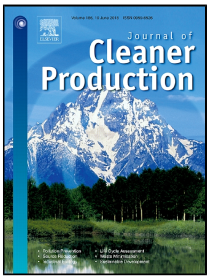

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USE OF RECYCLED AGGREGATES FOR LOW CARBON AND COST EFFECTIVE CONCRETE CONSTRUCTION

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ABSTRACT

Reducing the carbon footprint of activities and a more prudent use of natural resources require for concrete production is a significant concern on the grounds of environmental and economical sustainability. It is widely reported that the concrete industry contributes around 8% to total global carbon dioxide (CO_2) emissions whereas cement utilization contributes approximately 90% of these emissions. Moreover, natural resources are becoming scarce and the world has become environmentally conscious. Against this background, reported work carried out to assess BS EN 197-1 cement concretes made with natural and partially substituted recycled aggregates and thus their suitability for use in low carbon cost effective concrete construction. In that respect, supplementary cementitious materials (SCMs) additive cements were selected to reduce the potential carbon footprint and establish fresh and hardened properties of natural aggregate concrete (NAC) mixes for equivalent 28-day compressive cube strengths of 40 and 50 N/mm^2. Then, a further investigation was carried out to assess the potential embodied CO_2 (ECO_2) emissions and cost analysis and performance of partially substituted recycled aggregates (coarse recycled aggregate (RA) and recycled glass sand (RGS) with proportions of 25% and 15% respectively by mass replacement).

Results showed that SCMs incorporated NAC mixes has a potential to reduce ECO_2 emissions and cost of concrete whilst partially substituted recycled aggregate concrete (RAC) mixes provided comparable ECO_2 emissions but slightly increased cost for equal design strength. The loss of workability was found to be more for SCMs and recycled aggregate incorporated mixes. Studies of hardened concrete properties, comprising bulk engineering properties (compressive cube and cylinder strength, flexural strength, drying shrinkage) and durability (initial surface absorption) showed enhanced performance for SCMs concretes equivalent strength, except resistance to carbonation. However, the use of SCMs in RAC mixes slightly reduced the engineering and durability properties compared to corresponding NAC mixes.

Keywords: Initial surface absorption, carbonation, drying shrinkage, mineral admixtures, recycled glass sand, coarse recycled aggregate.

Notation List

CH : Calcium Hydroxide
CSH : Calcium-Silicate-Hydrate
ECO_2 : Embodied CO_2
FA : Fly ash
GGBS : Ground granulated blast-furnace slag
ISAT : Initial surface absorption test
ITZ : Interafacial transition zone
NAC : Natural aggregate concrete
PC : Portland cement
RA : Recycled coarse aggregate
RAC : Recycled aggregate
RGS : Recycled glass sand concrete
SCMs : Supplementary cementitious materials
SF : Silica fume
SP : Superplasticizer
WA : Water absorption

1. Introduction

The effect of global warming on the built environmental has reached to crucial levels. The average global temperature has risen 0.6°C in the last century and is expected to rise between 1.4 and 5.8°C in the next century [1]. Carbon dioxide (CO_2) is one of the greenhouse gases that trigger the global warming the most and the UK concrete industry takes CO_2 emissions of concrete into account to assess environmental credentials. The UK government has agreed to cut down its CO_2 emissions by 50% and 80% by the year 2025 and 2050 respectively [2]. In conformity with this, national Climate Change Act and international Kyoto Protocols agreed on reducing concrete emissions by 30% in comparison to baseline year, 1990 levels [3]. As Portland cement (PC) is the main contributor of CO_2 emissions, concrete construction industry is seeking to use various types of more environmentally friendly supplementary cementititous materials (SCMs) from other industries such as fly ash (FA), ground granulated blast-furnace slag (GGBS), silica fume (SF) and etc in conformity with BS EN 197-1 [4]. The use of these materials could reduce concrete CO_2 emissions significantly. At present, CO_2 emissions of standardised concrete production in the UK are estimated to be 76.3 kg CO_2 per tonne which is 26% lower than baseline levels agreed (103.1 kg CO_2 per tonne) [3]. The estimation for the embodied CO_2 (ECO_2) of concrete is approximately 100 kg CO_2 per tonne [5]. However, this is a representative figure for concrete production based on a specific amount of PC used and there is limited information on concrete CO_2 emissions for specific concrete classes. Currently ECO_2 is a standard practice to indicate environmental impact of concrete. A study [6] provided ECO_2 of concretes as 0.132 kg ECO_2/kg and 0.151 kg ECO_2/kg (132 kg ECO_2/tonne and 151 kg ECO_2/tonne) for 40 and 50 N/mm^2 design strength classes respectively. Addition to that, Jones [7] stated approximately 315 and 391 kg ECO_2 per m^3 (approximately 131 and 161 kg ECO_2/tonne) for 40 and 50 N/mm^2 cube strength concretes respectively. According to Purnell [8], ECO_2 emissions of concrete are based on concrete design strength and the replacement level of cementitious materials used. The UK Concrete Industry Sustainable Concrete forum stated ECO_2 emissions of concrete made with 300 kg cement content as 95 kg ECO_2/tonne [9]. Flower [10] revealed ECO_2 emissions of normal and blended cement concrete ranging between 0.225-0.322 kg/m^3, equivalent to 95-135 kg/tonne approximately. In addition, Knoeri [11] stated that recycled materials are not to be considered only in terms of ECO_2 emissions as the use of recycled materials prevents the extraction of raw materials. From the performance point of view, general trend observed that utilization of SCMs such as FA and GGBS resulted in lower performance at early ages (7 days>) whilst improves performance at latter ages (>28 days) [12-16]. In addition, SF incorporation was observed to improve mechanical performance at both early and later ages [17]. However, durability performance of SCMs additive concrete is still unclear.

Reducing the use of raw materials in the construction industry is another principle of producing sustainable concrete. Thus, Aggregate Levy has come into action by the UK government in order to prevent the use of natural resources and encourage the use of recycled or secondary materials. Primary aggregates, sand and gravel, are the most used materials in construction industry and use of these raw materials cause irreversible effects on the environment such as agricultural losses and rainforest destructions. Previously published reports stated that the global construction industry is estimated to use 48.3 billion tonnes of aggregates per annum [18]. In the UK, the consumption of primary aggregates is assumed around 210 million tonnes whereas 43%, approximately 90 million tonnes, of these are used in the concrete industry [19]. The use of recycled coarse aggregates (RA) in concrete is of significant interest due to its contribution to sustainable development by reducing demand on mineral extraction and minimizing landfill. RA is used in lower grade applications in conformity with BS EN 12620 [20] but it can also be used in higher grade applications when it meets and specifications of BS 8500. However, there is no generic requirement on the use of recycled fine aggregates. By means of its economic viability, crushed recycled glass sand (RGS), either washed or unwashed, can be used as a fine aggregate replacement in concrete. Its use in concrete reduces the overall greenhouse gas emissions and the use of natural aggregates, therefore, improves the sustainability credentials [21]. In the UK, use of recycled and secondary materials has increased significantly to 70 million tonnes per annum in 2007 compared to 30 million tonnes per annum in 1990. This is equivalent to 25% of market share which makes the UK construction industry a leading sector in the utilization of these waste and secondary aggregate materials amongst Europe [22]. There is 1.85 million tonnes of glass cullet obtained from waste glass are being collected annually. Having this said, the municipal recycling rate is 34% for container glass in the UK [23].

Existing researches on RA incorporated concretes found out that RA addition by 30% could reduce both mechanical and durability properties slightly compared to their conventional concrete mixes [24-28]. On the other hand, Limbachiya [12] reported RGS incorporation by 15% resulted in comparable mechanical performances. However, the effect of RGS on concrete durability is ambiguous.

The construction industry is very cautious about introducing new materials rather than well-tried materials due to performance related reasons. The use of recycled aggregates as a substitute to conventional natural aggregates in concrete production in order to reduce mineral extraction and minimize landfill concrete production is an area of interest to scientific community in the course of sustainable development. Existing studies mainly focussed on the environmental impact (ECO_2 emissions) of concrete mixes which PC is partially substituted by the SMCs associated with engineering and durability performances. However, production of energy efficient materials and use of environmentally friendly materials whilst minimising the cost of the construction are some of the major challenges that construction industry faces nowadays. Only, there is either few or no clear information on the ECO_2 emissions and cost analysis of SCMs concretes made with coarse and fine recycled aggregates. Therefore, this study presented here investigates the ECO_2 emissions and cost analysis of concrete mixes made with CEM II/B-M (65PC-30GGBS-5SF) and CEM V/A (40PC-30GGBS-30FA) cements in conformity with BS EN 197-1 and partially substituted coarse recycled aggregate (RA) and recycled glass sand (RGS). The 28-day design strengths of concrete mixes were sought as 40 and 50 N/mm^2. The mixes were tested for a key of engineering (compressive cube and cylinder strengths, flexural strength and drying shrinkage) and durability (initial surface absorption test and carbonation resistance) properties. Also, ECO_2 emissions and cost analysis on concrete performance and potential aspects for practical applications of developed concretes are also stated.

