

Suitability of Corncob Ash as a Supplementary Cementitious Material

John Kamau^{1*}, Ash Ahmed¹, Paul Hirst¹, Joseph Kangwa²

¹Civil Engineering Group, Leeds Beckett University, West Yorkshire, Leeds, England, UK.

²London South Bank University, London, England, UK

Corresponding author. Tel.: +44 113 812 1980; email: A.R.Ahmed@leedsbeckett.ac.uk

Manuscript submitted January 29, 2016; accepted November 8, 2016.

doi: 10.17706/ijmse.2016.4.4.215-228

Abstract: Cement is the most utilized construction material, and the second most consumed commodity in the world after water. Its demand has soared proportionately with the exponential rise in population in a bid to match the required development. The heavily energy-intensive processes that are involved in its production contribute to about 7 to 10 per cent (%) of the total global emissions, with potentially adverse environmental implications, and are also economically expensive. These processes, and generally those of the production of concrete consume heavily on natural resources such as sand, gravel, water, coal and crushed rock, mining of which mars the environment. It is however possible, that energy and cost efficiency can be achieved by reducing on the amount of clinker, and in its place utilising supplementary cementitious materials (SCMs) that require less process heating and emit fewer levels of carbon dioxide (CO₂). This study investigated the ability of corncob ash (CCA) to be used as a SCM by testing for pozzolanic or hydraulic properties and performance in sulfate environments. Experiments were carried out by supplementing cement by weight in concrete mixes with CCA at 5%, 7.5%, 10%, 15%, 20%, 25% and 30% steps at the point of need. Results were compared with a control specimen, which was made with 100% cement. Durability was tested using the sulfate elongation test. The results showed impressive compressive strengths that were suitable for structural applications. It was concluded from the sulfate elongation test that CCA supplemented concrete could be used in aggressive environments with an advantage. The results showed good repeatability and highlight the potential of CCA as an effective pozzolan, which could enhance the sustainability and economic aspect of concrete, as well as improve its properties in both the wet and hardened states.

Key words: Cementitious materials, corncob ash, partial cement replacements, pozzolans.

1. Introduction

It is reported in literature that apart from environmental friendliness, the use of supplementary cementitious materials (SCMs) such as pulverised fuel ash (PFA), ground granulated blast furnace slag (GGBS), Silica fume (SF) and rice husk ash (RHA) reduces the cost of concrete and improves the durability of hardened concrete, thereby enhancing the service life of structures [1, and 2]. This work investigated the suitability of corncob ash (CCA) for use as a SCM.

Cement is deemed to have a considerably high carbon footprint, contributing immensely to global anthropogenic CO₂ [3]. Global warming is a phenomenon that brings about a rise in global temperatures due to the presence of excessive carbon dioxide (CO₂) in the atmosphere, and is cumulative and irreversible

over timescales of centuries [4, and 5]. The burning of fossil fuels, in this case for the production of cement contributes to the greenhouse gas effect, which is a major cause of global warming [6]. Even though heavily energy intensive, cement is pivotal to development and is produced in virtually all countries [7]. One ton of concrete on average is produced every year for each human being in the world, a population that currently stands above 7 billion [8, 9]. The growing population, matched by a corresponding increase in demand for socio-economic infrastructure that is aimed at creating affluent societies, especially in the developing world and former socialite countries, has led to a gradual increase in the demand for cement in the past few decades, with construction investment directly linked to higher gross domestic product (GDP) [10, 11]. Cement was described by Al-Salami and Salem [12] as the most utilised construction material in the world, its global consumption only seconding that of water. It constitutes between 7%-15% of the total mass of concrete mixes [13], yet according to Sakai and Noguchi [11], the development of a nation is directly proportional to its consumption of concrete. Its yearly global production was 1.6 billion tons over 10 years ago, accounting for about 7% of the total global CO₂ loading in the atmosphere, a considerably high level of emissions when compared to 2% total global CO₂ emissions attributed to the aviation industry [14-16].

The production of a ton of cement emits approximately a corresponding ton of CO₂ [17], making it the most energy-intensive material produced after steel and aluminium [3, 14]. In as much as development is required to match increasing populations, it should also be sustainable [18]. The underlying principles of sustainability lie in the appropriate balance of economic, social and environmental impacts [19]. Steel et al. [18] defined sustainability as a road for society advancement in which progress must be in harmony with the natural world, rather than in conflict with it, while Gambhir [14], termed it as a regime in which endeavors are towards meeting the needs of the present generation without compromising those of future generations. With a heavy demand for concrete in the developing world and other major and equally populous economies such as China and India predicted, cement producing companies have not anticipated in the foreseeable future any major changes in production that will reduce on emissions [1]. However, energy efficiency can be achieved by reducing on the amount of clinker and utilising SCMs, which require less process heating and emit fewer levels of CO₂ [14].

Industrial and agricultural waste products such as PFA, GGBS, SF, RHA and CCA unnecessarily occupy space when stored or create environmental hazards when dumped in landfill [1]. Their utilisation in the construction industry reduces the overall cost of construction, mitigates on the technical and environmental nuisance that is associated with the production of cement, reduces solid waste, cuts on greenhouse gas emissions and conserves existing natural resources, thereby enhancing sustainability as well as improving the properties of fresh and hardened concrete [1, 20, 21]. Sulfate attack is a durability issue that causes concrete to lose its compressive strength, with severity depending on the type of sulfate [22-24]. All commonly available water-soluble sulfates are deleterious to concrete, but the most severe effects are observed when the attack is associated with magnesium cations [1]. Higher sulfate concentrations in water are due to Magnesium sulfate (MgSO₄), which is highly soluble in water at room temperature (20°C) when compared to sodium sulfate (Na₂SO₄) [1]. Both Na₂SO₄ and MgSO₄ attacks have deleterious action on concrete but with different resultant effects [1]. Na₂SO₄ attack is manifested and evaluated through expansion, while MgSO₄ attack is manifested and evaluated through the loss of strength of concrete [1]. MgSO₄ attack is determined by the diffusivity of hydroxide and sulphate ions, with hydroxide ions diffusing outwards to form brucite and sulfate ions diffusing inwards to form gypsum [25, 26]. This combined layer of gypsum and brucite retards the harmful effect of MgSO₄ attack in the early ages [1, 26, 27]. However, at latter ages, this protective skin peels off due to the formation of expansive gypsum and ettingite, which causes cracking in the surface of the brucite layer [1, 2, 26]. The subsequent decomposition of calcium silicate hydrate (C-S-H) gel to magnesium silicate hydrate (M-S-H) gel permits the

