Contribution Of Composite Cements In Reducing Embodied CO_2

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ABSTRACT

Over the last decades, there is a growing demand to reduce the Portland Cement (PC) content and increase the amount of various supplementary cementitious materials (SCMs) used in concrete mixture to help reduce the embodied CO_2 (ECO_2) of concrete and more generally, the environmental impacts of concrete industry. The main objective of this paper is to assess the CO_2 emissions associated with concrete production using various combinations of SCMs as per EN197-1 and further to develop concrete mixes with reduced ECO_2 and enhanced durability. The results indicate that the ECO_2 reduction in the composite cements is proportional to the substituted amount of PC by the SCMs in the concrete mix. In addition to the environmental benefits generated by the use of high content of SCMs as substitute of PC, the obtained results reveal a significant long-term improvement in strength properties and durability performance of composite cement concretes.

Keywords. Supplementary cementitious materials, Initial surface absorption, Mechanical properties, Sustainable concrete, Embodied CO_2

1. INTRODUCTION

Concrete is the most used construction material globally. Scarcity of raw materials and high energy and global CO_2 intensity of PC have jeopardized the development of the concrete industry. CO_2 is the most abundant of the greenhouse gases which triggers global warming the most and the contribution of concrete industry to CO_2 emissions is approximately 7% worldwide (NRMCA, 2012; Malhotra, 2000). Amongst cements, CEM I Portland Cement is the most common type of cement used worldwide and it is responsible for 90% of total concrete CO_2 emissions. Higher CO_2 emissions of PC have compelled concrete industry to come up with more environmentally friendly approaches. Over decades, contribution of SCMs such as fly ash (FA), granulated blast-furnace slag (GGBS) and silica fume (SF) has been a common practice in sustainable concrete production. Concretes with SCMs have been proved to improve engineering properties as well as durability parameters of the concrete which have significant importance from the sustainability point of view (Khatri, 1995).

In accordance with this background, most of the research in this field carried out on CEM I PC concrete and there is a lack of information on the performance of blended cement CEM V/A and CEM V/B concretes. This paper investigates the assessment of ECO_2 of developed concretes produced by blended CEM V/A and CEM V/B cements with constituents such as FA and GGBS in conformity with BS EN 197-1:2011. Four mixes with different cementitious materials contents were designed to achieve 28 day cube compressive strength of 40 MPa with different cementitious contents. These concretes were tested for basic mechanical and engineering properties (compressive and flexural strengths) and initial surface absorption (ISA) test along with environmental impact.

2. EXPERIMENTAL METHODS

2.1. Materials

Four different mixes with different cementitious contents, a control and three ternary mixes, with natural aggregates were investigated. The constituents used were OPC, FA and GGBS. PC used was CEM I 52.5N complying with BS EN 197-1:2011 throughout the study. The FA and GGBS used were all complying with BS EN 450-1:2012 and BS EN 15167-1:2006 respectively. Water reducer admixture was used in conformity with BS EN 934-2:2009.

2.2. Mix Proportions and concrete mix design

Concrete mixes were proportioned using four different w/cm ratios of 0.35, 0.39, 0.40 and 0.51 in conformity with Building Research Establishment Mix design. The mix design is based on the average relative density of coarse aggregate to determine the concrete density. The proportion of fine aggregates was determined by the sieve analysis of percentage fine aggregates passing 600 µm sieve. The mix proportions of concretes studied are given in Table 1 which were designed to have average slump between 60-180 mm in accordance with BS EN 206-1:2000 for S3 concrete workability class. The coarse aggregate content was kept constant for Mixes 2,3 and 4. The free water content was dependant upon the cementitious materials used. Cementitious contents were based on the efficiency of SCMs in achieving the target strength of 40 MPa (McCarthy, 2005). The first mix was a control mix containing only PC (ordinary PC) stated as mix 1. Three blended cements contained 20%, 30% and 40% PC together with 50%, 40% and 30% GGBS content respectively and FA content is limited to 30% as they are stated as mix 2,3 and 4 respectively. In parallel with GGBS content, PC content was reduced 10% increments (40%, 30% and 20%) for mixes 4, 3 and 2 respectively.

Concrete production and fresh concrete testing was carried out in accordance with BS EN 12350:2000 Part 1 and 2. After casting moulds, initial slump was recorded and slump loss was investigated at 30 and 60 minutes.

