Utilization of industrial and agricultural by-products in blended cement mortars – creating an effort of circular economy in Indian cement industry

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Abstract
India stands in second place as a manufacturer of cement in the world, accounting for over 8 % of the worldwide mounted capacity until the end of the year 2018. It is estimated that the production of the cement will touch 550 Mt by the year 2020 and will reach more than 600 Mt by 2025. Up to the year 2015, the total emissions of CO_2 from cement sector in India have touched the level of around 150 Mt in comparison to an amount of 52 Mt emitted in the year 2013. This amount of generation has been projected to increase by 9 %–10 % annually up to the year 2025. The boosting demand for construction activities results in incessant growth of the sector along with alarming environmental consequences and non-sustainability in the cement industry. Utilization of the various industrial and agricultural by-products as an alternative form of binder in the cement can reduce the perilous environmental impacts and their practice will further offer an auxiliary solution in fetching the concept of circular economy in the surging cement industry. Blended types of cement made up of industrial and agricultural by-products can successfully replace the limestone-based clinkers. The adoption of such practice could offer a significant reduction in CO_2 emissions approximately by 20 %. On the other hand, the abundant generation and the efficient utilization of industrial and agricultural wastes primarily having binder qualities similar to that of cement has set up a new challenge in the construction industry. Next to a review of industrial and agricultural clinker substitutes, this contribution estimates the impact of these clinker substitutes on CO_2 reduction in the Indian cement industry up to 2050.

Introduction
The rapid increase in the concentration of CO_2 has fastened the process of global warming on this planet. Cement production has austere impacts as it accounts for 2.4 % of the global CO_2 emissions and is therefore considered as a major source of global CO_2 (Marland et al. 1989). India is already the second-largest manufacturer of cement and it might produce 600 million tonnes of cement by 2025 and 1,500 Million tonnes by 2050 ("Cement" 2011). Recently, the Indian government has declared its target of dropping its greenhouse gas emission intensities by 20 %–25 % per ton of cement by 2030 compared to 2010 (CII 2010). But energy-efficiency improvements in the cement industry can decrease CO_2 emissions by a maximum of 18-20% (CII 2010). Reaching deep decarbonisation requires joint efforts by government agencies and privately owned cement sector.

Since the last decade, the Indian cement industry has been incessantly promoting and increasing the share of blended cement. Today, India already manufactures blended cement, but given the CO_2 reduction targets as well as the large amounts of industrial and agricultural wastes, it is aimed to manufacture blended cement with higher contents of industrial and agricultural wastes/by-products. Up to the end of the year 2015, blended cement holds a share of 65 %–70 %. Their production share has increased to 73 %–75 % in 2016 and 2017 (World Business Council for Sustainable Development 2018). Thus, the clinker factor has been decreased from 0.74 (in the year 2010) to 0.71 (in the year 2017) signifying the upgrading of the Indian cement industry (World Business Council for Sustainable Development 2018). Also, the cement industry is projected to further benefit due to infrastructure and construction needs (IBEF 2020; Burange and Yamini 2009). Developing blended types of cement confirms the drop in energy consumption, utilization of industrial and agricultural wastes, conservation of natural assets and a drop in CO_2 emissions. For the past three decades, conventional cement additions such as Fly ash (FA), Coal bottom ash (CBA), Ground-granulated blast furnace slags (GGBS) and Copper slag (CS) are vastly used as performance enhancers in the cement construction industry.

CEMENT AND CO_2 EMISSIONS

Cement is a binding material commonly used worldwide for civil engineering constructions. It is a finely ground material comprising of lime (CaO), silica (SiO_2) and alumina (Al_2O_3), which turns into a hard mass after mixing with water. Setting and hardening of cement are outcomes of the hydration process that yields gel-like formations with increased surface area (Calcium-Silica-Hydrate, CSH, and Calcium Aluminate Hydrate, CAH).

The Indian cement industry is targeting to condense its CO_2 emissions by around 0.35 tonnes of CO_2 per t of cement in 2050 (World Business Council for Sustainable Development 2018). Adoption of low-carbon technologies, in the Indian Cement industry like the implementation of Carbon Capture and Usage and Storage (CCUS) at the production of blended types of cement by end of 2050 could save up to 212 Million Tonnes CO_2 emissions (World Business Council for Sustainable Development 2018; WCA 2018). The blended types of cement are preferred options over the conventional cement for the past few decades in which clinker is generally altered with pozzolanic material(s)[1].

CO_2 is released as a by-product of the chemical process known as pyro-processing that is used for the production of clinkers, which are small nodules and charred products and usually emerged from the kilns after burning of ground calcareous and argillaceous raw materials (limestone and clay) at temperatures of 1,350–1,550 °C. The fuel used for firing can be any of pulverized coal/oil/natural gas etc., which further add to the CO_2 emissions. The foremost share of the CO_2 emission from the cement industry comes from clinker production. Therefore, the amount of clinker mixed in each ton of cement is an important factor that drives CO_2 emissions from the cement industry. Further, the formation of clinker involves various processes like heating, calcining and sintering of raw materials and these processes turn cement manufacturing as the third largest cause of manmade CO_2 emissions ("Clinker Replacement Climate Technology Centre & Network" n.d.). Cementitious materials like industrial and agricultural by-products are generally considered as the preferable alternatives of the clinkers.