2. Experimental and testing programme

The research programme was divided into three main parts. Initially, broad range of concrete properties in the fresh and hardened state is established. In addition, ECO_2 emissions and cost analysis are carried out on the developed concretes. Finally, the practical implications on the use of concretes investigated are stated.

2.1. Materials

2.1.1. Cements

The cement types used were CEM I, CEM II/B-M and CEM V/A conforming to BS EN 197-1. A CEM I, 52,5N PC used for reference mixes. Other cement main constituents used were GGBS, FA and SF and blended with PC to produce CEM II/B-M and CEM V/A cements for this study. GGBS was obtained from iron-making production in the UK conforming to BS EN 15167-1 [29]. FA and SF used were conforming to BS EN 450-1 [30] and BS 13263-1 [31] respectively. FA was obtained from Drax coal-fired power station in the UK. SF incorporated was in slurry form including 50% water and 50% silica powder. Physical properties and chemical composition of cement constituents used are given in Table 1.

2.1.2. Aggregates

Natural river sand and natural uncrushed Thames valley gravel were used as fine and coarse aggregates with maximum nominal sizes of 5 and 20 mm respectively in conformity with BS EN 12620. The coarse recycled aggregate (RA) and recycled washed glass sand (RGS), meeting the requirements of BS EN 12620, were used in RAC mixes to substitute natural aggregates by 25% on mass basis. RA was graded 20-5 mm aggregates and observed to be irregular shaped compared to natural coarse aggregates. Recycled washed glass sand (RGS) with maximum nominal size of 5 mm was observed to be coarser than natural sand. Both natural and recycled aggregates used were in the saturated surface dry condition. The physical and mechanical properties of natural and recycled aggregates used are given in Table 2 and Figure 1. Total water content was determined considering water absorption and moisture content characteristics of both types of aggregates prior to mixing to maintain the estimated free water content.

Table 1. Chemical properties of cementitious constituents

Compound	Percentage (%)			
	PC	FA	GGBS	SF
SiO_2	19.77	50.4	36.76	94.84
Al_2O_3	4.90	28	13.38	-
Fe_2O_3	2.33	9	0.37	-
CaO	62.56	6	39.56	0.41
MgO	2.64	1.50	7.33	-
SO_3	3.08	0.40	0.08	0.32
K_2O	0.66	2.50	0.54	0.88
Na_2O	0.17	0.90	0.32	0.26
Loss on ignition	1.65	4.50	0.92	1.56
Fineness (m^2/kg)	372	280	501	22700
Density (g/cm^3)	3.14	2.28	2.92	1.4

Table 2. Physical and mechanical properties of aggregates used

Properties	Type of aggregates			
	Natural		Recycled	
	Sand	Gravel	Glass sand	Gravel
Physical (BS EN 1097, part 6)				
Unit weight (g/m^3)	1.61	1.49	1.35	1.37
Percentage of voids (%)	41.7	39.9	42.3	43.2
Apparent density (g/m^3)	2.78	2.59	2.38	2.57
Water absorption capacity (%)	0.17	1.69	0.66	2.57
Specific gravity	2.76	2.52	2.36	2.47
Fineness modulus	2.62	3.31	3.10	3.54
**Mechanical (BS 812, parts 110-112)*				
Aggregate crushing value (% ACV)	-	15.7	-	18.0
Aggregate impact value (% AIV)	-	10.7	-	6.5

*Mechanical properties were measured on 10-14 mm test samples

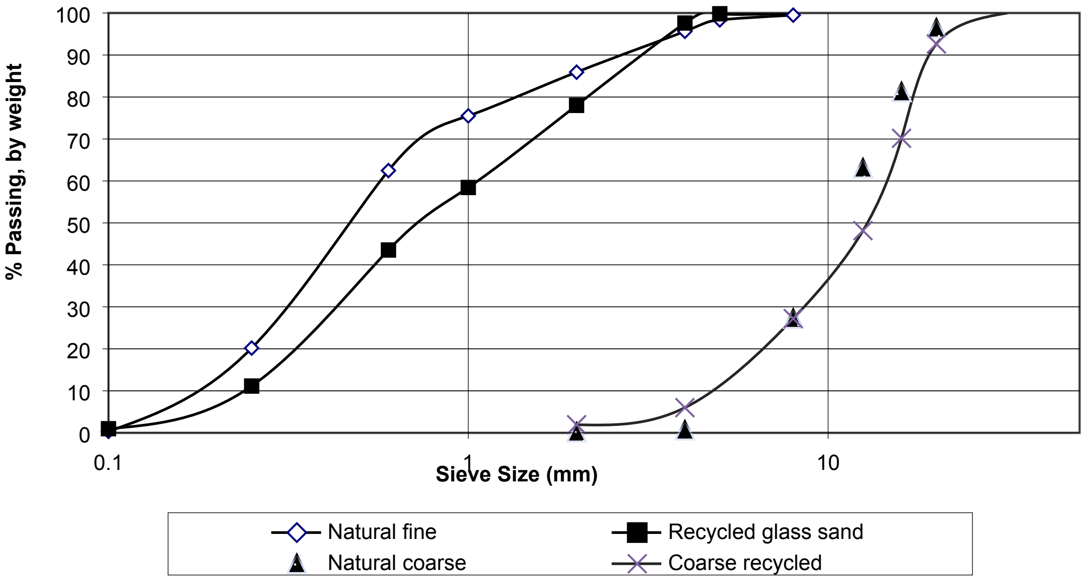


Figure 1. Particle size distribution of natural and recycled aggregates used in this study

2.1.3. Admixture

Water reducer liquid SP, ADVA 655, obtained from Grace Construction Products Limited based on polycarboxylate molecules was used to provide slump retention to improve workability of CEM II/B-M and CEM V/A cement and recycled aggregate incorporated mixes. Its use was in conformity with BS

EN 934-2:2009+A1:2012 [32].The dosage required was arranged during the optimisation of the mixes dependent upon w/c ratio and the amount and nature of cementitious materials used.

2.1.4. Water

Standard tap water was used during the concrete production for all mixes. In addition to that, de-ionised water was used to carry out ISAT for the concrete durability.

2.2. Mix proportions and concrete mix design

Conventional BRE mix design method [33] was used to produce trial mixes for a given design strength. Mixes were designed to achieve workability between 60-180 mm in conformity with BRE mix design document and S3 consistency class in accordance with BS EN 206-1. The 28-day cube strengths sought were 40 and 50 N/mm^2. The free water contents of these mixes were modified in accordance with the cement type used. To achieve equivalent 28-day cube strength as CEM I concrete, the w/c ratios and total cementitious contents were altered depending upon the relationship between the compressive cube strength and the w/c ratios of trial mixes. Detailed summary of mix proportions used are given in tables 3 and 4. It is noteworthy to mention that SF values given is in slurry form, therefore the same amount of half of SF used was on mass basis was reduced from the free water content to maintain the water content. For CEM II/B-M cement mixes, free water/cement ratio can be defined by adding free water content and half of the SF used and divided by cementitious content including binders and other half of the SF used.

The initial mix was a control mix with PC only specified as CEM I and a Portland-composite cement mix was CEM II/B-M (65%PC/30%GGBS/5%SF). In addition to these, a composite cement mix stated as CEM V/A (40%PC-30%GGBS-30%FA). At first, these cements were used to produce natural aggregate concrete (NAC) mixes. Having NAC mixes established, optimisation of concrete mixes was carried out to determine the replacement ratios of recycled aggregates, both recycled glass sand and recycled coarse aggregate, for the optimum strength concrete for a margin of no more than 10% strength loss compared to corresponding NAC mixes. The replacement ratios were determined as 25% and 15% for RA and RGS as coarse and fine aggregates respectively for the production of recycled aggregate concrete (RAC) mixes.

Table 3. Mix proportions for 28-day 40 and 50 N/mm^2 design strength NAC mixes

Design strength	Cements	Mix proportions (kg/m^3)									Free water/cement ratio
		Water	Cementitious constituents				Aggregates				
			PC	FA	GGBS	SF	Gravel		Sand		
							NA	RA	NS	RGS	
40 N/mm^2	CEM I	195	385	-	-	-	1120	-	645	-	0.51
	CEM II/B-M	175	210	-	95	30	1120	-	720	-	0.59
	CEM V/A	170	165	120	120	-	1135	-	650	-	0.41
50 N/mm^2	CEM I	195	460	-	-	-	1085	-	620	-	0.41
	CEM II/B-M	175	270	-	125	40	1085	-	660	-	0.47
	CEM V/A	170	175	130	130	-	1085	-	670	-	0.39

Table 4. Mix proportions for 28-day 40 and 50 N/mm^2 design strength RAC mixes

Design strength	Cements	Mix proportions (kg/m^3)									Free water/cement ratio
		Water	Cementitious constituents				Aggregates				
			PC	FA	GGBS	SF	Gravel		Sand		
							NA	RA	NS	RGS	
40 N/mm^2	CEM I	195	385	-	-	-	840	280	550	95	0.51
	CEM II/B-M	175	210	-	95	30	840	280	610	110	0.59
	CEM V/A	170	165	120	120	-	850	285	575	105	0.41
50 N/mm^2	CEM I	195	460	-	-	-	815	270	515	90	0.41
	CEM II/B-M	175	270	-	125	40	815	270	555	100	0.47
	CEM V/A	170	175	130	130	-	815	270	570	100	0.39