easy diffusion of sulphate ions into the hardened cement matrix [1, 26, 27]. This alteration of C-S-H to M-S-H is the major process of $MgSO_4$ attack [28, 29]. Low sulfate resistance is influenced by high contents of calcium hydroxide ($Ca(OH)_2$), Sulfite (SO_4), iron oxide (Fe_2O_3) and alite (C_3A), and low levels of silicon dioxide [SiO_2] [24, 30-33]. A high molar ratio of (sulfate) SO_3 to aluminium oxide (Al_2O_3) increases the risk of the formation of monosulfate that otherwise results in expansive ettringite and gypsum on exposure to sulfate attack [1, 34, 35]. Higher levels of reactive Al_2O_3 can mean less expansion at low replacement levels of SCMs [1]. Corn is the main staple food in the Eastern and Southern Sahara Africa, accounting for more than 20% of domestic food production [36]. Corncob is the hard central core of corn which bears the grain of the ear cob, while CCA is the remnant of incinerated corncob [1, 37].

2. Research Significance

CCA has neither been widely studied nor applied in practice. It was termed by (Bapat) as one of the remotely known but potentially useful admixture. Even though Bapat [1], Shetty [33], Rao, et al. [38] and Zhou, et al. [39] reported that SCMs improve the workability of fresh concrete, Olafusi and Olutoge [37], Adesanya and Raheem [40] and Udoeyo and Abubakar [41] recorded a decrease in workability with an increase in the content of CCA, and attributed the behavior to a high water demand that is caused by the large amounts of silica that are present in CCA. This is not consistent with the behaviour of SCMs and hence calls for further investigations. Previous studies have also looked at blending CCA with cement at the factory and not mixing at the point of need. There is generally a shortage of portable tap water for mixing concrete, especially in the developing world [42]. Most people, especially from peri-urban settings will use any available water for this purpose, such as that obtained from boreholes, sewages and swamps [42, 43]. Some of the water from these environments may be contaminated and can be a source of aggressive ions on concrete, which can lead to a reduced service life of resultant structures due to expansion, cracking, spalling and loss on compressive strength [22-24, 42, 44]. Limited work was found on the resistance of CCA supplemented concrete to sulfate attack. This study involved replacing cement with CCA at the point of need, and investigated the compressive and tensile strengths, density, workability as well as sulfate attack on hardened CCA supplemented concrete.

3. Methods

CCA was sourced from Kenya, from where corncobs were incinerated under uncontrolled conditions in open air using charcoal fuel, at temperatures of about 650°C to 800°C for over 8 hours until they turned to ashes. The cement used was type CEM 1 52.5 N conforming to BS EN 197-1: 2000 [45]. Cube moulds that were used to make specimens measured 100mm x 100mm x 100mm conforming to European codes, BS EN 12390-1:2012 [46] and the specimens were cast conforming to BS EN 12390-2:2009 [47]. The target mix of the study was strength class C32/40 at mix proportions of 1: 2: 3 (cement: sand: aggregates). Cement was substituted with CCA by weight in percentages of 0%, 5%, 7.5%, 10%, 15%, 20%, 25% and 30%. The 0% replacement also referred to as the 'control specimen' was used as the reference to which the performance of all replacements was measured [40]. A constant water cement ratio (WCR) of 0.5 was used for all mixes for a good balance of workability and strength in line with Abram's law which states that the strength of a concrete mix is determined by the WCR, with lower WCR spelling higher strengths and vice-versa [48]. To ensure repeatability, a total of three cubes were cast for each testing age and the average compressive strength was reported [6, 49]. The cubes were left in the molds for 24 hours, before being stripped, marked and submerged in a water tank at temperatures of $20^{\circ} \pm 2$ until their testing age. Compressive tests conformed to BS EN 12390-4:2000 [50] at 7, 28, 56 and 91 days. Splitting tensile strengths were carried out using 150mm diameter cylinders, equally cured in a water tank at temperatures of $20^{\circ} \pm 2$ for 91 days, with

tests conforming to BS EN 12390-4:2000 [50]. The sulfate elongation tests conformed to the American Society for Testing and Materials (ASTM) C1012/C1012M [49]. Cubic prismatic samples measuring 160mm x 40mm x 40mm and cubes measuring 100mm x 100mm x 100mm for sulfate elongation and strength deterioration tests respectively were prepared, demolded after 24 hours and cured in water for 6 days. Three cubes were crushed on the sixth day to ensure that the compressive strength was not below 20N/mm². The specimens were then immersed in 5% Na₂SO₄, 5% MgSO₄ and mixed 2.5% + 2.5% Na₂SO₄ and MgSO₄ solutions. A pH of between 6 and 8 was maintained on the sulfate solutions throughout the testing period. Length change was measured at 1, 2, 3, 4 and 8 weeks, and 4, 8 and 9 months, and calculated to ASTM [49] using (1) below.

$$\Delta L = \frac{L_x - L_i}{L_g} \times 100 \tag{1}$$

where:

ΔL is the percentage change in length at measuring age, L_x is the veneer calipers reading of specimen at measuring age, L_i is the veneer calipers reading of specimen at immersion and L_g is 160mm (nominal length between the innermost ends of the moulds used)

Strength deterioration was assessed using the strength deterioration factor (SDF) using (2) after Moon, et al. [51].

$$SDF = (f_{cw'} - f_{cs'}) / f_{cw'} \times 100 \tag{2}$$

where $f_{cw'}$ is the compressive strength of control specimen cubes and $f_{cs'}$ is the compressive strength of sulfate immersed specimen cubes. Surface deterioration was observed at 270 days.