AVAILABLE BY-PRODUCTS

In an estimation, 1,340 Million tonnes of coal are required up to the year 2030 for fulfilling the electricity demands of India and this will lead to an annual generation of around 536 Mt to 603 Mt of coal combustion products (CCP's) which are mainly fly ash and coal bottom ash ("Fly Ash Utilisation" n.d.). Out of this quantity, the fly ash consumption will be around 310 Million tonnes by 2030 while the remaining amount will be left as unused ("Fly Ash Utilisation" n.d.). Likewise, the generation of coal bottom ash will increase by three-four times to the current annual generation of 20 Million Tonnes approximately (M. Singh and Siddique 2014; CEA New Delhi 2018; N. Singh, Mithulraj, and Arya 2018; N. Singh, Kumar, and Goyal 2019). An additional area of around 2,300 hectares and approximately 1.3 billion cubic meters of water are required for sound management/disposal of coal combustion products. Currently, more than 64 % out of a total generation of fly ash (in 2016-17) has been succefully utilized in various sectors like manufacturing of different types of concrete and concrete products, bricks, fire-proof products, road and embankment construction, pavement constructions as well as embankment constructions etc. while there are no reliable figures available for the effective use of coal bottom ash up to the end of the year 2018–19 (CEA New Delhi 2018). Apart from fly ash (IS 3812-1981) and ground granulated blast furnace slag (IS 16714-2018), no provisions/guidelines have been prepared or recommended by Indian standards for blended cement. Based on the codal recommendations, the effective incorporation of fly ash/ground granulated blast furnace slag as a replacement of clinker in the manufacturing of blended cement can save CO_2 emissions maximum up to 40 % depending upon the percentage content of fly ash/ground granulated blast furnace slag. Further, it has been estimated that in year 2019, India has generated about 107 Million Tonnes of steel resulting in production of 22 MT of blast furnace slag that is left untreated (World Steel Association 2019; Indian Minerals Yearbook 2017). It is worthwhile to mention that the aforesaid estimates are based on existing use and future predictions up to a maximum of the year 2040–50 as the Indian power sector is highly dependant on the use of non-renewable sources for upcoming three decades (Thambi, Bhattacharya, and Fricko, n.d.).

On the other hand, agricultural wastes are generated from various pre- and post-agricultural operations. Most of the agricultural wastes are bio-degradable but generally turned into hazardous forms after post-management treatments. The burning of agricultural wastes is the most adopted option for managing the huge quantum of agricultural wastes (Nagendran 2011). The Indian Ministry of New and Renewable Energy reported in the year 2016, that India produces approximately 500 Million tonnes of crop residue every year (Jabrinder Singh 2018). India ranks second in rice-producing countries after China in the world and generates about 155 Million Tonnes of rice annually (Munshi and Sharma 2016). Around one-fourth of the total

1. Pozzolans are finely divided materials that fall under the broad class of silica and aluminium materials which, in themselves, have little or no cementitious values. However, on reacting with calcium hydroxide in the presence of water at ordinary temperatures, these pozzolans result in additional compounds having cementitious properties. Such pozzolans do not require the pyro-processing and can be directly added as cement replacement in making mortars and concrete. Additional calcium silicate hydrate gels are formed due to the presence of pozzolans which further enhance the overall properties of mortars/concretes (Chung 2017). Industrial waste like fly ash, coal bottom ash, blast furnace slag, etc. along with agricultural wastes like rice husk ash, sugarcane bagasse ash shows this pozzolanic behavior and result in achieving three-way benefits of solid waste management, reducing clinker-to-cement ratio and lowering the emissions from cement industry and leading towards overall decarburization of cement manufacturing. Blended cement provides flexibility for altering the behavior of conventional cement, which enables the efficient performance of these blended cements under different conditions. Blended cement preferred over conventional cement due to advantages like i) attaining sustainability while conserving natural resources and ii) disposal concerns of industrial and agricultural wastes.

residue produced in India comes from the rice-wheat system. Up to the year 2017, cereal crops contribute almost 70 % of the total crop residue, which is nearly 352 Million tonnes comprising 34 % by rice crop only. Out of 82 Million Tonnes of surplus residue, nearly 43 Million tonnes of rice straws are burnt annually. The Centre for Sustainable Agriculture reported that the burning of one tonne of straw releases 1,460 kg of CO_2 along with other harmful gases in the air (Kaur 2017). The other major forms of agricultural by-products generated from sugarcane and corncob crops are sugarcane bagasse ash and corncob ash (Pappu, Saxena, and Asolekar 2007). The record shows an estimated amount of 785 Million tonnes of corn cob ash (CCA) as global production per year around the world (Rashad 2016; Kumar, Upadhyaya, and Negi 2010).

