siddique (2015)	@ 90 (12.3%) @180 (2.2%)	Water absorption—increased Abrasion resistance—decreased	0.45	Concrete	30% of sand	Compressive strength improvement due to pozzolanic reaction of CBA
Aggarwal and Siddique (2014)	19.4 @ 7 (− 24.3%) 31.8 @ 28 (−12.3%) 37.4 @ 90 (− 14.9%) 42.7 @ 1y (3.9%)	Flexural strength—decreased	0.55	Concrete	15% of sand	Late age compressive strength development due to pozzolanic behavior of CBA
Rafieizonooz et al., (2016)	16.3 @ 7 (− 18.6%) 26.3 @ 28 (− 15.1%) 35.1 @ 90 (0.2%)	Workability—decreased Drying shrinkage—decreased	0.55	Mortar	50% of sand	CBA affects the compressive strength at later age
Hosseini et al., (2021)	65 @ 7 (− 33.7%)	Water demand—increased	0.34	Geopolymer	50% of Fly ash	CBA, fly ash, and sodium silicate were ground together for one-part mixing
Kumar and Revathi (2016)	35 @ 1 (700%) 57 @ 3 (612.5%) 60 @ 7 (215.8%) 75 @ 28(114.3%)	Not mentioned	0.48	Geopolymer mortar	50% of metakaolin	CBA was ground and its specific surface area was 3460 cm ² /g

process should be regulated to obtain its reactive phases for bulk utilization.

- 3) Iron oxide dominates EAF slag's composition, so it is difficult to use in bulk as an OPC replacement material due to its low calcium and silica content. Direct application of as-received EAF slag could only replace 15% of OPC. The formation of calcium sulfate, Friedel's salt, and ettringite can increase the application of EAF slag by up to 50% when NaCl and Na₂SO₄ are used.
- 4) LF slag contributes cementitious properties from the silicate phases (C₂S, C₃S) and aluminate phases (C₁₂A, Ca₂Al₂Si₃O₁₂). With LF slag, 25% to 50% replacement of OPC is possible; however, free lime is a concern with LF slag. Cracks can appear in con-

crete prepared with LF slag due to the late hydration of lime.

- 5) CBA can be used as cementitious material on the basis of its chemical components. The sum of SiO₂, Al₂O₃, and Fe is generally more than 75% in its composition. Although CBA decreases the early compressive strength, it can be beneficial to the compressive strength after 90-day curing. The pozzolanic reaction of CBA is slow, but it produces extra CSH from the reaction with portlandite.

Based on the assessment, it also stated that more research is required before these wastes may be used commercially in cementitious binder synthesis. In the case of WCP, more research is needed to improve the

typical WCP activation method. Future research should look into the changes in the chemistry of activated WCP. In addition, the current study recommends that a long-term combination of chemical and thermal activation WCP be used. Steel slags include free lime; hence the late age effect of slags must be well investigated. The use of LD slag, EAF slag, and LF slag in UHPC and other types of concrete is a possibility in the future. The use of CBA as a cementitious binder should also be investigated further. Because CBA has a smaller surface area, it is ineffective as a binding material. As a result, more study is needed to improve CBA's reactivity. This research provides a holistic insight on binder fabrication from WCP, steel slag, and CBA. Therefore, the authors believe this paper can provide a single document to serve as a reference and potential guide for those who produce industrial waste and for those looking to utilize the waste materials for cementitious material with less clinker factor. Not only will the use of these materials save natural resources, but it will also assist to reduce landfilling difficulties and encourage cleaner production by lowering carbon emissions.

Acknowledgements

Not applicable.

Author contributions

PV: conceptualization, methodology, investigation, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization; SPark: methodology, investigation, validation, formal analysis, data curation, writing—original draft preparation, writing—review and editing; SPyo: writing—review and editing, resources, supervision, project administration, funding acquisition; All authors read and approved the final manuscript.

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Funding

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (Nos. 2021H1D3A2A02041471 and 2021R1A4A1030867).

Availability of data and materials

The data and materials are included in the manuscript.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no conflicts of competing interest.

Received: 3 March 2022 Accepted: 19 June 2022

Published online: 27 September 2022

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