4. Results and Discussions

4.1. Chemical Analysis

Table 1. Oxide Composition of CCA

Oxide	Percentage Composition
Calcium oxide (CaO)	1.8
Silicon dioxide (SiO ₂)	38.8
Aluminium oxide (Al ₂ O ₃)	7.9
Ferric oxide (Fe ₂ O ₃)	7.4
Magnesium oxide (MgO)	2.1
Potassium oxide (K ₂ O)	23.5
Sodium oxide (Na ₂ O)	0.9
Sulphur trioxide (SO ₃)	0.6
Loss on ignition (LOI)	10.8

Table 1 shows the oxide composition of CCA obtained by X-ray diffraction (XRD). The chemical pozzolanic requirements of ASTM C618 [52] and BSI [45] of SiO₂+Al₂O₃+Fe₂O₃ of greater than or equal to (≥) 70% or the LOI requirements of BSI [45] or ASTM [52] of less than 5% and 10% respectively were not satisfied. The cementitious properties of a CaO content of greater than 20% or the pozzolanic and cementitious properties of a CaO content of between 10% and 20% as discussed by Al-Akhras [53] were not satisfied. The ratio of CaO + MgO/SiO₂ to exceed 1 for cementitious materials to BSI [45] was also not satisfied. However, a conclusion that CCA could possess pozzolanic properties can be arrived at since the BSI's

requirement of a SiO₂ content of at least 25% was satisfied [45]. The chemical composition inferiority of CCA used for this study could be attributed to uncontrolled incineration, since Bapat [1] posited that incinerating rice husks under controlled conditions can help to improve the oxide composition of the resultant RHA, a concept which could also be applied to corncobs. For the requirements discussed by Tishmack, et al. [35] on sulfate attack resistance, CCA used for this research had relatively low levels of SiO₂ and high Fe₂O₃, which is an indication of low resistance to sulfate attack, even though CaO and the ratio of SO₃/Al₂O₃ were relatively low, a quality which, according to Tishmack, et al. [35], contributes to higher sulfate resistance.

4.2. Compressive Strength

Table 2 and Fig. 1 show compressive strengths at 7, 28, 56 and 91 days of hardened concrete with 0%, 5%, 7.5%, 10%, 15%, 20%, 25% and 30% CCA replacement.

Table 2. Compressive Strength of CCA Replaced Mixes (N/mm²)

Curing age (days)	Compressive strength at percentage replacement (N/mm ²)							
	Control	5%	7.50%	10%	15%	20%	25%	30%
7	56.2	42.0	42.3	32.1	28.1	19.2	16.2	15.3
28	61.6	49.0	51.3	37.9	34.3	23.5	18.9	19.3
56	67.6	51.8	54.4	43.1	38.3	25.9	23.0	22.0
91	71.3	55.9	63.5	47.8	41.5	29.8	24.0	23.5

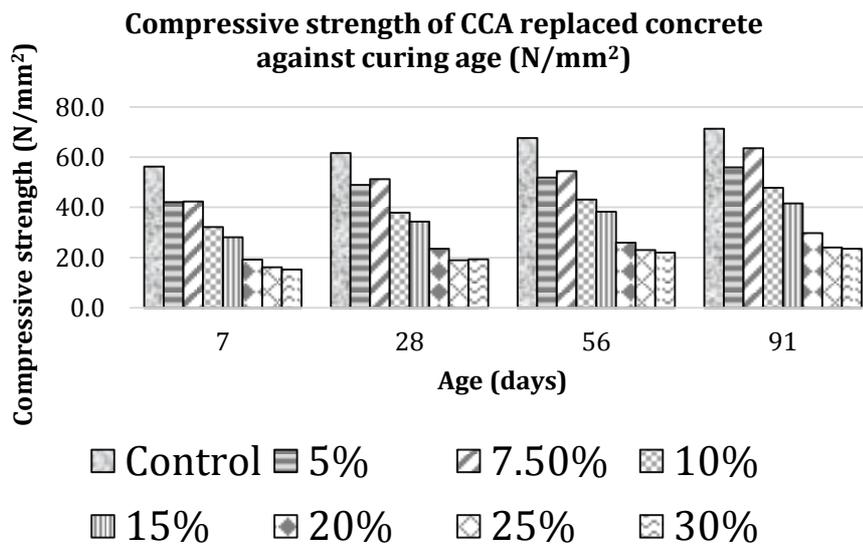


Fig. 1. Compressive strength of CCA replaced concrete (N/mm²)

Replacements of up to 15% achieved strengths that were above the targeted class C32/40 at 91 days, which is among strength classes listed by BS EN 1992-1-1: 2004 [54] and BS 8500-1:2015 [55], as being suitable for structural applications. However, all replacements showed impressive strengths. Compressive strengths increased with curing age, and an addition of CCA resulted in a decrease in compressive strength, consistent with the behavior of SCMs [1, 33, 37, 40, 56]. According to Shetty [33] and Bapat [1], the early age strength was solely due to the hydration of cement, with CCA only acting as an inert filler of voids and not contributing to the strength gain, while the latter age strength was due to the reaction of SiO₂ present in the CCA with free lime [Ca(OH)₂] from the hydration of cement in a secondary reaction over time, to form strength giving compounds such as calcium silicate hydrate (C-S-H).

4.3. Tensile Strength

Table 3. Tensile Strength of CCA Replaced Concrete at 91 Days (N/mm²).

Specimen	Control	5%	7.5%	10%	15%	20%	25%	30%
Tensile strength (N/mm ²)	3.6	3.5	2.3	2.8	1.3	2.1	1.6	2.2

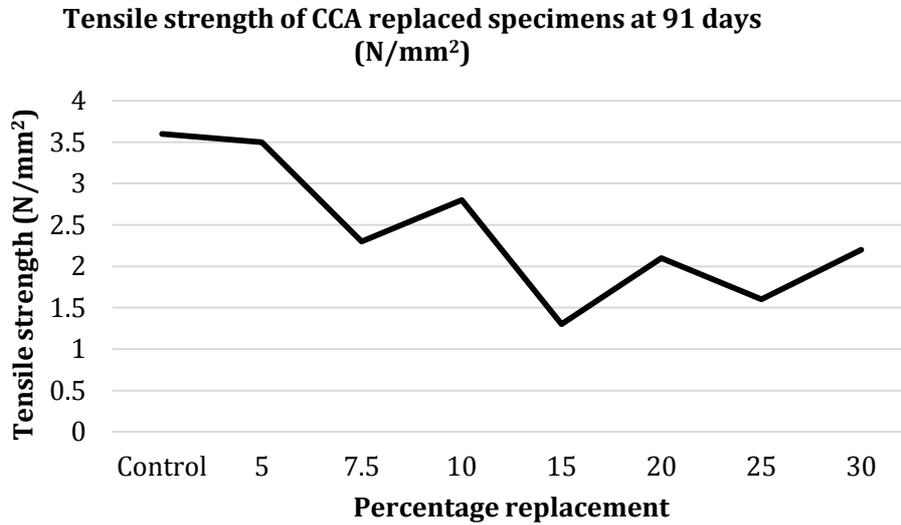


Fig. 2. Tensile strength of CCA replaced concrete at 91 days (N/mm²).