It has been revealed that rice straw ash, sugarcane bagasse ash, and corncob ash comply with the requirements of ASTM Class N, F, and C as pozzolans (Wang and Wu 2013). Burning the agricultural residues generates 140 Million tonnes of ashes (rice husk ash, corncob ash, sugarcane bagasse ash) out of the total weight (500 Mt) of residues (rice husk straw, corncob, and sugarcane bagasse). This amount of ashes could be accounted as the bottom line since the predicted population growth will increase the overall demand for crops in the future. As the northern part of India generates more than 70 % of the total food crops for the country, it generates about the corresponding amount of agricultural residues as well. Therefore, the transport of these agricultural wastes is more demanding compared to industrial wastes since the sources are widely scattered. The prime challenge in substitution of cement from alternative sources depends upon the availability of the material close to the cement plants. Longer transportation of ashes from industries to batching plants will also result in the emission of CO_2. Resulting emission factor due to transportation also limits the use of these waste into the cement industry (Jamora et al. 2020).

For net emission reduction, determination of the critical distance is required to maintain transportation emission lesser than the potential reducible CO_2 emissions. Transport emission factors for countries like Australia and Philippines range from 0.209–0.2516 kg/$CO_{2,eq}$/ton-km (Jamora et al. 2020; O'Brien, Ménaché, and O'Moore 2009). Previous studies conclude the maximum transported distance ranging from 833–3,800 km (Panesar, Kanraj, and Abualrous 2019; Jamora et al. 2020; O'Brien, Ménaché, and O'Moore 2009). Based on the same assumptions projections can be considered in the current investigation. It is worthwhile to mention that, the ashes distribution in India is generally not considered as a major concern as around 70 % of the total land is under cultivation of various kinds of crops with the easy proximity of regional cement, mortar and concrete sectors. Hence, in this study CO_2 emissions through the transportation is neglected.

PROMOTION OF CIRCULAR ECONOMY IN CEMENT/MORTAR INDUSTRY

The cement and mortar industry can contribute to conserving natural resources by using alternative materials generated from industrial and agricultural wastes and can become an integrant part of the circular economy. The substitution of clinkers with alternative constituents is an option for achieving sustainability in this industry. The reduction of clinker in blended cements relies on the availability of cement additions. The approach of the circular economy comes into picture in the form of using available by-products in blended cement and mortars during its manufacturing. Alteration of some amount of clinker with either industrial or agricultural by-products leads directly towards the implementation of circular economy in the Indian cement and mortar industry. In 2000, the Bureau of Indian Standards recommended the use of fly ash between 15 %–35 % by weight of cement. In the same year, similar recommendations have been made for the use of ground granulated blast furnace slag as a substitute for clinker. The trend of manufacturing blended cement has initiated merely two decades earlier. Correspondingly, it has gained its acceptance due to strict mandates and regulations imposed by the Indian Government. This initiative has significantly pushed the Indian cement, mortar and concrete industry towards the concept of circular economy ("ACC – Cement User Guide | Concrete | Cement" n.d.). The current proposal is also an effort for identifying the economic applicability and viability of the utilization of industrial and agricultural by-products in blended mortars and concretes for supporting the circular economy initiative.

This contribution evaluates the CO_2 intensities of different blended types of cement that use either industrial or agricultural wastes. While information is available for some industrial wastes based cements and concretes, there is less literature available on the CO_2 emission reduction from blending cement with agricultural wastes. To overcome this observed gap, this contribution focuses on the performance of the blended mortars based on agricultural wastes and compares the results with cement blended with industrial wastes. Herein, a generalized approach has been adopted for estimating CO_2 emissions reductions for such blended mortars satisfying the parental need (i.e. compressive strength) regardless of any environmental constraints.

Table 1. Ash generation from various crop residuals in India.

Crop Name	Crop Residue (Mt)*	Ash Generation (Mt)*
Rice	170	42.5
Sugarcane	12 (Crop residue)	3 (crop residue) 17.5 (Bagasse burning)
Maize	61	15.25
Wheat	68	17
Millets	41	7
Others (Fibres, oilseeds, pulses)	148	37
Total	**500**	**139.25**

** Jabrinder Singh 2018; NPMCR Govt. of India 2014.*

This paper sheds some light on the impact of industrial and agricultural wastes as clinker substitutes on the compressive strengths of blended mortars and estimates the resulting CO_2 reductions compared to conventional mortar mix made with Portland cement.

Materials and Methods

CEMENT AND NATURAL FINE AGGREGATES

Portland cement of 43 grade has been used during the entire experimental program. Natural river-based sand was used during the experimental program with a maximum particle size of 4.75 mm. The natural fine aggregates (NFA) were procured from the regional quarry (Pathankot, India) complying with the relevant standards (ASTM C136 / C136M – 19 2019; ASTM C128 – 15 2015).