2.3. Test procedures

Concrete production and testing was carried out in accordance with BS EN 12350:2000 Parts 1 and 2. Initial slump was recorded following to concrete production. Then, slump loss was investigated through compacting factor test with 30 minutes intervals up to 150 minutes. Produced mixes were covered under polythene sheets for 24 hours after casting under moist condition, prior to testing or exposure to 20 °C water curing condition in conformity with BS EN 12390-2 [34]. Engineering properties examined covered compressive and flexural strengths and drying shrinkage. Compressive strength developments of concrete mixes were investigated through 100 mm cubes conforming to BS EN 12390-3. Compressive cylinder strengths were determined through testing 150 mm diameter and 300 mm high cylinder specimens. Four-point loading test equipment was used to test flexural strength of concrete mixes with specimen dimensions of 100 mm x 100 mm x 500 mm in accordance with BS EN 12390-5. Drying shrinkage was measured on 75 mm x 75 mm x 280 mm prism specimens. The samples were cured under water for the first 7 days and then stored in drying environment (22 °C and 55% RH) in conformity with BS ISO 1920-8. Drying shrinkage values were recorded using stainless strain gauge pins fixed through both edges up to 112 days. In addition, initial surface absorption test and carbonation resistance were investigated to establish durability performance of concrete mixes. Table 5 shows test ages for the range of properties stated. 3 samples were tested and averaged for different types of tests at given test ages.

All concrete samples were cured under 20±2 °C water in conformity with BS EN 12390-2 until the test age complying with the relevant standard. Different curing schemes of CU2 and CU3 were considered for samples subjected to various engineering and durability tests in accordance with BS ISO 1920-8 and BS 1881-210 respectively. Details of the curing conditions for the appropriate tests carried out are given in table 6.

Table 5 – Age at test for the range of properties considered

PROPERTY	TEST AGES
Compressive strength, N/mm^2	1, 3, 7, 28, 56, 90, 180 and 365 days
Compressive cylinder strength, N/mm^2	28, 56 and 90 days
Flexural strength, N/mm^2	7, 28 and 56 days
Drying shrinkage, 10^{-6}	7, 14, 21, 28, 56 and 112 days
Initial surface absorption, ml/m^2/s x 10^{-2}	28 days
Carbonation resistance, mm	13, 26 and 52 weeks

Table 6. Curing conditions applied prior to engineering and durability tests

CODE	CURING METHOD	TEST
CU1	Under water (20±2 °C)	Compressive strength, flexural strength, initial surface absorption, carbonation
CU2	7-days CU1, then air 20±2 °C and 55% RH	Drying shrinkage
CU3	28-days CU1, then 14-days CU2	Resistance to carbonation

2.3.1. Permeation property

Concrete sustainability requires improved performance from the durability point of view. Concrete performance against penetration of hazardous chemicals plays significant role on concrete durability and therefore service life of concrete. In the light of these, permeability property is one of the indicators to assess the durability of concrete. Permeability of concrete was determined using the initial surface absorption test (ISAT), as described in BS 1881-208 [35]. 150mm cube samples were cast and cured in 20°C water for 28 days, then followed by pre-conditioning through oven drying at 105 °C to constant mass prior to test. The contact surface area was sealed to avoid leaking during the test while testing and evaluation of the volume flow is obtained by measuring the length of flow along the capillary tube with a known dimension. ISAT values were determined after ten minutes (ISAT-10) in ml/m^2/second.

The ISAT-10 value of 50 x 10^{-2} ml/m^2/sec is mostly assumed as high whilst below 25 x 10^{-2} ml/m^2/sec is assumed as low. Moreover, N-value which indicates rate of decay in the absorption with time are also provided in accordance with the ISAT values of concretes.

2.3.2. Carbonation penetration

100 mm cubes were used to investigate carbonation penetration of developed concretes. The samples were cured under CU1 conditions and stored in ambient conditions for at least 14 days to air dry. The samples were left in a chamber with 3.5 to 4.0% CO_2 concentration at standard 20 °C and 60% relative humidity as described in BS 1881-210. The top and bottom faces and two opposite sides of test samples were coated with epoxy based paint to allow CO_2 penetrate only through particular location. Test samples were exposed to CO_2 by 13, 26 and 52 weeks. Samples of thicknesses of not less than 10 mm were cut with water-cooled diamond saw and carbonation depth was measured by spraying phenolphthalein indicator solution (1 gr phenolphthalein indicator in a solution 70 ml ethanol and 30 ml demineralised water). Following to spraying indicator solution, sections with pH values less than 9.2 which indicates carbonated areas remained colourless. In addition, areas having pink colour due to change in its alkalinity demonstrated non-carbonated sections. The carbonation depth indicated by the boundary where the concrete turned pink. Three or four readings from each side were taken and averaged. It is worthy to mention that the depths behind the coarser aggregates were ignored.

2.4. ECO_2 emissions and cost analysis

This section covers the ECO_2 emissions calculations and cost analysis of NAC and RAC mixes. The relevant information regarding to ECO_2 emissions and cost of materials obtained from the relevant trade associations such as Mineral Products Association, Cementitious Slag Makers Association and the UK Quality Ash Association and the suppliers are provided table 7. In addition, relevant data for SF and admixture was obtained from the distributors and manufacturers.

The ECO_2 emissions of concrete mixes were calculated by multiplying the mass of each ingredient by its ECO_2 value provided for each mix design for the equal 28-day design strength. The ECO_2 emissions for each constituent are then added to find the overall environmental emissions of concrete mixes. It is worthwhile to mention that overall ECO_2 emissions of each concrete mix were divided by the concrete density and final results were expressed as kg ECO_2/tonne. For simplicity, the assessment of ECO_2 includes 'cradle to factory gate' emissions and emissions arise from the transportation from the place of manufacture of the material to the concrete plant and concrete plant to the construction site was not considered.

Table 7. ECO_2 emissions and cost of concrete constituents obtained [36]

Concrete constituents	**ECO_2 (kg CO_2/ton)**	**Price (£)**
PC	913	350 (/ton)
FA	4	150 (/ton)
GGBS	67	110 (/ton)
SF	14	200 (/ton)
Natural sand	5.2	32.5 (/ton)
Recycled glass sand	11	32.5 (/ton)
Natural gravel	5.2	39.75 (/ton)
Recycled coarse aggregate	7.9	58 (/ton)
Admixture	770	1.4 (/litre)

3. Results and Discussion

3.1. Slump Test

Fresh concrete performances were investigated through slump and loss of workability over time tests. Results obtained can be seen in Table 8 and 9 for NAC and RAC mixes respectively. As the initial target for concretes to have S3 consistency class (100-150 mm) with respect to BS EN 206-1, the admixture contents used were adjusted to achieve the target slump values. Thus, admixtures required were recorded as 300, 1250, 2000 and 750, 1350 and 2500 ml/m^3 for CEM I, CEM II/B-M and CEM V/A cement 40 and 50 N/mm^2 design strength concrete mixes respectively. In addition, admixtures contents required was observed to increase for RAC mixes, thereby admixtures contents used were 1250, 1650, 2600 and 1600, 1900 and 3300 ml/m^3 for CEM I, CEM II/B-M and CEM V cement mixes respectively. Loss of workability for equal design strength NAC and RAC mixes are shown in Figures 2 and 3 respectively.

It is observed that CEM I mixes with higher free water content compared to other mixes reduced demand for SP for achieving the set target. Moreover, SP content used increased for the same consistency class for CEM II/B-M and CEM V/A mixes. This is also in line with previous researches [37-40] that SP demand increases when the replacement level of PC by SCM increases. It is noteworthy to mention that CEM V/A mixes were influenced more compared to CEM II/B-M mixes due to lower w/c ratio than CEM II/B-M mixes. In comparison to NAC mixes, RAC mixes needed more SP in order to achieve target consistency class. It is believed to be related with the higher WA of recycled aggregates therefore required more SP to cover higher WA. However, decrease in fresh properties could be attributed to lack of fines therefore lead to increase in SP content.

3.2. Loss of workability over time

It can be seen from the results that compacting factor values reduced with the increasing design strength. This is believed to be due to w/c ratio was lowered as the design strength increased. This is also coherent with McCarthy and Dhir [40]. The results showed that CEM II/B-M mixes performed similar results as CEM I for the particular durations. It could be attributed to the better dispersion and smooth and dense surface characteristics of GGBS as it absorbs less water over time [13].

Having the highest w/c ratio compared to CEM I and CEM V/A mixes, CEM II/B-M mixes except 50 N/mm^2 design strength NAC mixes provided quite similar results as CEM I mixes which is believed to be due to SF incorporation resulted in increased water demand due to extreme fineness of SF and thereby reduced concrete workability over time [24]. CEM V/A mixes with the lowest free water content indicated the lowest CF values amongst all mixes. Even though GGBS incorporated CEM II/B-M mixes showed similar results as CEM I mixes, FA contribution in CEM V/A cement mixes were observed to reduce concrete workability dramatically.