The tensile strength of CCA replaced concrete decreased with increasing CCA replacement as shown in Table 3 and Fig. 2, consistent with the behavior of SCMs [6, 20, 21, 34, 35].

4.4. Density

Table 4 and fig. 3 show the densities of CCA replaced specimens over 91 days curing. Consistent with literature that SCMs provide an advantage by decreasing the mass of concrete per unit volume due to their lower particle specific gravities, the densities of CCA replaced specimens were lower than those of 100% cement at all replacements, and decreased with further CCA replacement [1, 57] Densities were also observed to decrease with curing age, also consistent with literature that SCMs reduce the densities of concrete with time due to the consumption of SiO₂ that is present in SCMs and free lime from cement hydration in the secondary reaction over time to form strength giving compounds such as C-S-H, which are less dense than the cement components from which it is generated [1, 58].

Table 4. Density of CCA Replaced Specimens at Different Curing Ages (Kg/m³)

Curing age (days)	Density at percentage replacement							
	Control	5%	7.50%	10%	15%	20%	25%	30%
7	2350	2354	2350	2310	2307	2300	2280	2242
28	2350	2350	2337	2301	2305	2270	2267	2241
56	2323	2334	2336	2288	2284	2263	2259	2236
91	2366	2333	2330	2286	2278	2260	2253	2236

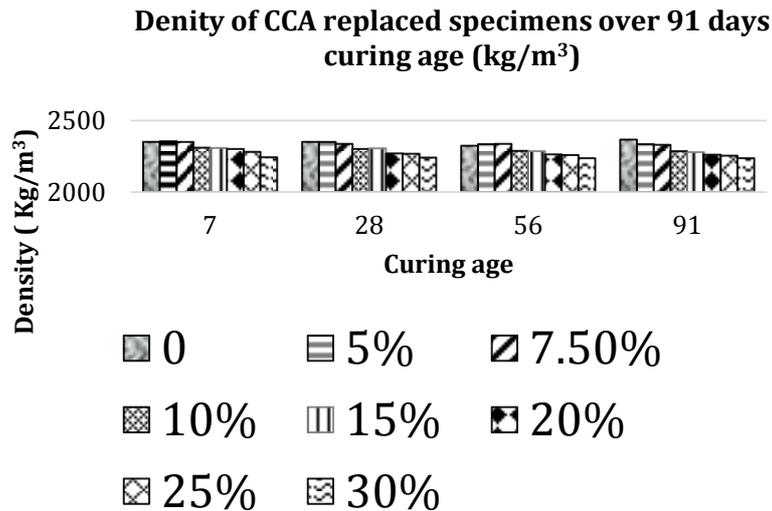


Fig. 3. Density of CCA Replaced Specimens at Different Curing Ages (Kg/m³)

4.5. Workability

Table 5 and Fig. 4 show the slumps of CCA replaced mixes at different replacement levels. Workability was observed to increase with increased replacement. This was not consistent with the findings of Adesanya and Raheem [40], Olafusi and Olutoge [37] and Udoeyo and Abubakar [41] who reported a decrease in workability with an increase in CCA replacement. However, the results were consistent with the behaviour of other established SCMs such as PFA and matakaolin which have been reported to improve the workability of fresh concrete due to their lower densities which increase the volume of mixes, prevent block formation of cement particles, and by the filler effect of their fine particles between aggregates and cement grains, reduce friction between particles and facilitates a better flow of concrete [1, 59]. This improved workability highlights the possibility of using less water in CCA replaced concrete to optimise on strength in line with Abram’s law of WCR [48].

Table 5. Slump of CCA replaced concrete

Specimen	Control	5%	7.50%	10%	15%	20%	25%	30%
Slump (mm)	30	10	20	40	100	250	260	280

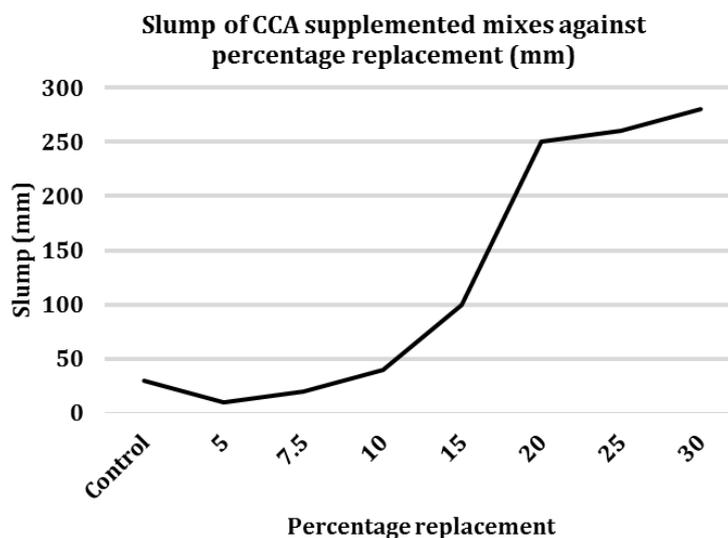


Fig. 4 . Workability of CCA replaced mixes

4.6. Sulfate Resistance

Tables 6, 7 and 8, and Figs. 5, 6 and 7 show elongation of specimens in the Na_2SO_4 , MgSO_4 and the mixed sulphate solutions. The elongation of CCA specimens was lower than that of the control specimens in the Na_2SO_4 solution, but higher in the MgSO_4 and mixed sulphate solutions at 9 months, consistent with the works of Moon et al and Cao [25, 60] who reported lower expansions in the Na_2SO_4 solution for silica fume (SF) replaced specimens. According to literature, Pozzolanic reactions from SCMs help in resisting sulfate attack as they refine pores, dilute C_3A and remove $\text{Ca}(\text{OH})_2$ by converting it into a cementitious material, thereby reducing the quantities of gypsum formed [1, 12, 33, 51]. In contrast with cement hydration, $\text{Ca}(\text{OH})_2$ does not precipitate on the cement grain, but in the void space between the grains of SCMs [1]. Increased C-S-H content that results from pozzolanic reactions, consuming and reducing the amount of $\text{Ca}(\text{OH})_2$ and aluminate hydrate (CaAl_2O_4), and the filler effect of unreacted pozzolans can explain the ability of SCM concretes to resist Na_2SO_4 attack [12, 25, 28, 61]. Although according to literature MgSO_4 attack is not characterised by expansion [25, 26], some expansion was recorded for both the MgSO_4 and the combined sulfate solution, which could be attributed to the lower alkalinity that is associated with the formation of brucite in the cement matrix [25, 26],