Table 1. Mix proportions of concretes investigated

Mix	w/cm	Admixture (ml)	Water (kg)	OPC (kg)	FA (kg)	GGBS (kg)	Aggregates (kg)	
							Fine	Coarse
1	0.51		195	385	-	-	675	1100
2	0.35	2550	170	95	145	240	590	1135
3	0.39	2250	170	130	130	170	640	1135
4	0.40	2025	170	170	125	125	650	1135

2.3.Test Methods

Mechanical properties studied were compressive and flexural strengths. Cubes of 100mm were cast to investigate compressive strength of concrete at 3, 7, 28, 56 and 91 days complying with BS EN 12390-3:2009. Together with cube samples, 150 mm diameter and 300 mm high cylinders were cast and tested for compressive strength at 28, 56 and 91 days. Flexural strength tests were performed at 7, 28 and 56 days under four point loading using 100 mm x 100 mm x 500 mm beams in conformity with BS EN 12390-5:2009.

First 24 hours after casting, the specimens were kept in moist conditions at 20±3 °C. After demoulding, all specimens were stored in water tank at 20±2 °C until the test age complying with BS EN 12390-2:2009. Three concrete specimens were tested for each type of concrete and the average value was reported.

2.3.1. Initial Surface Absorption Test

ISA has been carried out in conformity with BS 1881-208:1996. It is one of the indicators to evaluate the durability of concrete. The test measures the porosity of the concrete by the rate of water penetrating into concrete under a hydrostatic pressure of 200 mm head that flows into the capillary suction through a known surface area. The contact area is sealed to prevent any leaking out during the test. Evaluation of the volume flow is determined by measurement of the length of flow along a capillary tube of known dimension at 10 minutes (ISAT-10). 150 mm cube samples were cured under water for 28 days in accordance with BS EN 12390-2:2009 and then the samples were taken out and put in the oven for 24 hours at a constant temperature of 105±5 °C prior to test to get rid of moisture content of concrete to provide more consistent results. The contact area of water is 5675 mm^2 (85 mm diameter) complies with the relevant BS 1881-208:1996.

3. RESULTS AND DISCUSSIONS

3.1.Fresh Properties

In general, all mixes have achieved targeted slump values. Loss of workability was measured at 30 and 60 minutes after casting by mixing the concrete sample in the pan and taking the slump value. The results are presented in percentages in Fig. 1. After mixing, slump values had started to decrease dramatically. Control mix had superior results during the whole test and had kept its flowability comparing to ternary mixes. At 30 minutes, mix 1 had achieved 42% of its initial workability whereas ternary mixes were reported as 19%, 25% and 35% for mixes 2,3 and 4 respectively. After 60 minutes, the moisture loss had become apparent and all ternary mixes had zero slump values and control mix had kept 5% of its initial slump. These significant slump losses might be attributed to the higher cementitious content and the lower PC content. Other ternary mixes have showed similar behaviour as moisture loss has visibly become apparent at 50 minutes. However, viscous characteristics of ternary mixes can be explained by the presence of FA (Gesoglu, 2009).