CEMENT ADDITIONS

Industrial By-Products

Fly ash was obtained from the coal-based thermal power plant in Ropar, Punjab. Coal bottom ash was also procured from the same power plant. Ground granulated blast furnace slag was brought in raw form from the integrated steel plant Mandi Gobindgarh, Punjab. The chemical properties of fly ash (FA), coal bottom ash (CBA), copper slag (CS), and ground granulated blast furnace slag (GGBS) are summarized in Table 2 (N. Singh, Shehnazdeep, and Bhardwaj 2020; N. Singh, M, and Arya 2019).

Agricultural By-Products

The sugarcane bagasse ash (SCBA) used for this investigation was obtained from sugar mill waste situated in Bhogpur, Punjab India. The Rice husk ash (RHA) used for this investigation was obtained from rice mill situated in Bhidhipur, Punjab. The Corncob ash (CCA) was prepared in the laboratory by burning the corncob, with incinerating temperature not exceeding 700 °C (Michael 2016). Collectively, all types of ashes i.e., RHA, SCBA, and CCA were sieved through 90-micron sieve. The chemical properties of rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA) are also summarized in Table 2 (Verma et al. 2015; Mutua, Nyomboi, and Mutuku 2016; Cheah and Ramli 2011; Michael 2016).

MIX DETAILS AND PROPORTIONS

Two different groups of mortar mixes were prepared for the current investigation wherein the first group was prepared for structural grades of mortars while the second group was prepared for non-structural grades. As per the literature, mortar mixes based on industrial wastes results in higher strengths compared to agricultural wastes based mortar mixes. Therefore, higher percentage replacement levels were selected for the industrial wastes based mixes while lower replacement levels were selected for agricultural wastes based mixes. In both groups, the gradation curves were matched and were prepared for a constant water/binder ratio of 0.4 for industrial wastes and of 0.45 for agricultural wastes. All the mortar mixes were designed for a fixed flow range of 105–115 mm. The binder content of industrial and agricultural wastes based mortar mixes was kept as 575 kg/m^3 and 563 kg/m^3 respectively for compressive strength tests along with water/binder ratio of 0.40 (ASTM C109/C109M 2016). A total number of four mortar mixes containing 20 % replacement levels of PC by weight with FA, CBA, and GGBS with PC were prepared. For all mortar mixes the level of replacement level was kept at 20 % which is found to be optimum from previous studies (Feng et al. 2019; Hu et al. 2017; Korde et al. 2018; Mapa, T., and Murthy 2015; Mohan and Mini 2018; Jagmeet Singh and Singh, n.d.; Jagmeet Singh, Singh, and Kaur 2016). The summary of the various cement mortars along with the replacement levels and notations are described in Table 3. The specimens were prepared by relevant ASTM codes of practice (ASTM C109/C109M 2016). The water/binder ratio of 0.40 and 0.45 has been maintained for industrial and agricultural wastes based mortars respectively during the entire experimental program. All the blended mortar mixes were prepared by manual mixing.

The details of the blended mortar mix proportion containing the different agricultural wastes are also presented in Table 3. Portland cement was replaced by agricultural-by-products (RHA/SCBA/CCA) at the rate of 5 %, 10 % and 15 % by weight. The percentage of replacement dosages were adopted on the ground of earlier available studies. For estimation of freshly made blended mortars flow test was conducted before the casing of specimens for compressive strength tests.

EXPERIMENTAL PROGRAM

The evaluation of mechanical strength is the leading deciding factor for depicting the performance of any of the mortar irrespective of environmental constraints.On the other hand, the estimation of durability aspects confirms the long-term serviceability of blended mortars exposed to special environmental exposures. Herein, a generalized approach has been adopted for estimating CO_2 emissions reductions for such blended mortars satisfying the parental need (compressive strength) regardless of any environmental exposures.

Compressive strength tests

This test covers the determination of the compressive strength of cement mortars, using 50 mm × 50 mm × 50 mm cubical specimens following(ASTM C109/C109M 2016). Manual mixing was adopted for preparing the different mortar mixes. The cubes were casted and kept in steel molds in temperature-controlled curing tanks with 27 °C ±2 ° for 24 hours. Then they were de-molded. Two curing periods of 7 days and 28 days were selected for performing the preceding tests.

CALCULATIONS OF CO_2 EMISSIONS

The production of one ton of Portland cement emits 0.55 tons of CO_2 through the calcination of limestone and emits further 0.39 tons of CO_2 through the fuel consumption for generating heat for burning and grinding. This results in a total of 0.94 tons of CO_2 per ton of cement (Deshpande, Kulkarni, and Patil 2011; Lo, Tang, and Nadeem 2008). Herein, considering all parameters (collection of raw material, processing, manufacturing and transportation) and for ease in calculations, the production of one ton of cement congruently produces one ton of CO_2 in environment ("Emissions from the Cement Industry" n.d.). The current estimation has adopted a similar pattern for calculation of CO_2 emissions for the designed industrial and agricultural wastes-based mortar mixes.