Table 6. Elongation of CCA Supplemented Specimens in the Sodium Sulfate Solution

Specimens	Week 1	Week 2	Week 3	Week 4	Week 8	4 months	8 months	9 months
Control	0.000	0.003	0.012	0.016	0.037	0.053	0.075	0.094
7.5% CCA	0.000	0.003	0.003	0.013	0.025	0.028	0.062	0.088

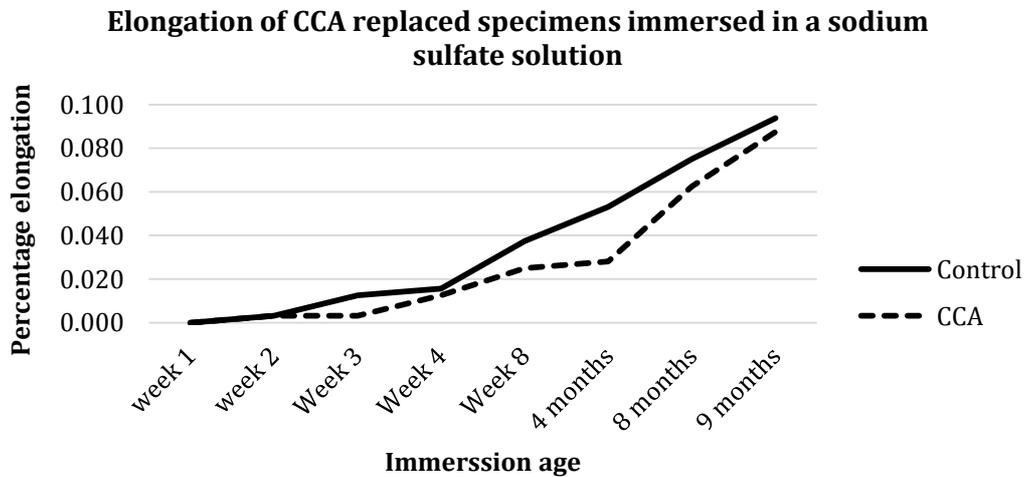


Fig. 5. Elongation of CCA supplemented specimens in the sodium sulfate solution

Table 7. Elongation of CCA supplemented specimens in the magnesium sulfate solution

Specimen	Week 1	Week 2	Week 3	Week 4	Week 8	4 months	8 months	9 months
Control	0.000	0.000	0.016	0.016	0.016	0.019	0.019	0.022
7.5% CCA	0.000	0.006	0.006	0.009	0.009	0.014	0.019	0.044

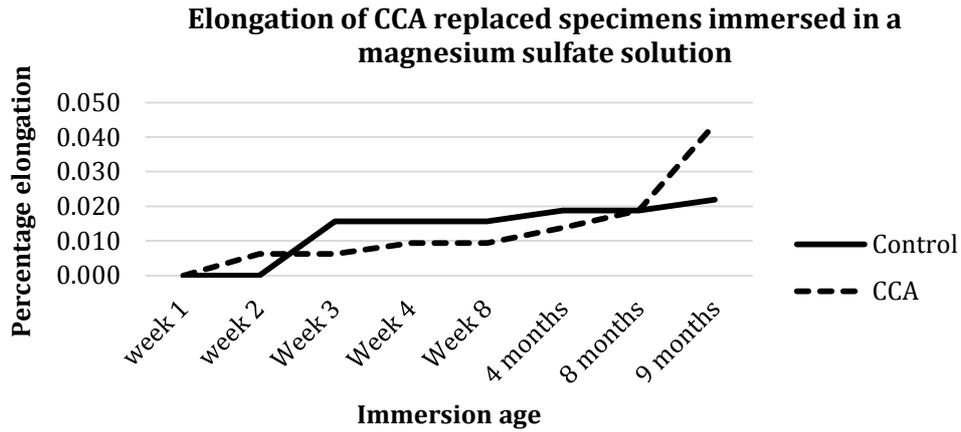


Fig. 6. Elongation of CCA supplemented specimens in the magnesium sulfate solution

Table 8. Elongation of CCA Supplemented Specimens in the Mixed Solution of Magnesium and Sodium Sulfate Solution

Specimens	Week 1	Week 2	Week 3	Week 4	Week 8	4 months	8 months	9 months
Control	0.000	0.000	0.000	0.000	0.025	0.062	0.066	0.075
7.5% CCA	0.000	0.000	0.000	0.000	0.012	0.028	0.038	0.053

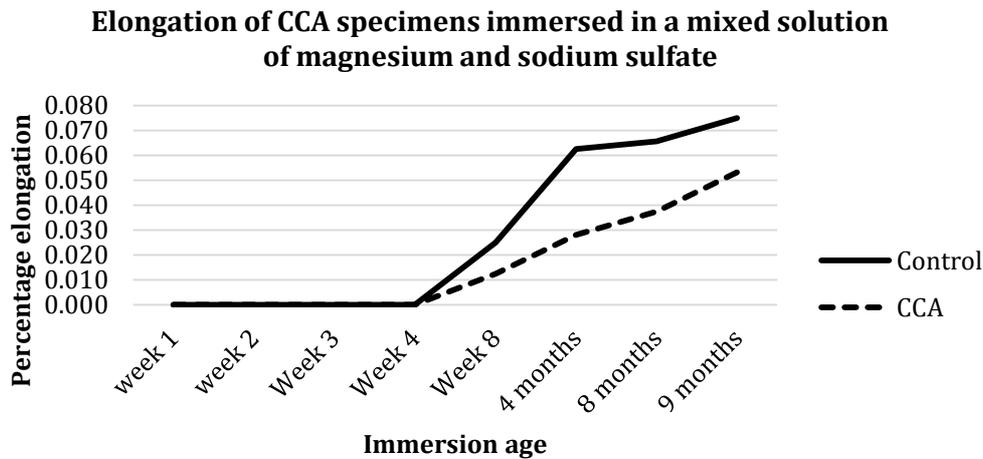


Fig. 7. Elongation of CCA supplemented specimens in the mixed solution of magnesium and sodium sulfate solution

5.7. Strength Deterioration

Table 9. Strength deterioration Factor (SDF) of CCA specimens in Na₂SO₄, MgO₄ and mixed sulfate solutions

Specimens	Sodium sulphate solution	Magnesium sulphate solution	Sodium and magnesium sulphate solution
Control	8.6	17.6	26.9
CCA	4.9	18.6	19.7