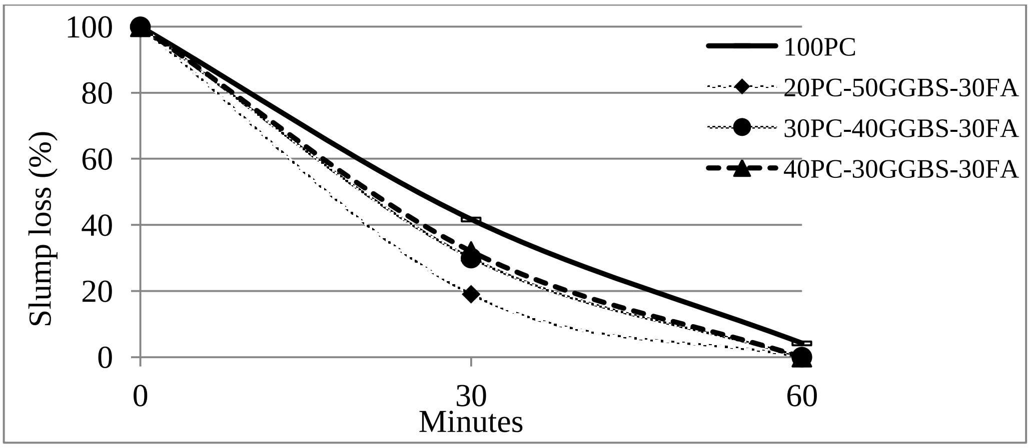

Fig. 1: Slump loss

3.2. Mechanical Performance

3.2.1. Compressive Cube Strength

Compressive strength values of all mixes are represented in Figure 2. All mixes were designed to achieve 28 days strength of 40 MPa with different cementitious content due to efficiency of SCMs that were used. Therefore, 28 days strength results were taken as 100% for all mixes as all mixes have strengths within the determined margin of 40±5 MPa. Comparisons were carried out according to 28 days cube strengths. It is noticeable that control mix has developed an early strength gain at 3 and 7 days ages (76% and 90% respectively) comparing to ternary mixes. The strength developments of ternary mixes at 3 days were recorded as 52%, 48% and 44% at 3 days for mixes 2, 3 and 4. This can be attributed to the reduction in the PC content along with increased FA content which resulted in decrease in CaO straightaway. Despite this, these mixes have gained approximately half of their target design strength at 3 days. Similar trend can be also seen at 7 days as strength developments were 79%, 69% and 63% for mixes 2,3 and 4 respectively. Mix 2, with the lowest PC content (20%) and the highest total cementitious content (480 kg), has developed higher strength development comparing to other ternary mixes with PC contents 30% and 40% at initial ages. It can be explained that increase in total cementitious content compensates the strength development of mixes with reduced PC content (20%, 30% and 40%). However, SCMs concretes have provided better results at longer ages (>28 days) compared to control mix. Mix 2 has showed the highest development of 123% at 56 days as control mix has 107%. As total cementitious content decreases, strength developments were also decreases. This is believed to delayed calcium-silicate-hydrate (C-S-H) formation, proportional to the amount of cementitious content, to occur due to pozzolanic reaction. Previous researches have also noted that contribution of SCMs to pozzolanic reaction takes place after 28 days (Gonen, 2007). Further strength developments were even more noticeable at 91 days with 127% and 112% for mixes 2 and 3 respectively as they both have higher cementitious content. It is also coherent with previous researches (Johari, 2011; Berndt, 2009), increased GGBS content compensates early the strength loss that was expected by the presence of FA. Additional secondary C-S-H formation from SCMs contribution can be thought as the reason of the strength development at longer ages. Having less cementitious content, mix 4 and control mix have showed negligible strength developments. These support the previous statement on delayed C-S-H formation due to SCMs content in the mixes.

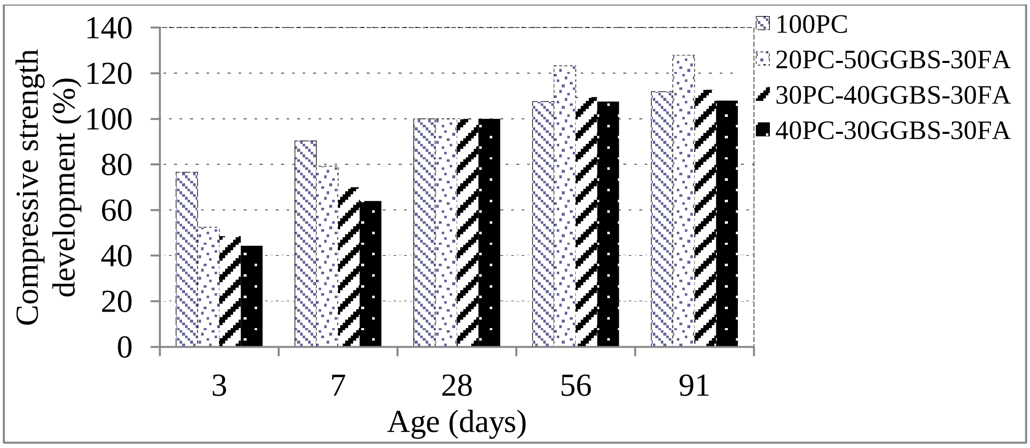

Fig. 2: Cube compressive strength development of mixes

3.2.2. Cylinder compressive strength

Results of the cylinder compressive strength development of developed concretes are presented in Fig. 3. 28 days cylinder compressive strengths were again taken as a basis and strength developments over time were assessed. As expected, control mix had showed the least strength development over age. The strength developments were recorded as 105% and 110% at 56 and 91 days respectively. Similar to compressive cube strength developments, mix 2 had showed the best performance at both ages with 120% and 136%. Same trends for mix 3 and mix 4 were also monitored along with 114% and 112% of their compressive strength at 56 days and 120% and 113% at 91 days. This indicates the strength development is intensely increasing as the total cementitious content increases.