Table 2. Chemical composition of industrial and agricultural wastes in relative to PC.

Compounds		Industrial Wastes*				Agricultural Wastes**		
	PC (%)	FA (%)	CBA (%)	CS (%)	GGBS (%)	RHA (%)	SCBA (%)	CCA (%)
SiO_2	20.1	56.50	57.76	39.41	34.06	93.15	61.59	66.38
Al_2O_3	6.80	17.70	21.58	2.84	18.8	0.21	5.92	7.48
Fe_2O_3	4.30	11	8.56	53.45	0.7	0.21	7.36	4.44
CaO	61.3	3.20	1.58	5.61	32.4	0.41	5.0	11.57
MgO	2.6	5.40	1.19	2.63	10.75	0.45	1.17	2.06

* *N. Singh, Shehnazdeep, and Bhardwaj 2020; N. Singh, Mithulraj, and Arya 2019.*

** *Verma et al. 2015; Mutua, Nyombi, and Mutuku 2016; Cheah and Ramli 2011; Michael 2016.*

Table 3. Details of blended mortar mixes containing different proportions of industrial and agricultural wastes.

Designation	Mix proportions for industrial waste based mortars				Mix proportions for agricultural waste-based mortars									
	Kg/m³ (cement to sand ratio of 1:2.75; W/C 0.40)				Kg/m³ (cement to sand ratio of 1:2.75; W/C 0.45)									
	20 % replacement				RHA at 5, 10, and 15 % replacement				SCBA at 5, 10, and 15 % replacement			CCA at 5, 10, and 15 % replacement		
	C-0	CFA-20	CCBA-20	CGGBS-20	C-0	CRHA-5	CRHA-10	CRHA-15	CSCBA-5	CSCBA-10	CSCBA-15	CCCA-5	CCCA-10	CCCA-15
PC	575	460	460	460	563	535	507	479	535	507	479	535	507	479
Replacement content	0	87	96	104	0	18.5	37.5	56.5	18	36	54	19	38	57
Sand	1,627	1,627	1,627	1,627	1,592	1,592	1,592	1,592	1,592	1,592	1,592	1,592	1,592	1,592
Water	226	226	226	226	253	253	253	253	253	253	253	253	253	253
Superplasticizer	14.3	12.3	10.3	5.6	2.3	11	13.5	16	2.8	3.8	7.5	3.4	4.9	10.5

Results and Discussions

COMPRESSIVE STRENGTH TESTS RESULTS

Industrial wastes-based mortars

In the blended mortar mixes, the effect of replacement of Portland cement with cement additions (Fly ash/coal bottom ash/ground granulated blast furnace slag) on the compressive strength has been evaluated. The noticed variation in the compressive strength of the blended mortars on account of the variation of aforesaid cement additions has been quantified. Thereafter, the effectiveness of cement additions in terms of compressive strength has been discussed. Figure-1 describes the results of the compressive strength tests conducted on the blended mortar mixes made with Fly ash/coal bottom ash/ground granulated blast furnace slag as a replacement of Portland cement at various exposure periods. A complex behavior has been noticed for the results of the compressive strength tests conducted on the blended mortars. The compressive strength of blended mortar mixes containing 20 % of fly ash (CFA-20) has been observed to be higher than that of the control masonry mix at all curing periods. A marginal increase of an order of 5.5 %, 2.4 %, 2 % has been observed after curing the age of 7, 28 and 56 days of curing on in comparison to control mix C-0. Furthermore, the compressive strength has been decreased marginally up to 5 % for the mortar mix CCBA-20 after a curing period of 56 days compared to that of control mortar mix C-0. The compressive strength values of the mortar mix CGGBS-20 are better than that of control mortar mix C-0 after a higher curing period (>28 days) despite initial reduction at 7 days of curing. However, the compressive strength of all mortar mixes has increased with the curing period due to pozzolanic behavior, refinement of pore structure, the formation of additional strength imparting hydration products such as C-S-H, etc. The noticed behavior is similar to that of mortar mixes made with and without incorporation of cement additions as replacement of Portland cement (Wongkeo, Thongsanitgarn, and Chaipanich 2012; Naganathan et al. 2016; Menendez et al. 2014; Cheng 2012).