In comparison with NAC mixes, RAC mixes indicated lower CF values which could be attributed to higher WA characteristic of recycled aggregates used. Considering WA and moisture content of mixes were compensated prior to mixing, this is believed to be higher WA of both RA and RGS than natural aggregates. This is believed to increase in water content which is also coherent with Tu [41] and Limbachiya [42]. In addition, the reduction in consistency is believed to be lack of fines which required more SP.

Table 8 - Workability results for NAC mixes

28-day design strength (N/mm2)	Cement	w/c ratio	Free water content (kg/m3)	SP (ml)	Slump value (mm)
40	CEM I (100PC)	0.51	195	300	125
	CEM II/B-M (65PC/30FA/5SF)	0.59	175	1250	120
	CEM V/A (40PC/30GGBS/30FA)	0.40	170	2000	150
50	CEM I (100PC)	0.44	195	750	100
	CEM II/B-M (65PC/30FA/5SF)	0.46	175	1350	100
	CEM V/A (40PC/30GGBS/30FA)	0.38	170	2500	140

Table 9 - Workability results for RAC mixes

28-day design strength (N/mm2)	Cement	w/c ratio	Free water content (kg/m3)	SP (ml)	Slump value (mm)
40	CEM I (100PC)	0.51	195	1250	125
	CEM II/B-M (65PC/30FA/5SF)	0.59	175	1650	135
	CEM V/A (40PC/30GGBS/30FA)	0.40	170	2600	85
50	CEM I (100PC)	0.44	195	1950	120
	CEM II/B-M (65PC/30FA/5SF)	0.46	175	1250	120
	CEM V/A (40PC/30GGBS/30FA)	0.38	170	2000	150

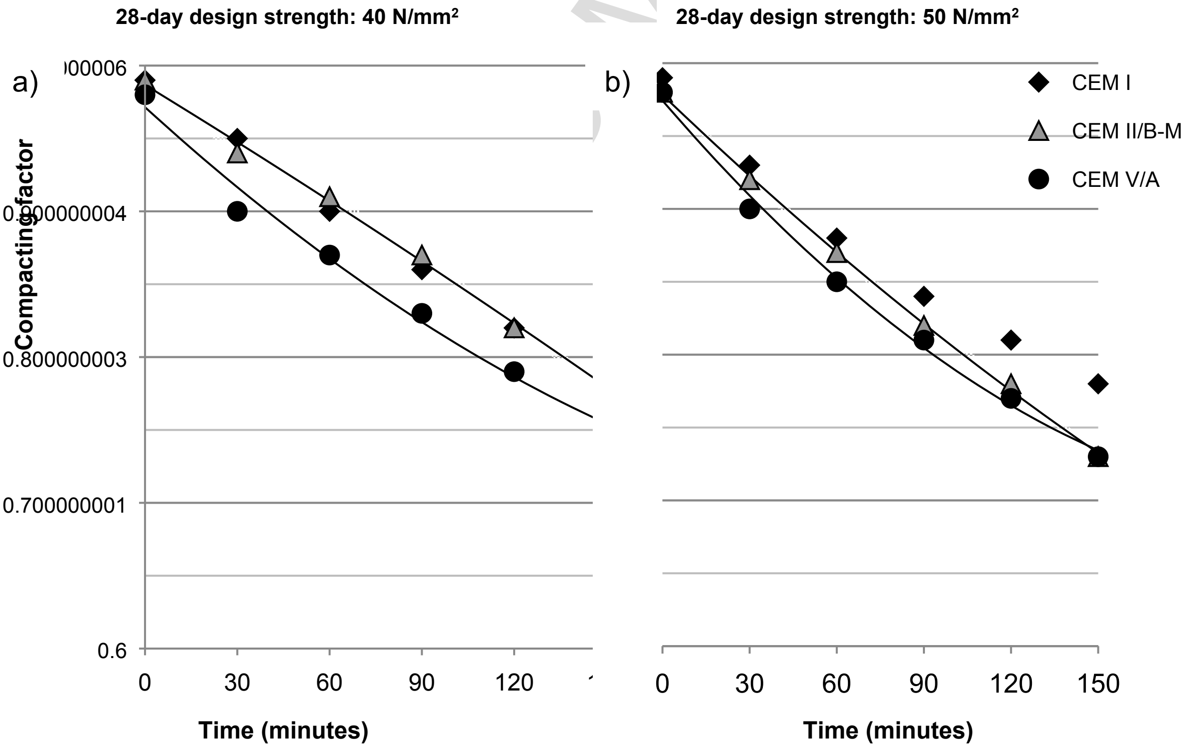


Figure 2. Loss of workability over time of equal design strength NAC mixes

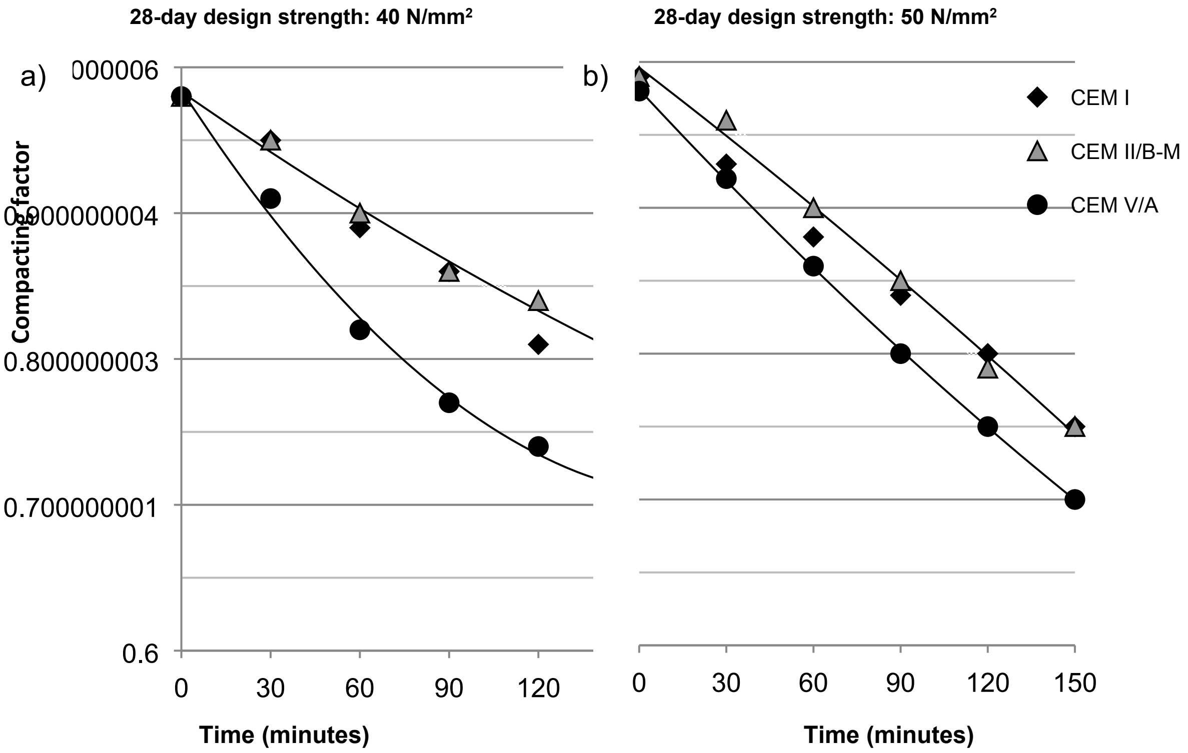


Figure 3. Loss of workability over time of equal design strength RAC mixes

3.3. Strength Properties

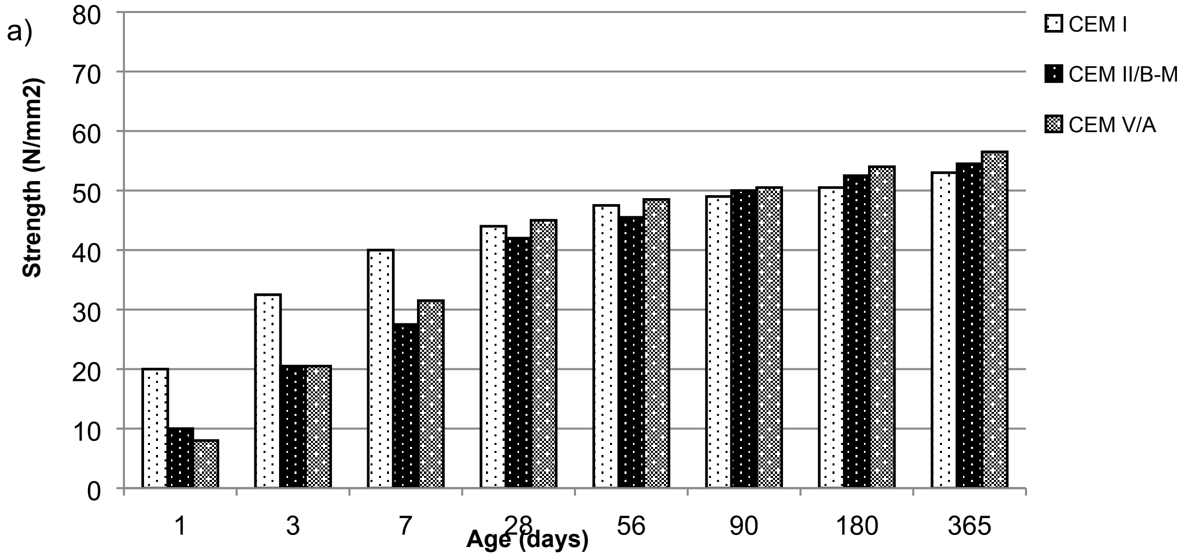
Concrete compressive strength is a standard way of indicating whether concrete fulfils necessary quality criteria. It is therefore a great concern for SCMs and recycled aggregate incorporated concretes to satisfy necessary conditions.