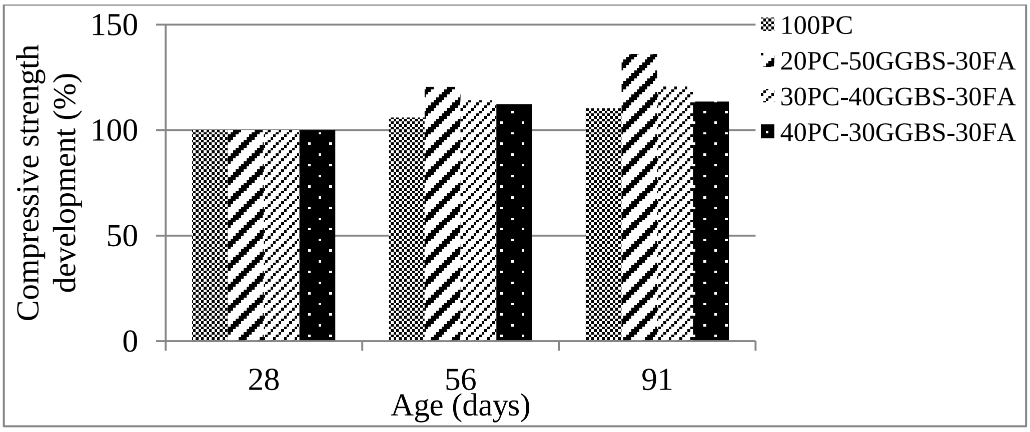

Fig. 3: Cylinder compressive strength development

Detailed investigation was carried out on comparing cylinder compressive strength against compressive cube strength at particular ages. All mixes had achieved 68% to 72% of their compressive cube strength at 28 days and indicated consistent results throughout the test ages.

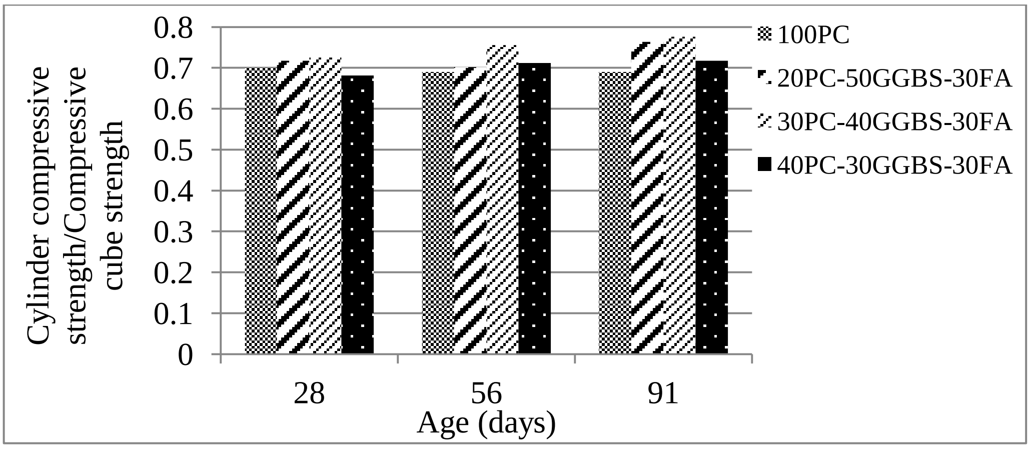

Fig. 4: Cylinder compressive strength/Compressive cube strength

3.2.3. Flexural Strength

Fig. 5 shows the results of flexural strength development of all mixes. Similar to cube compressive strength, 28 days strength is taken as basis and 7 and 56 days strength developments were compared with 28 days strengths. Same trend as cube compressive strengths, control mix has showed higher strength development at 7 days with 88% of its 28 days strength comparing to ternary mixes with 80%, 74% and 78% for mixes 2, 3 and 4 respectively.