Agricultural wastes-based mortars

As explained earlier that the current study is a part of larger investigation in which estimation of CO_2 emissions and utilization of industrial wastes and agricultural wastes in blended mortars are studied independently. In general, blended mortar/concrete mixes gain more than 90 % of the total strength after curing period of 28 days while marginal increments up to 2 %–3 % have been noticed after 56 days of curing. Therefore, for the same reason at least the results up to 28 days of curing have been reported in the current manuscript for both groups of blended mortars. Herein, it worthwhile to mention that the mutual comparison of two independent groups (in-

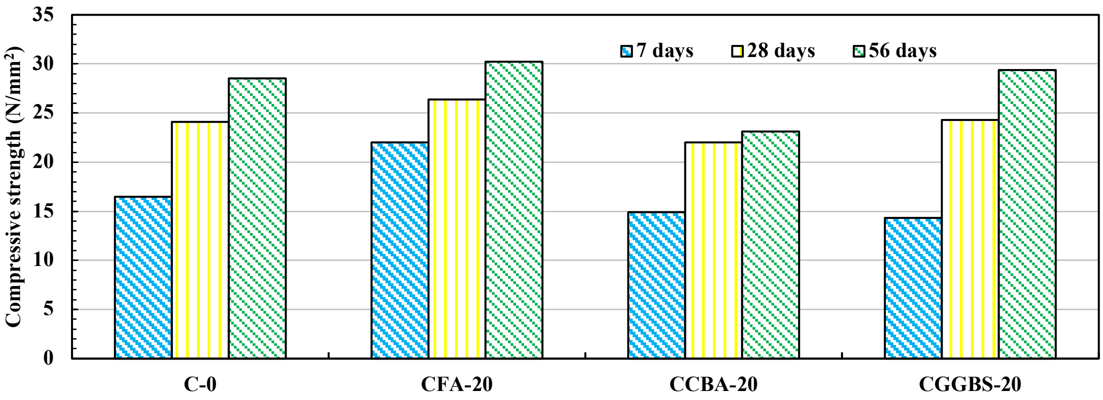

Figure 1. Compressive strength tests result for blended mortars containing industrial wastes.

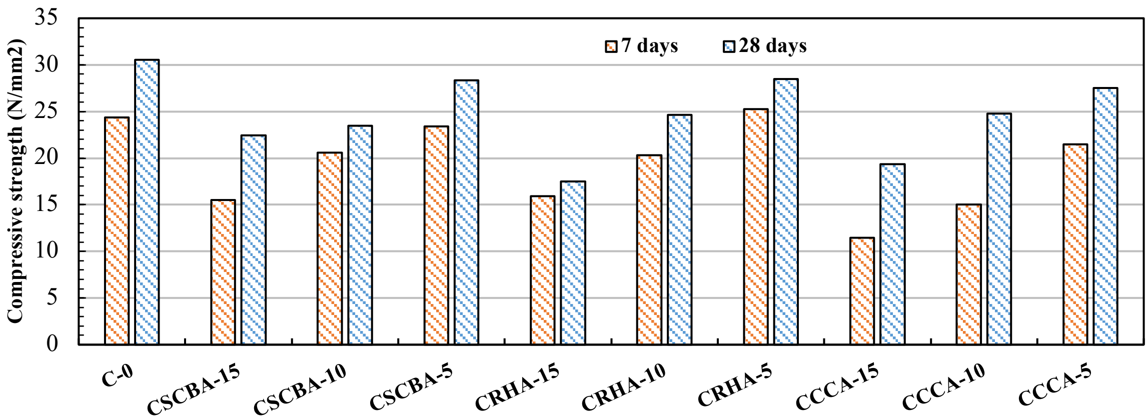

Figure 2. Compressive strength tests result for blended mortars containing agricultural waste.

dustrial wastes and agricultural wastes) is not the objective of the current investigation, rather in each group the blended mortar mixes were compared with their own control mortar mix only. The blended mortar mixes of different replacement levels made with agricultural wastes as shown in Table 2 were tested for the compressive strength tests at various curing ages. Figure 2 presents the summarized results of the compressive strength tests conducted after 7 days and 28 days. The test results revealed that with an increase in percentage replacement of agricultural wastes (rice husk ash/sugarcane bagasse ash/ corncob ash) the compressive strength of masonry mortars has been decreased compared to control mortar mix. The compressive strength test results indicate that rice husk ash-based mortar mixes have the highest compressive strength values followed by sugarcane bagasse ash and corncob ash-based mortar mixes. Hence, the following sequence has been suggested for the blended mortars based on the compressive strength test results: CRHA>CSCBA>CCCA. Rice husk ash-based mixes results in the best performance in terms of compressive strength tests results as compared to other agricultural wastes. It has been observed that an increment of around 4 % in compressive strength has been noticed for mortar mix CRHA5 after 7 days of curing. For the same mix, at 28 days the compressive strength has been decreased by 6 % in comparison to control mortar mix C0. For mortar mix CRHA10 the compressive strength values were found to be decreased by around 16 % for 7 days curing and 23 % for 28 days curing, while for CRHA15 a significant decrease of about 34 % and 42 % for the same curing periods have been observed in comparison to control mix C0 respectively. Similar findings have verified the observed trends of the current investigation where a higher percentage of rice husk ash content, lowers the compressive strength at an early age (Ai-khalaf and Yousift 1984). However, the presence of rice husk ash for higher curing periods results in a significant increase in compressive strength compared to that of the control mix (Fapohunda, Akinbile, and Shittu 2017).