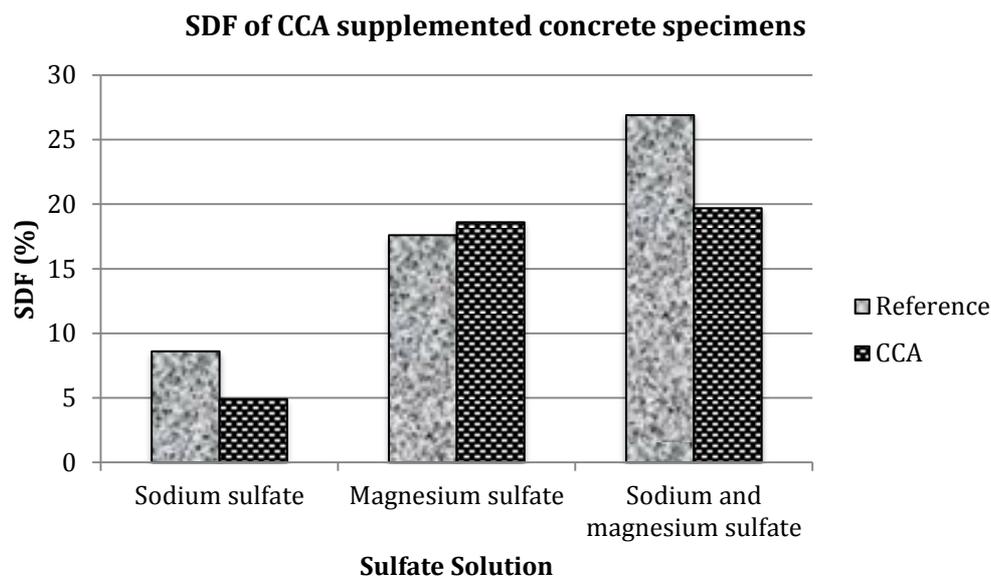


Fig. 8. Strength deterioration Factor (SDF) of CCA specimens in Na_2SO_4 , MgSO_4 and mixed sulfate solutions

Table 9 and Fig. 8 show the percentage strength deterioration factors (SDFs) of specimens inserted in solutions of Na_2SO_4 , MgSO_4 and mixed sulfate solutions. The SDFs of CCA replaced specimens were 4.9, 18.6 and 19.7 while those of the control specimens were 8.6, 17.6 and 26.9 for the Na_2SO_4 , MgSO_4 and mixed sulfate solutions respectively. The results show that CCA added an advantage to the specimens immersed in the Na_2SO_4 and mixed sulfate solutions. However, CCA's performance was lower than that of the control specimens in the MgSO_4 solution. The results were consistent with literature, that MgSO_4 attack is manifested and evaluated through the loss of strength of concrete, and is more pronounced in pozzolanic concretes [26, 51]. The reaction between MgSO_4 and $\text{Ca}(\text{OH})_2$ produces the insoluble brucite, which blocks the capillary pores, forming a sulphate impermeable layer, an explanation as to why the control concrete performed better in the magnesium sulfate solution [26, 51]. However, since SCMs contain less $\text{Ca}(\text{OH})_2$ and more C-S-H, MgSO_4 readily reacts with the secondary C-S-H gel to form magnesium silicate hydrate (M-S-H) gel, which in turn allows the easy diffusion of sulfate ions into the concrete matrix [1, 26, 51]. The results were also consistent with those of Moon, et al. [51], who observed a lower SDF on SF specimens in the Na_2SO_4 solution compared to those of the control, while for specimens immersed in solutions with MgSO_4 , the SDF of SF specimens were higher than those of the control specimens. For Moon, et al. [51], the SDFs of all specimens were higher for the combined sulfate solution, compared with individual sulphate solutions, with SF specimens showing higher SDFs than those of the control specimens. However, CCA replaced specimens showed a lower SDF than the control specimens in the mixed sulfate solutions, even though the SDF was higher for both types of specimens compared to those immersed in individual sulfate solutions. The results were also consistent with literature that the predominance of the more aggressive MgSO_4 attack over Na_2SO_4 attack is spelled in the mixed sulfate solution [33, 51, 61]. It can therefore be concluded that the low CaO levels and the low ratio of $\text{SO}_3/\text{Al}_2\text{O}_3$ according to Tishmack, et al. [35], contributed to the higher sulfate resistance of CCA in the Na_2SO_4 and mixed sulfate solutions.

4.8. Surface Deterioration

Visual observations showed more deterioration to the surface of specimens for both solutions that contained magnesium sulfate, consistent with Shetty [33], Moon, et al. [51], Baghabra, et al. [61], that the attack from MgSO_4 is more severe than that from Na_2SO_4 . The presence of gypsum and brucite confirmed by Moon, et al.

[51] from specimens immersed in $MgSO_4$ solution was considered by the authors as the cause of deterioration to the surface.

From the evidence obtained by this research, it can be concluded that CCA replacement could be used with an advantage over 100% cement in sodium sulfate and mixed sulfate environments.

4.9. Sustainability Implications of Using CCA

From this study, it can be concluded that CCA can be used with replacements of up to 15% to achieve strengths above class C32/40, which is among strength classes that are specified by BSI [54] and [55] use in structural concrete. From the trend of compressive strength gain seen on fig. 1, it is possible to predict that all replacements could achieve strengths that are far above this class after 91 days. Energy efficiency can be achieved by reducing on the amount of clinker and utilising CCA as a SCM, because it requires less process heating and emits fewer levels of CO_2 compared to cement clinker during incineration [14]. CCA, like other agricultural waste products creates environmental hazards when dumped in landfill [1]. Its utilisation in the construction industry can reduce on the overall cost of construction, mitigate on the technical and environmental nuisance associated with the production of cement, reduce solid waste, and conserve existing natural resources, thereby enhancing sustainability as well as improving the properties of fresh and hardened concrete [1, 20, 21].

5. Conclusion

This study investigated the suitability of corncob ash as a supplementary cementitious material. Chemical analysis showed that CCA contained at least 25% of SiO_2 by mass as required by [45]. It is possible that the oxide composition of CCA could have been improved by using controlled incineration as opposed to uncontrolled incineration. The compressive and tensile strengths and sulfate resistance tests showed good repeatability, with strengths capable of structural applications being observed over replacements of up to 20% at 91 days. These results show that CCA can be used as a supplementary cementitious material to mitigate on the cost of cement and its impacts on the environment, thereby enhancing the sustainability of cement

Acknowledgement

The authors would like to acknowledge Kevin Smith, the Materials Laboratory Manager at the Leeds Beckett University for his help, Agnes Mwangi and Samwel Kibiribiri for patiently processing and supplying corncob ash, Rebecca and Tamia Chege for helping out in the lab and Philomena Chege, for her patience.