3.3.1. Compressive cube strength

The compressive cube strength development results are given in Figures 4 and 5 for 40 and 50 N/mm^2 design strength NAC and RAC mixes respectively. It is noteworthy to mention that the standard deviation was calculated as 1.43 N/mm^2. It is obvious that CEM II/B-M and CEM V/A cement mixes reduced the compressive cube strength dramatically compared to conventional CEM I mixes for both NAC and RAC mixes at early ages (<7days). This is in line with previous researches [13, 39]. This could be attributed to SCMs with lower surface area do not take part in the strength development at early ages. Moreover, chemical composition, Figure 1, suggests that lower CaO content of FA and GGBS slows down hydration process and leads in lower strength at pre-7 days. However, this is observed to be compensated at 28 days. This is a clear indication that pozzolanic reaction by the contribution of SCM’s starts to take place between 7 and 28 days which is in agreement with Gonen [24] and Limbachiya [25]. However, it is worth mentioning that total cementitious contents vary with mixes in aiming to achieve target design strength at 28 days. At post 28-days, CEM II/B-M and CEM V/A mixes showed improved results in comparison to CEM I mixes. CEM I mixes indicated 17% and 18% increment for 40 and 50 N/mm^2 design strength concretes between 28 and 365 days. However, CEM II/B-M mixes indicated 30% and 32% increments for 40 and 50 N/mm^2 design strength concrete whereas 25% and 34% strength improvement was observed for CEM V/A mixes for NAC mixes at the same ages. For RAC mixes, 17% improvement was observed for CEM I mixes between 28 and 365 days whilst, 32% and 19% and 34% and 27% increments were reported for CEM II/B-M and CEM V mixes between this particular ages. It is obvious that SCMs addition provides pozzolanic reactions and contributes more to strength development in comparison to conventional mixes. These also show that SCMs incorporated concretes require longer (>28 days) curing period in order to trigger pozzolanic reaction for the strength development. In general, CEM V/A mixes indicated higher strength development amongst all three mixes. This could be explained by either higher total binder content than other mixes, which is in line with Bernal [16] or depletion of SF over time may reduce the rate of hydration and therefore resulted in lower strength development. Even though, higher strength development of CEM II/B-M mixes could be explained by the extra CSH development provided by GGBS hydration.

It was observed that recycled aggregates substituon with natural aggregates with particular replacement levels achieved slightly reduced strengths at all ages. However, the effect of both RA and RGS, solely, is not obvious. The reduction in compressive strength could be dependant upon the several factors. Initially, the incorporation of RA with lower density leads to decrease concrete density and concrete strength. This reduction there is in accordance with the previous researches reported earlier [14, 25-27].   In addition, the use of RGS and RA increased the fineness modulus of the aggregates. This is thought to decrease the concrete density and resulted decrease in the bond strength between recycled aggregates and the cement paste. Also, the inclusion of RGS is believed to form a weak adhesion between the interface between the RGS and the cement pastes as stated previously by Kou [14] and Ling [43]. Strength loss could also be attributed to lack of fines due to coarser particle sizes of RGS which diminished the filler effect of fine aggregates and resulted in more porous matrix. On the other hand, insufficient water content as a result of higher WA capacity of RA is believed to lead to deficiency in the hydration of cement paste which reduced the compressive strength. In addition, strength loss can also be attributed to weaker characteristics of RA due to higher porosity reduced the strength of ITZ which resulted in reduction in concrete strength.

28-day design strength: 40 N/mm²



28-day design strength: 50 N/mm²

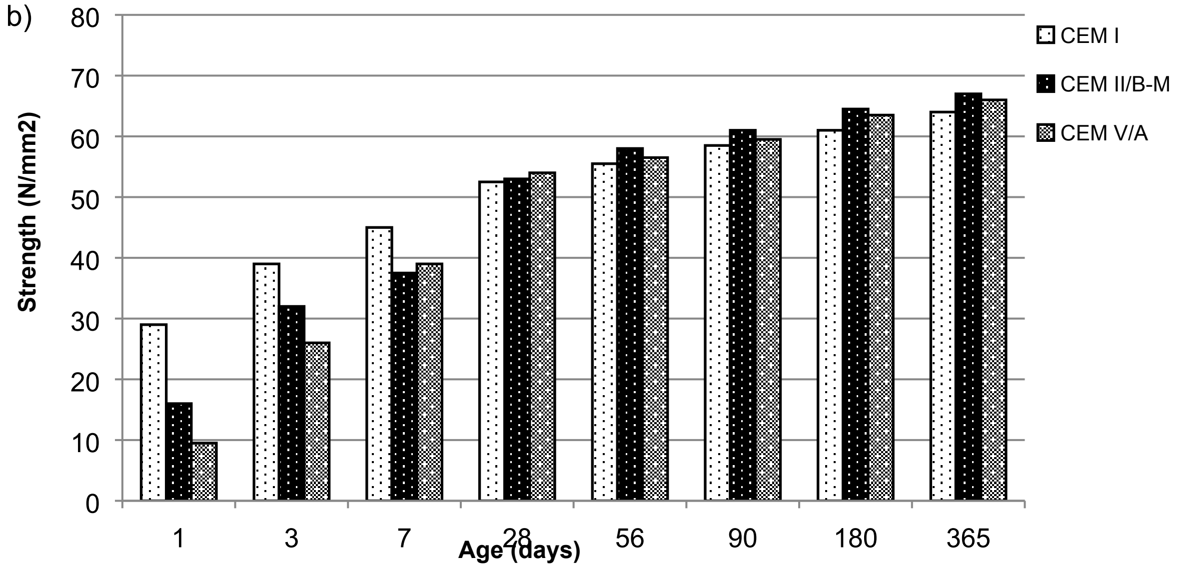


Figure 4. Compressive cube strength development of equal design strength NAC mixes