All sugarcane bagasse ash-based blended mortars resulted in lower compressive strength values compared to control mortar mix C0 at all curing periods. A marginal decrease of around 4 % and 7 % have been noticed for the mortar mix CSCBA5 compared to control mix C0 at 7 days and 28 days of curing periods respectively. The maximum decrease in compressive strength values was noticed up to 36 % for the mortar mix CSCBA15 after 7 days of curing compared to that of the control mortar mix. Further, significant drops in compressive strength were noticed for the blended mortars containing 15 % of SCBA wherein the strength has been reduced up to 26 % after the curing period of 28 days. Likewise, for mortar mix CSCBA10 the compressive strength has been decreased by a maximum of 23 % compared to the control mortar mix for the same curing periods (Figure 2). The possible cause for the reduction is due to the higher content of SCBA as the replacement of PC along with low pozzolanic reaction at an early age (Chi 2012). However, the proper proportion of SiO_2 obtained from the inclusion of sugarcane bagasse ash and $Ca(OH)_2$ (as a by-product of hydration reaction) develops C-S-H subsequently increasing the compressive strength (Muangtong et al. 2013).

A significant reduction of nearly 11 % and 10 % for the mortar mix CCCA5 compared to control mix C0 at 7 days and 28 days of curing respectively. Similarly, for mortar mixes CCCA10 and CCCA15 the reduction to an extent of 18 % and 36 % in compressive strength has been noticed after 28 days of curing (Figure 2). The observed trends have been found similar to that of the available literature wherein, a significant reduction for corncob ash-based mixes have been observed for the early age of curing (Ettu et al. 2013; Adesanya 1996). However, the gain in strength has also been expected for the blended mortar based on corncob ash after longer curing periods.

CO_2 EMISSIONS REDUCTIONS

Following the aforesaid approach, it has been observed that for the manufacturing of every one cubic meter of non-conventional mortar/concrete, it saves the same amount of CO_2 emissions. For example, considering the case of industrial wastes-based mortar mixes wherein 20 % of reduction in weight of Portland cement (as alteration with fly ash, bottom ash, and blast furnace slag) cuts the amount of cement by 115 kg per cubic meter. Figure 3 shows the CO_2 reduction by replacement of PC with Agricultural/Industrial wastes products (per m^3). In other words, production of Portland cement along with the utilization of fly ash, coal bottom ash, and blast furnace slag (say 80 % of Portland cement and 20 % of fly ash/bottom ash/blast furnace slag) reduces the production of CO_2 by at least 20 %. Likewise, the use of agricultural wastes like rice husk ash, bagasse ash, and corn cob ash would probably reduce the production of CO_2 in the environment up to the maximum by 15 % during the manufacturing process of agricultural bi-products based mortars. Corresponding to the projected production of 1,500 MT of cement in India by end of year 2050 and the utilization of alternatives with either of industrial/agricultural by-products (minimum 15 % and maximum 40 % by weight) would assuredly reduce the production of cement and subsequently saving of 225 Million Tonnes–600 Million Tonnes of CO_2 assuming the reduction potential of 1 t of CO_2 per ton of Portland cement production. The analysis results in saving of overall cost of mortars made with alternative material compared to conventional mortars. From the calculations and comparison with conventional mortar mix, it was observed that merely 10 % of replacement of Portland cement results in satisfactory economic saving i.e., 4 % less to that of conventional mortars while the variation moves up from 4 % to 6 % for 20 % replacement levels. Similar economic benefits are noticed for higher replacement levels of Portland cement with alternative materials.

Discussion

The performance of any mortar mix towards external forces can be judged using compressive strength values. However, compressive strength values cannot predict the long-term performance of blended mortars. Thus, durability play a vital role in deciding the overall satisfactory performance. Therefore, the current study promotes the idea of investigating the durability aspects of blended mortars with industrial and agricultural wastes for the real application in the construction industry. One of the key challenges of the current applicability of blended mortars is the non-availability of the standard guidelines which depict the specific replacement(s) of clinkers with aforesaid substitutes. Another challenge is the availability of these industrial and agricultural wastes in the vicinity of the required construction sites. In general, long-distance transportation cannot be encouraged as CO_2 emitted during transportation of these materials probably drop the CO_2 emissions reductions achieved by replacement of cement with either of wastes. Despite neglecting the CO_2 emissions during transportation, the current study offers encouraging results for practice of the aforesaid methodology.