References

- [1] Bapat J. D. (2012). *Mineral admixtures in cement and concrete*: CRC Press,.
- [2] Mohammed, O. H., Hamid, R. B., and Taha, M. R. (2012). A review of sustainable supplementary cementitious materials as an alternative to all-portland cement mortar and concrete. *Australian Journal of Basic & Applied Sciences*, 6.
- [3] Brien E. J. O., Dixon, A. S., and Sheils, E. (2012). *Reinforced and Prestressed Concrete Design to EC2: The Complete Process*: Spon Press.
- [4] Akinboboye, F., Ogunfayo, I., and Dawodu, H. (2012). Assessment of the severity of CO_2 emission from anthill soils used as replacement for shale in cement manufacture.
- [5] Cline, W. R. (1992). *The Economics of Global Warming*: Peterson Institute.
- [6] Yerramala, A., and Desai, B. (2012). Influence of fly ash replacement on strength properties of cement mortar. *International Journal of Engineering Science and Technology*, 4.
- [7] Soyka, M. J.G, P., and Conneely, D., CO_2 emissions from cement production. *Good Practice Guidance and*

Uncertainty Management in National Greenhouse Gas Inventories, n.d.

- [8] Lippiatt B., and Ahmad S. (2004). Measuring the life-cycle environmental and economic performance of concrete: the BEES approach, *Proceedings of the International Workshop on Sustainable Development and Concrete Technology*, 213-230.
- [9] Worldometers. (2016, 9.6). *Population*. Available: <http://www.worldometers.info/world-population/>
- [10] Muga H., Betz K., Walker J., Pranger C., Vidor A., Eatmon T. (2005). *et al.*, Development of appropriate and sustainable construction materials. *Civil and Environmental Engineering Sustainable Futures Institute, Michigan Technology University*.
- [11] Sakai K. , and Noguchi T. (2012). *The Sustainable Use of Concrete*: CRC press.
- [12] Al-Salami A., and Salem, A. (2010). Effects of mix composition on the sulfate resistance of blended cements, *International Journal of Civil & Environmental Engineering*, 10.
- [13] Islam M. (2013). Strength and durability characteristics of concrete made with fly-ash blended cement, *Australian Journal of Structural Engineering*, 14.
- [14] Gambhir, *Concrete Technology 4e*: Tata McGraw-Hill Education, 2009.
- [15] Mehta P. K. (2001). Reducing the environmental impact of concrete, *Concrete International*, 23, 61-66.
- [16] Johnson M. E., and Gonzalez A. (2013). Estimating cost savings for aviation fuel and CO₂ emission reductions strategies, *Collegiate Aviation Review*, 31.
- [17] Khan R., Jabbar, A., Ahmad I., Khan, W., Khan, A. N., and Mirza J. (2012). Reduction in environmental problems using rice-husk ash in concrete, *Construction and Building Materials*, 30, 360-365.
- [18] Steele K., Cole G., Parke G., Clarke B., and Harding J. (2002). The application of life cycle assessment technique in the investigation of brick arch highway bridges. *Proceedings of Conf. for the Engineering Doctorate in Environmental Technology*.
- [19] Davison B. and Owens G. W., *Steel Designers' Manual*: Wiley. com, 2011.
- [20] Malhotra, V. and Mehta, P. (2005). High-performance, high-volume fly ash concrete: Materials, mixture proportions, properties, construction practice, and case histories. *Supplementary Cementing Materials for Sustainable Development Inc., Ottawa, ON, Canada*.
- [21] Sengul O., and Tasdemir, M. A., Compressive strength and rapid chloride permeability of concretes with ground fly ash and slag, *Journal of materials in civil engineering*, vol. 21, pp. 494-501, 2009.
- [22] Reddy M., Ramana R. I., and Kumar, R., Experimental studies on mortars containing pozzolonic materials like fly ash, rice husk ash and silica fumes. *IUP Journal of Structural Engineering*, 6, 2013.
- [23] Skalny J. (2002). Internal sulfate attack—points of agreement and disagreement," *Int. RILEM TC 186-ISA Workshop on Internal Sulfate Attack and Delayed Ettringite Formation*, 265-276.
- [24] Veiga K. and Gastaldini A. (2012). Sulfate attack on a white Portland cement with activated slag, *Construction and Building Materials*, 34, 494-503.
- [25] Moon, H., Lee S., and Kim H., The selection of effective Korean cement for sulfate environments, *Proceeding of the 3rd International Conference on Concrete Under Severe Conditions, CONSEC*, 2001, pp. 349-356.
- [26] Türker F., Aköz F., Koral S., and Yüzer N., (1997). Effects of magnesium sulfate concentration on the sulfate resistance of mortars with and without silica fume, *Cement and Concrete Research*, 27, 205-214.
- [27] Bonen D., and Cohenm M. D., (1992). Magnesium sulfate attack on portland cement paste—II. Chemical and mineralogical analyses, *Cement and concrete research*, 22, 707-718.
- [28] Al-Amoudi O. S. B., Maslehuddin M., and Saadi M. M., (1995). Effect of magnesium sulfate and sodium sulfate on the durability performance of plain and blended cements. *ACI Materials Journal*, 92, 15-24, 1995.
- [29] Cohen M. D., and Mather B. (1991). Sulfate attack on concrete: research needs, *Materials Journal*, 88,

62-69.