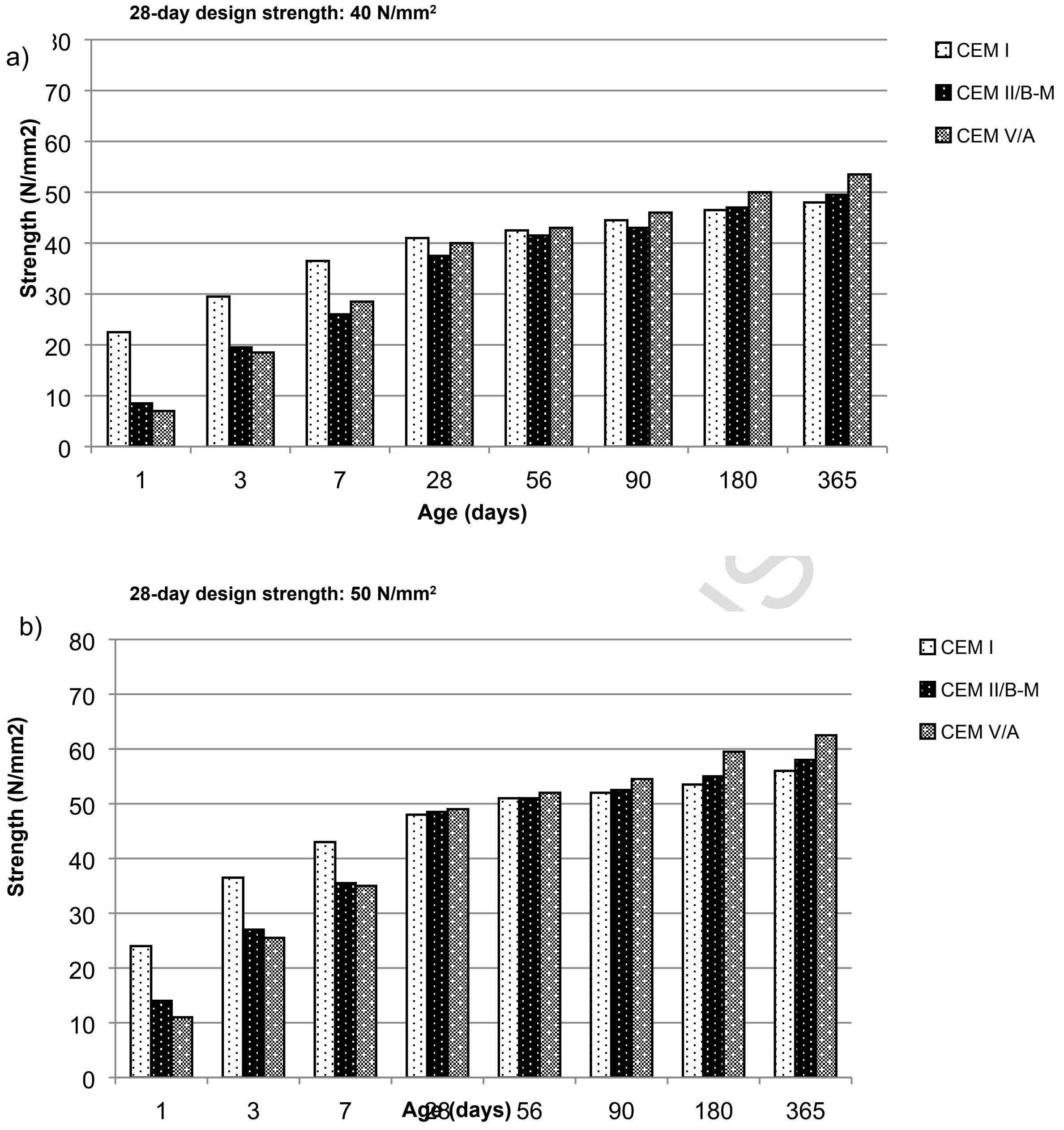


Figure 5. Compressive cube strength development of equal design strength RAC mixes

3.3.2. Compressive cylinder strength

It is noteworthy to mention that constituents of concrete mixes were optimised in aiming to achieve carbon efficient sustainable concrete production for particular design strength through compressive cube strength. Even though compressive cube strengths achieved targeted 28-day design strength, some standards take compressive cylinder strength into account in order to monitor concrete conformity. In addition, British standards design parameter BS EN 206 uses the ratio of 0.8 to express relationship between cylinder and cube compressive strength ($f_{c,cyl}/f_{c,cube}$).

Compressive cylinder strengths were tested at 28, 56 and 90 days to monitor the relationship between compressive cylinder and cube strengths. Existing studies reported by Nikbin [44] and Bhanja [45] $f_{c,cyl}/f_{c,cube}$ ratios between 0.58 and 0.94. The correlation of compressive cylinder and cube strengths including 28, 56 and 91 days are given in Figures 6(a) and 6(b) for NAC and RAC mixes respectively. Also, the results for $f_{c,cyl}/f_{c,cube}$ ratios for NAC and RAC are given in Figures 7(a) and 7(b) and Figures 8(a) and 8(b) respectively for both design strength concretes. In addition to these, the comparison between the NAC and RAC mixes are given in Figure 9.

For NAC mixes, correlation values (R^2) were reported as 0.97, 0.98 and 0.94 for CEM I, CEM II/B-M and CEM V mixes respectively. In general, all NAC mixes indicated lower $f_{c,cyl}/f_{c,cube}$ ratios than design factor 0.8 at all ages except 40 N/mm^2 design strength CEM II/B-M mixes at 56 days. CEM I mixes achieved $f_{c,cyl}/f_{c,cube}$ ratios of 0.70, 0.68, 0.69 and 0.75, 0.75 and 0.75 for 40 and 50 N/mm^2 design strengths at 28, 56 and 90 days respectively whilst 0.75, 0.80, 0.79 and 0.74, 0.74, 0.76 and 0.68, 0.71, 0.69 and 0.76, 0.77, 0.77 were reported at 28, 56 and 90 days for CEM II/B-M and CEM V/A mixes respectively. Reported results were in the range reported earlier [44-45].

The results for RAC mixes showed correlation values of 0.11, 0.94 and 0.98 for CEM I, CEM II/B-M, CEM V/A mixes respectively. This lower correlation of CEM I mixes could be attributed to the higher compressive cylinder strength results of 40 N/mm^2 design strength concrete mix compared to 50 N/mm^2 design strength concrete. In addition, the $f_{c,cyl}/f_{c,cube}$ ratios were reported 0.61, 0.62, 0.62 and 0.47, 0.47, 0.51 for CEM I mixes at 28, 56 and 90 days respectively. The $f_{c,cyl}/f_{c,cube}$ ratios for CEM II/B-M mixes were obtained as 0.48, 0.53, 0.53 and 0.60, 0.59, 0.70 whilst CEM V/A mixes indicated 0.49, 0.47, 0.49 and 0.48, 0.48, 0.50 $f_{c,cyl}/f_{c,cube}$ ratios for 40 and 50 N/mm^2 design strength concretes at 28, 56 and 90 days respectively. All RAC mixes indicated extremely lower $f_{c,cyl}/f_{c,cube}$ ratios than 0.8 and resulted in lower $f_{c,cyl}/f_{c,cube}$ ratios than specified previously [44-45] except 40 N/mm^2 design strength CEM I and 50 N/mm^2 design strength CEM V/A cement RAC mixes.

It is clearly seen from Figure 9 that incorporation of recycled aggregates effected the compressive cylinder strength adversely compared to NAC mixes. This is also coherent with Ling [43] and Kou [14] that rough and uneven surface characteristic of both RA and RGS may weaken the adhesion between cement paste and aggregates. This then resulted in weaker bond.

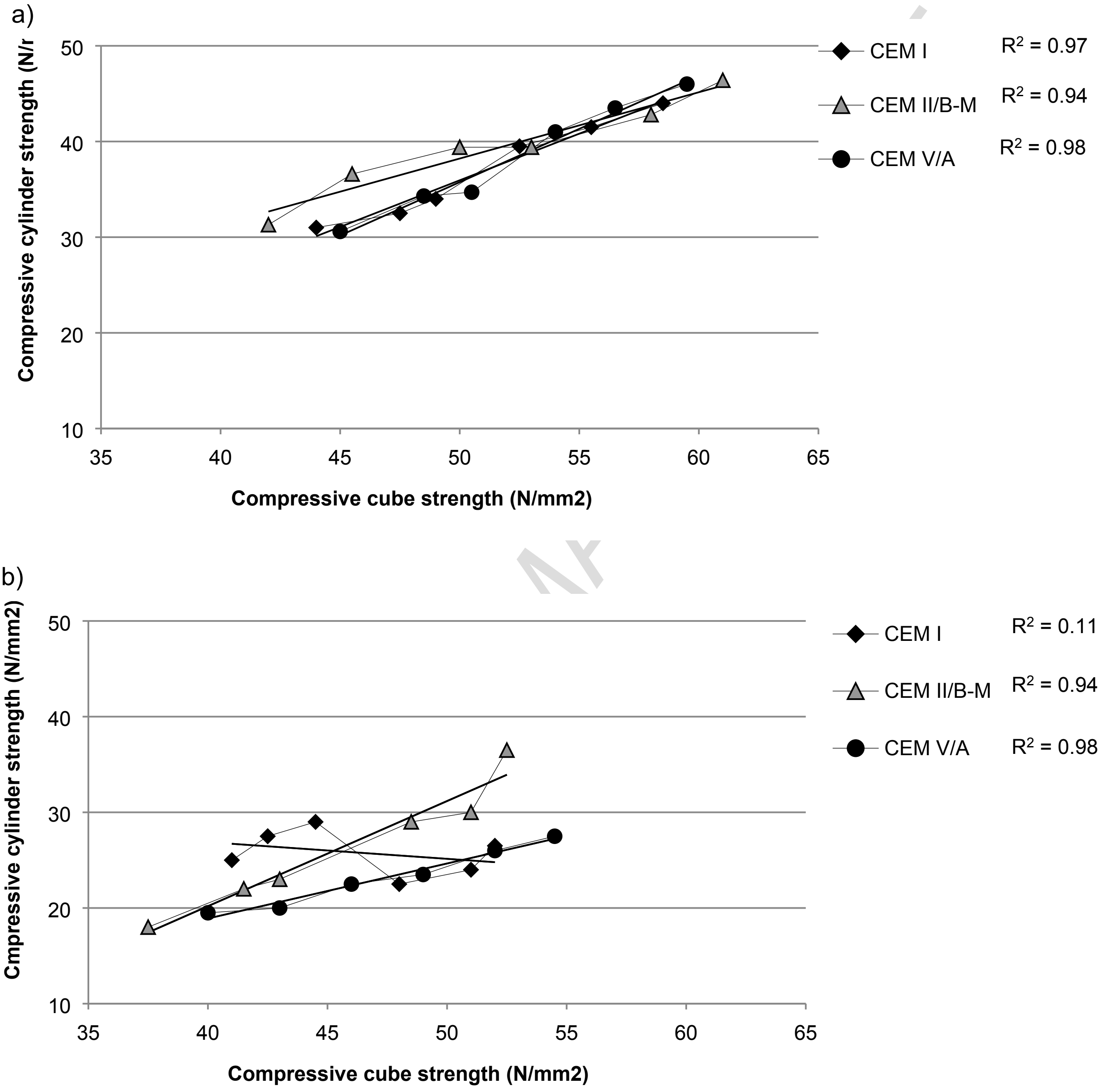


Figure 6. The relationship between compressive cylinder and cube strengths of equal design strength a) NAC and b) RAC mixes at 28, 56 and 91 days