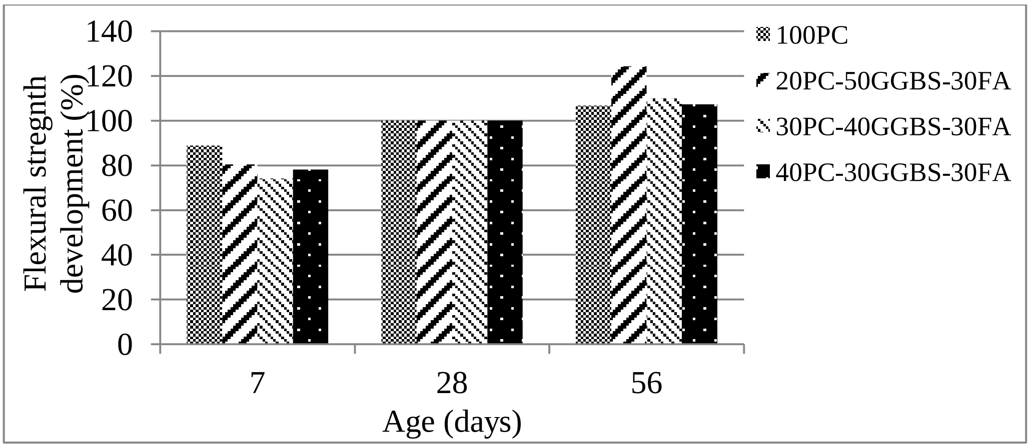

Fig. 5: Flexural strength development

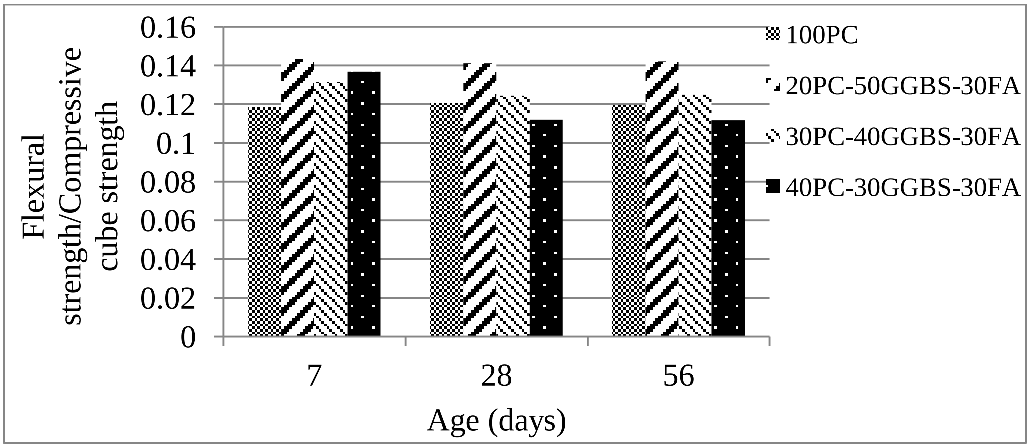

Fig. 6: Flexural strength/Compressive cube strength

Further investigation was carried out comparing flexural strengths with cube compressive strengths at particular ages. Results showed that mix 2 was superior as it has achieved over 14% of cube strength at all ages. However, mix 4 had demonstrated different behaviour and achieved higher value then the other two mixes at 28 days but decreased over time as expected. Mix 1 had kept consistent results about achieving around 12% its cube strength at all ages. Same trend was observed for mix 3 as it had achieved 12-13% for its cube strength.