- [30] Kandasamy S., and Shehata M. H. (2014). Durability of ternary blends containing high calcium fly ash and slag against sodium sulphate attack," *Construction and Building Materials*, 53, 267-272.
- [31] Santhanam M., Cohen M. D., Olek J. (2003). Mechanism of sulfate attack: a fresh look: Part 2. Proposed mechanisms, *Cement and Concrete Research*,. 33, 341-346.
- [32] Sarkar S., Mahadevan S., Meeussen J., Van der Sloot H., and Kosson D. (2010). Numerical simulation of cementitious materials degradation under external sulfate attack, *Cement and Concrete Composites*, 32, 241-252.
- [33] Shetty M. (2005). *Concrete technology: theory and practice*: S. Chand,.
- [34] Sumer M., (2012). Compressive strength and sulfate resistance properties of concretes containing Class F and Class C fly ashes," *Construction and Building Materials*, 34, 531-536.
- [35] Tishmack J., Olek J., and Diamond S., "Characterization of high-calcium fly ashes and their potential influence on ettringite formation in cementitious systems," *Cement Concrete and Aggregates*, vol. 21, pp. 82-92, 1999.
- [36] Byerlee D., and Heisey P. W. (1997). Evolution of the African maize economy, *Africa's Emerging Maize Revolution*, 9-22.
- [37] Olafusi O., and Olutoge F. (2012). Strength properties of corn cob ash concrete, *Journal of Emerging Trends in Engineering and Applied Sciences*, 3, 297-301.
- [38] Rao K. J., Mujeeb M. A., and Sastri M. (2014). Behavior of ternary blended concrete with fly ash and silica fume, *IUP Journal of Structural Engineering*, 7, p. 25.
- [39] Zhou X. M., Slater J. R., Wavell S. E., and Oladiran O. (2012). Effects of PFA and GGBS on Early-Ages Engineering Properties of Portland Cement Systems, *Journal of Advanced Concrete Technology*, 10, 74-85.
- [40] Adesanya D. A. and Raheem A. A., (2009) A study of the workability and compressive strength characteristics of corn cob ash blended cement concrete, *Construction and Building Materials*, 23, 311-317.
- [41] Udoeyo F. F., and Abubakar S. A. (2003). Maize-cob ash as filler in concrete, *Journal of Materials in Civil Engineering*, 15, 205-208.
- [42] Mulwa M. O., Karanja T. O. J., and Wachira M. J. (2016), Effect of sulphate ions in mixing water on cement mortar performance. Chemistry Department, Kenyatta University, Kenya. School of Pure and Applied Sciences, Embu University College, Kenya., *IOSR Journal of Applied Chemistry (IOSR-JAC)*, 9, 11-15.
- [43] BRE, *Building Research Establishment. The Concrete Centre, Concrete in Aggressive Ground, Special Digest 1, 3rd edn, BRE Construction Division, Garston, UK, 2005.*
- [44] Neville A. (2000). Water and concrete: A love-hate relationship, *Concrete International*, 22, 34-38.
- [45] BSI, "BS EN 197-1: 2000. Part 1 Cement composition, specifications and conformity criteria for common cements. British Standards Institution (BSI), London, UK," *BSOL*, 2000.
- [46] BSI, "BS EN 12390-1:2012. Testing hardened concrete. Part 1: Shape, dimensions and other requirements for specimens and moulds. British Standards Institution (BSI), London, UK," 2012.
- [47] BSI, "BS EN 12390-2:2009. Making and curing specimens for strength tests. British Standards Institution (BSI), London, UK," 2009.
- [48] Oluokun F. A. (1994). Fly ash concrete mix design and the water-cement ratio law, *Materials Journal*, 91, 362-371.
- [49] ASTM, "C1012/C1012M-15. Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution1," *American Society for Testing and Materials*, 2015.

- [50] BSI, "BS EN 12390-4:2000. Testing hardened concrete. Compressive strength. Specification for testing machines. British Standards Institution (BSI), London, UK," ed: Lithuanian Standards Board. Vilnius, 2000.
- [51] Moon H. Y., Lee S.-T., and Kim S.-S. (2003) Sulphate resistance of silica fume blended mortars exposed to various sulphate solutions, *Canadian Journal of Civil Engineering*, 30, 625-636.
- [52] ASTM, "C618: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, American Society for Testing and Materials, ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/C0618-12,," *American Society for Testing and Materials*, 2012.
- [53] Al-Akhras, N. M. (2006). Durability of metakaolin concrete to sulfate attack. *Cement and concrete research*, 36(9), 1727-1734., (Khedr and Idriss, 1995).
- [54] BSI, "BS EN 1992-1-1: 2004: Eurocode 2: Design of Concrete Structures, Part 1-1: General Rules and Rules for Buildings. British Standards Institution (BSI), London, UK," 2004.
- [55] BSI, "BS 8500-1:2015:Concrete – Complementary British Standard to BS EN 206. Part 1: Method of specifying and guidance for the specifier. British Standards Institution (BSI), London, UK," 2015.
- [56] Adesanya D. (1996). Evaluation of blended cement mortar, concrete and stabilized earth made from ordinary Portland cement and corn cob ash," *Construction and Building Materials*, vol. 10, pp. 451-456, 1996.
- [57] Sathawane S. H., Vairagade V. S., and Kene K. S. (2013). Combine effect of rice husk ash and fly ash on concrete by 30% cement replacement, *Procedia Engineering*, 51, 35-44.
- [58] C. L. Page and M. M. Page, *Durability of concrete and cement composites*: Elsevier, 2007.
- [59] Le H. T. and H.-M. Ludwig, "Effect of rice husk ash and other mineral admixtures on properties of self-compacting high performance concrete," *Materials & Design*, vol. 89, pp. 156-166, 2016.
- [60] Cao H., Bucea L., Ray A., and Yozghatlian S. (1997). The effect of cement composition and pH of environment on sulfate resistance of Portland cements and blended cements," *Cement and Concrete Composites*, 19, 161-171.
- [61] Baghabra O. S., Al-Amoudi M. M., and Saadi M. M., Effect of magnesium sulfate and sodium sulfate on the durability performance of plain and blended cements, *ACI Materials Journal*, 92, 1995.



John Kamau, the main author was born in Kenya in 1973. He graduated with a Bachelor of Science with honors degree in civil engineering from Leeds Beckett University, Leeds, West Yorkshire, United Kingdom (UK) in 2010 and a Master of Science degree in structural engineering from the University of Leeds, Leeds, West Yorkshire, UK in 2011. He is currently undertaking a research programme on supplementary cementitious materials at the Leeds Beckett University, Leeds, West Yorkshire, UK. He has worked in the past as a CIVIL ENGINEER and is currently working as a STRUCTURAL ENGINEER in Barnsley, South Yorkshire, UK.



Ash Ahmed, was born in Manchester, UK. He graduated with a Bachelor of Science with honors degree in Materials Science from Manchester University, United Kingdom (UK) and a Master of Philosophy degree in Metallurgy from the University of Manchester, UK. He then completed his PhD in Polymer Science from Heriot-Watt University, Edinburgh, UK. Dr Ahmed has been a Senior Lecturer at Leeds Beckett University since 2005, teaching modules in materials science at undergraduate and postgraduate levels. Previously Head of Civil Engineering, Dr Ahmed's area of research is in the field of sustainable construction materials using recycled and waste products.