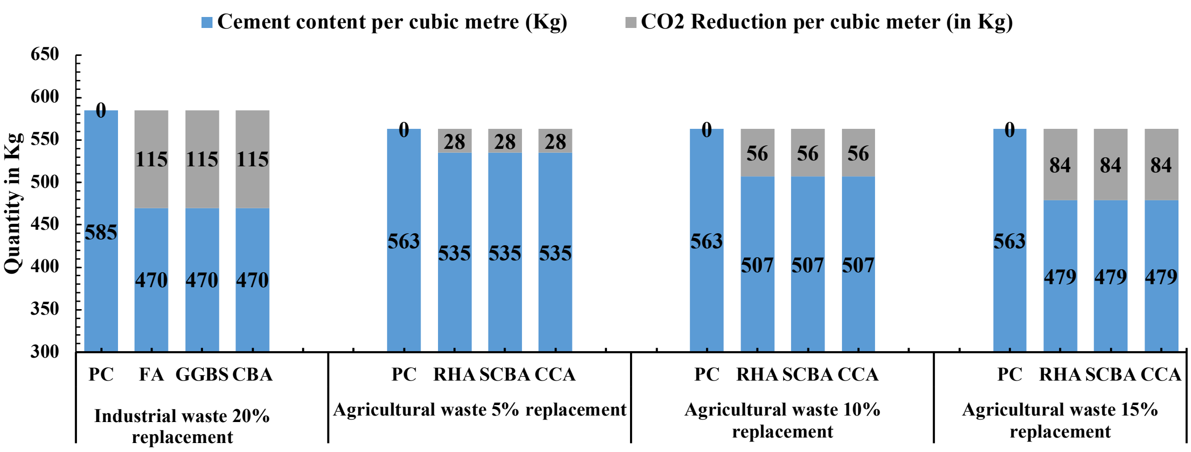

Figure 3. CO_2 reduction by replacement of PC with agricultural/industrial wastes products (per m^3).

Conclusions

Portland cement is mainly used for the manufacturing of masonry mortars and concrete for civil engineering structures. Supplementing the cement with pozzolans enhances the binding properties and is generally considered a decent option for achieving the desired quality and toughness. The use of industrial and agricultural wastes in cement is not only crucial for CO_2 reduction in cement production but also it is important to limit the environmental impacts of industrial production and agriculture. Moreover, the approach offers a decrease in air contamination as well as assist in diminishing the degradation of landfills due to the dumping of various industrial and agricultural wastes. Based on the compressive strength results, the current study suggests the use of such blended mortars for minor engineering works where the mechanical strength is not the deciding criteria for the satisfactory performance of the structure.

The Indian cement and mortar industry has moved from conventional practice towards blending options for the manufacturing of non-conventional cements and mortars. The practice of reducing clinker by the substitution with various industrial and agricultural by-products has increasingly been in demand over the past three decades. Industrial by-products like fly ash, coal bottom ash, ground granulated blast furnace slag, copper slag and agricultural by-products like rice husk ash, sugarcane bagasse ash, corncob ash are the most preferred options for blending of cement/mortars mainly for three reasons, i.e. (i) the existing benefit of the pozzolanic behavior; (ii) the availability along with its abundant availability; and (iii) the attainment of comparable performance without compromising the mechanical and durability aspects compared to cement and mortars made without blending.

The experimental outcomes revealed that the inclusion of Fly ash increases the compressive strength of the blended mortars followed by the mortars made with ground Granulated blast furnace slag and Coal bottom ash at 56 days of curing. Out of all cement additions, the inclusion of fly ash has resulted in a maximum increase in compressive strength due to higher pozzolanic activity compared to other cement additions. Due to the identical chemical composition of Ground granulated blast furnace slag to Portland cement, it is widely used as an alternative to Portland as its incorporation enhances the compressive strength at higher ages. Further comparable compressive strength has been noticed for the blended mortars made with Coal bottom ash compared to the control mortar mix. The inclusion of agricultural wastes results in the decrease of the compressive strength for higher replacement levels. However, comparable performance has been noticed for replacement level of 5 % of Portland cement with Rice husk ash, Sugarcane bagasse ash, and Corncob ash while a significant reduction in compressive strength has been noticed compared to control mortar mix up to 28 days of curing. Further, the compressive strength has been improved considerably with an increase in the curing period for aforesaid mortar mixes.

Blended cement made with industrial or agricultural by-products can successfully replace limestone clinkers. Based on the experimental results, the adoption of blended cement and mortars could probably contribute to a drop the CO_2 emissions in cement production by 15 %–20 %. Being the world's second-largest cement manufacturer, the Indian Government has been continuously hovering and endorsing the sustainable options for the existing and upcoming cement and mortar industry through various initiatives. Several goals have been set for increasing the utilization of industrial and agricultural by-products in blended cement mortars and curtailing the CO_2 emissions generated particularly from the Indian cement industry. The projected approach, however, is not sufficient to reach future CO_2 emissions reductions targets up to 2050. Thus, other options such as carbon capture and usage or storage, or alternative binders such as carbon cured binders or binders with reduced limestone content have to be explored as well that especially suit the Indian context.

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