3.3.Durability Performance

3.3.1. Initial Surface Absorption Test

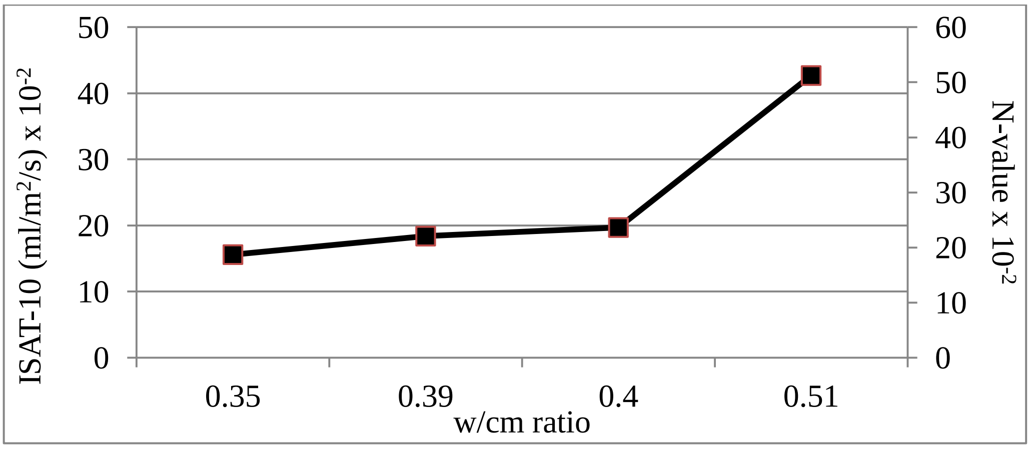

Fig 7. ISAT-10

The test results of the ISA of the concrete after 10 minutes (ISAT-10) and N-value (rate of decay) results at 28 days are shown in Fig. 7 plotted against w/cm ratio. All ternary mixes with SCMs have superior performances comparing to control mix. Results clearly show that ISAT-10 and N-values are directly related with w/cm as mix 2 with the lowest w/cm ratio has the lowest ISAT-10 and N-values. These improvements in pore structure can be attributed to finer characteristics of SCMs fill the pore structure and result in dense microstructure. These results are in agreement with those reported earlier (Dhir, 1999; Johari, 2011). N-value results showed similar trends to the ISAT-10 values.

3.4.Environmental Impact

Environmental assessment has been carried out to evaluate ECO_2 emissions of concretes. Evaluation has been carried out with the experimental data obtained values. However, these values represent cradle-to-gate and do not cover transportation to the site. As can be seen in Fig. 8, control mix had the highest ECO_2/tonne amongst all mixes with 154 kg ECO_2/tonne.

It is clearly seen that ECO_2 emissions are directly proportional to the presence of PC content. Along all mixes, mix 2 had the lowest ECO_2 emissions of 50 kg ECO_2/tonne. Even though total cementitious content is higher than control mix (490kg>385kg), this significant reduction in mix 2 is directly related with the reduction in PC content from 385 kg to 100 kg. As PC content increases in mix 3 and 4 to 130 kg and 170 kg, ECO_2 emissions also increase to 59 kg ECO_2/tonne and 74 kg ECO_2/tonne respectively. ECO_2 emissions have been reduced dramatically by using FA and GGBS. This can be explained by FA and GGBS do not require clinkering as PC does during their production (Lottenbach, 2011).

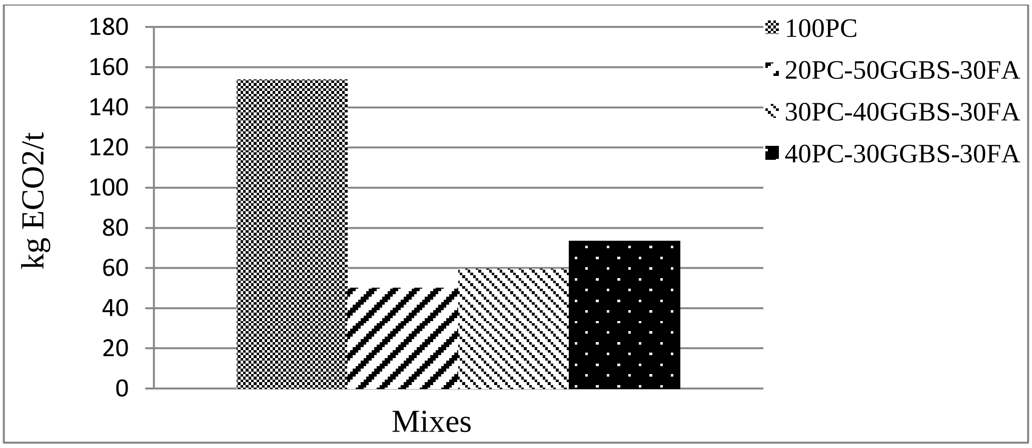

Fig. 8: Embodied CO_2 emissions per tonne

4. CONCLUSIONS

Within this study it was demonstrated that ECO_2 emissions of concrete production can be reduced by using SCMs whilst providing improved mechanical properties. It is monitored that concretes with SCMs have superior strength development.

The main conclusions are as follows;

- SCMs contribution reduces the fluidity of the concrete and makes it less workable.
- Reduction in PC content results in significant strength losses for all blended cement concretes at early ages. Nevertheless, the increase in total SCMs content compensates the strength loss and provides better strength developments at longer ages.
- Concretes with SCMs achieve similar cylinder/cube compressive and flexural/cube strength values at all ages as control mix. Therefore, they maintain serviceability of concrete from mechanical performance point of view.
- Replacing PC with finer SCMs improves pore structure resulting in impermeable concrete structure. Rate of decay is proportional to impermeability of concrete.
- The increase in PC replacement by SCMs reduces concretes' environmental impact remarkably. ECO_2 emissions were cut down up to 68% for the same concrete strength class.

5. ACKNOWLEDGEMENT

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