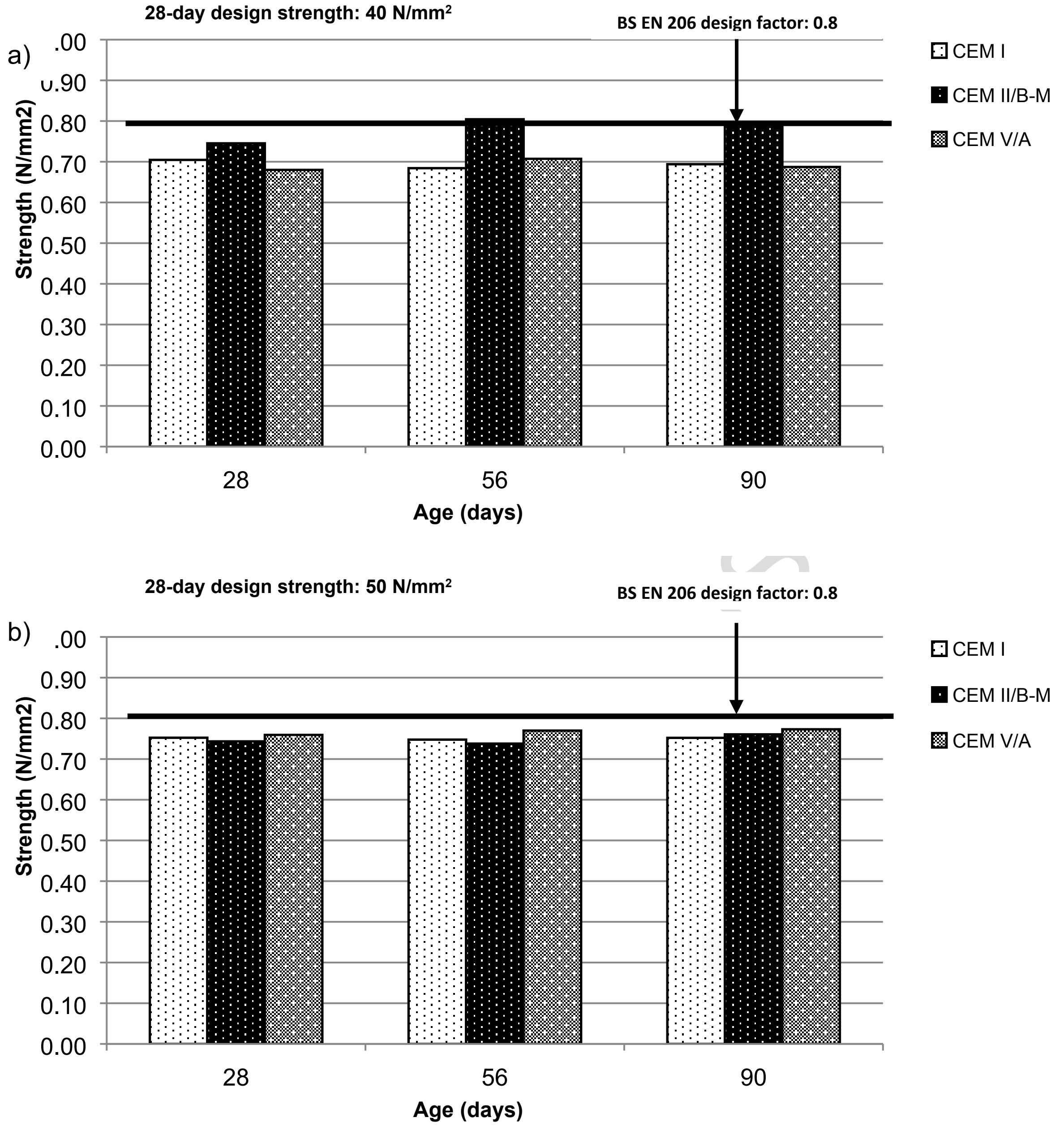


Figure 7. The ratio between compressive cylinder and cubes strengths (f_{cyl}/f_{cube}) of NAC mixes

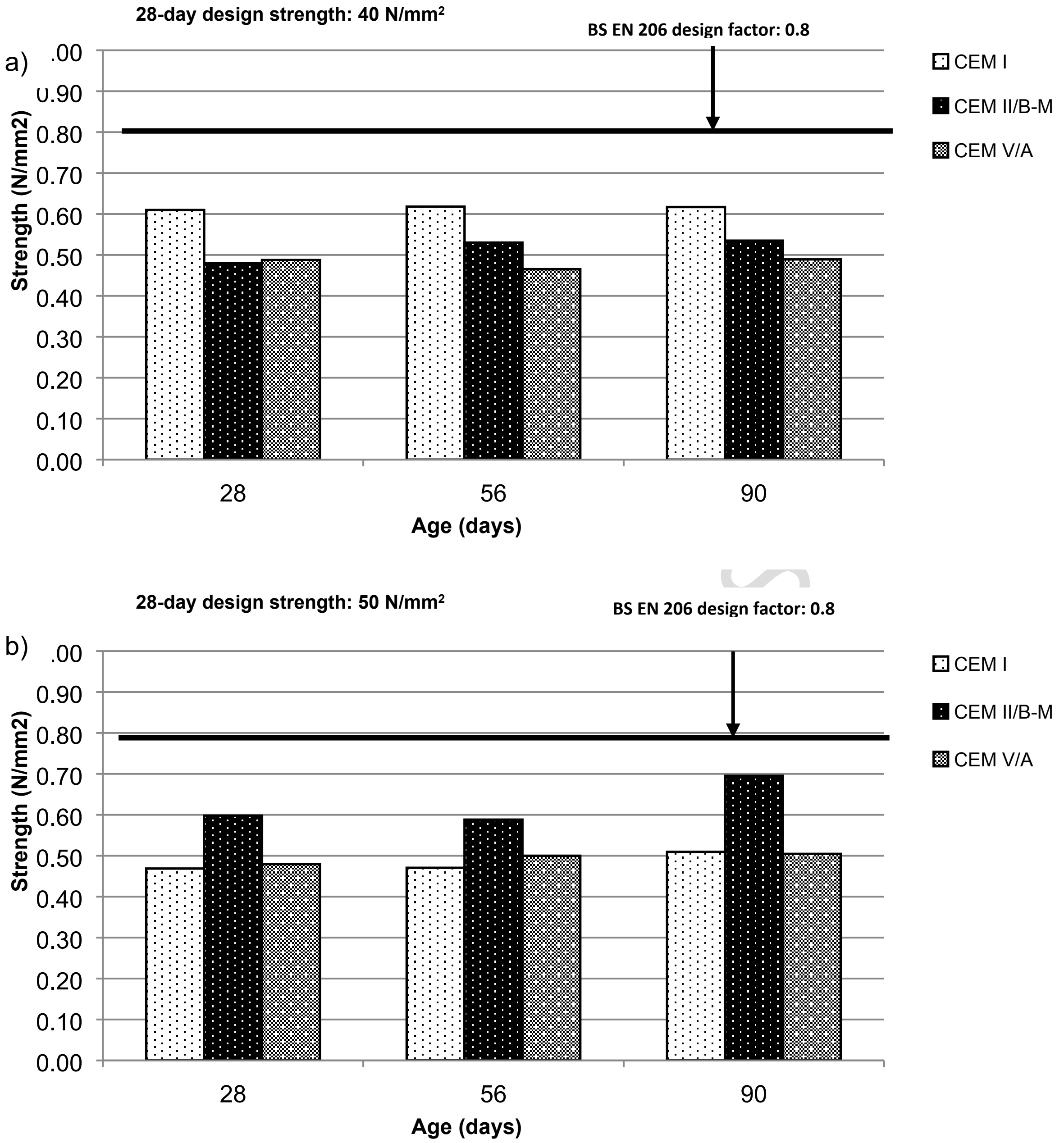


Figure 8. The ratio between compressive cylinder and cubes strengths (f_{cyl}/f_{cube}) of RAC mixes

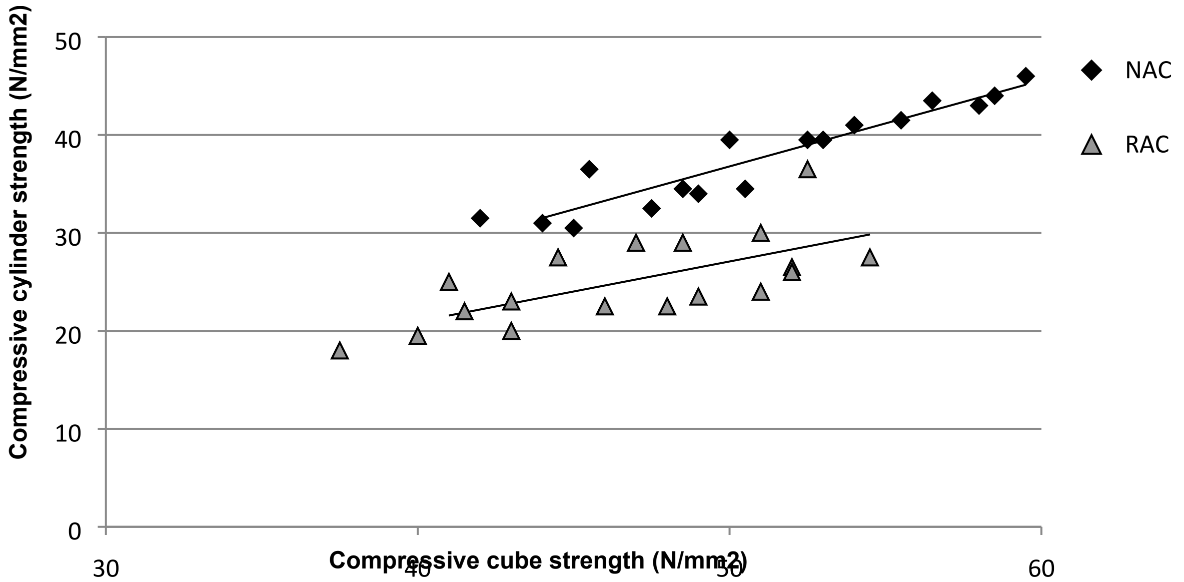


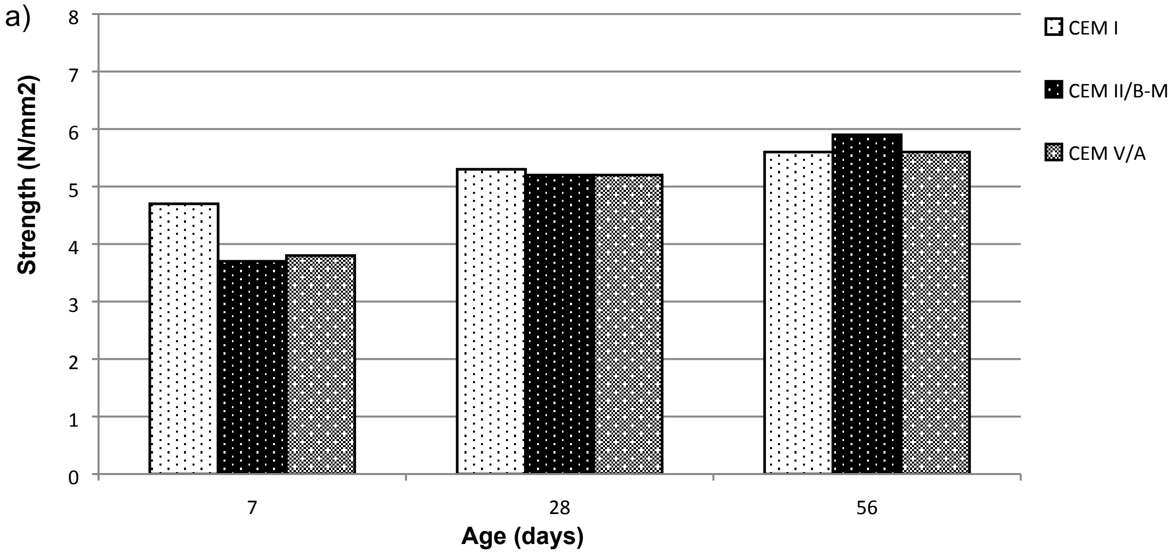
Figure 9. Relationship between compressive cylinder and cube strength for NAC and RAC mixes

3.3.3. Flexural strength

The results for NAC and RAC mixes are given Figures 10(a) and 10(b) and 11(a) and 11(b) respectively for 40 N/mm^2 and 50 N/mm^2 design strength mixes. In general, there is no significant trend observed except NAC mixes tested at 7 days which provided slightly higher results compared to CEM II/B-M and CEM V/A mixes. This is believed to be due to replacement of PC with mineral admixtures lowered CaO content in the cement paste and thereby delayed hydration process. CEM II/B-M and CEM V cement NAC mixes provided similar results as conventional mixes at 56 and 90 days. This supports the fact that the pozzolanic reaction is believed to start taking place between 7 and 28 days.

For RAC mixes, CEM II/B-M and CEM V mixes indicated similar results as reference CEM I mixes at all ages. RAC mixes made with the combination of both RA and RGS were in line with those specified earlier [12, 25] that the use of RA less than 30% and RGS up to 15% could provide comparable results as PC mixes.

It is noteworthy to mention that RAC mixes indicated similar results compared to NAC mixes except 50 N/mm^2 design strength CEM I mix. This could be due to superior performance of 50 N/mm^2 design strength CEM I cement NAC mixes indicated higher flexural strength results. Strength loss was expected initially due to addition of both recycled aggregates as both aggregates had higher WA compared to natural aggregates. From visual inspection point of view, RA used had rough and uneven texture, the authors believe that the incorporation of elongated and angular shaped RGS provided an internal friction and resulted in similar flexural strength results nevertheless RA presence.



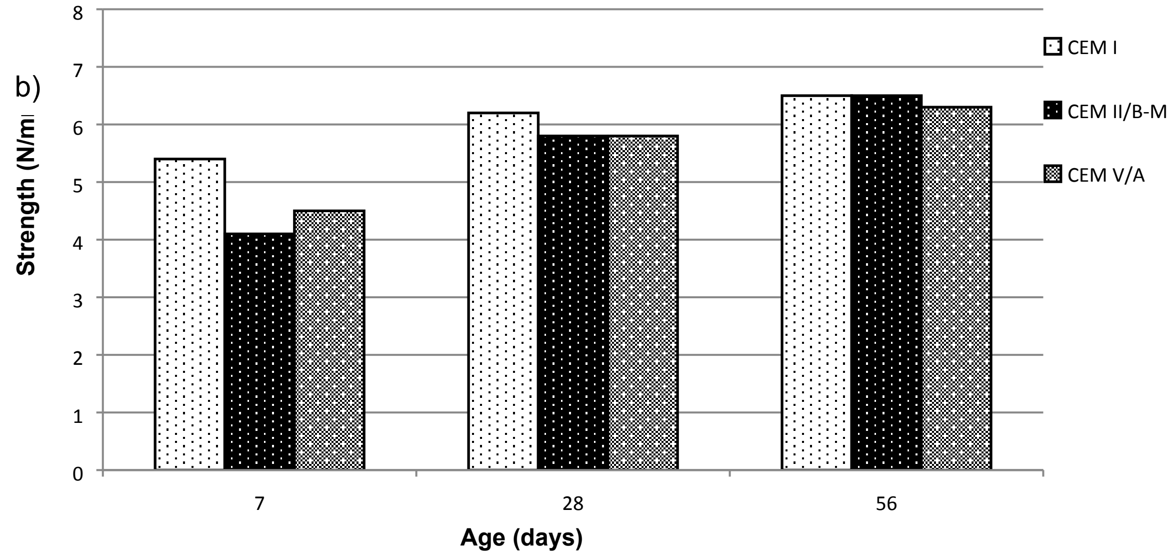
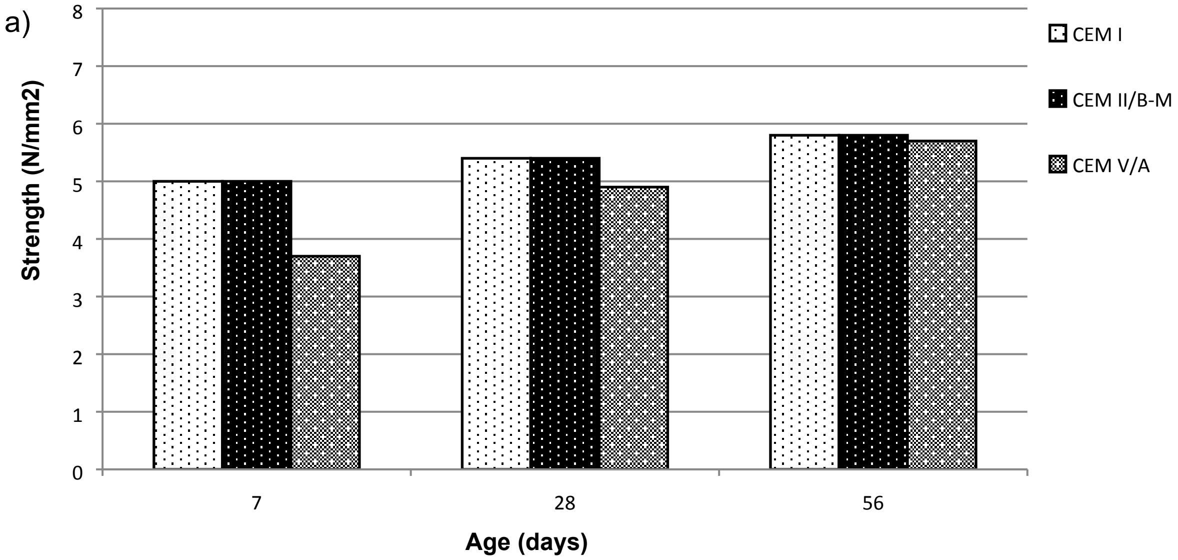


Figure 10. Flexural strengths of a) 40 N/mm^2 and b) 50 N/mm^2 design strength NAC mixes



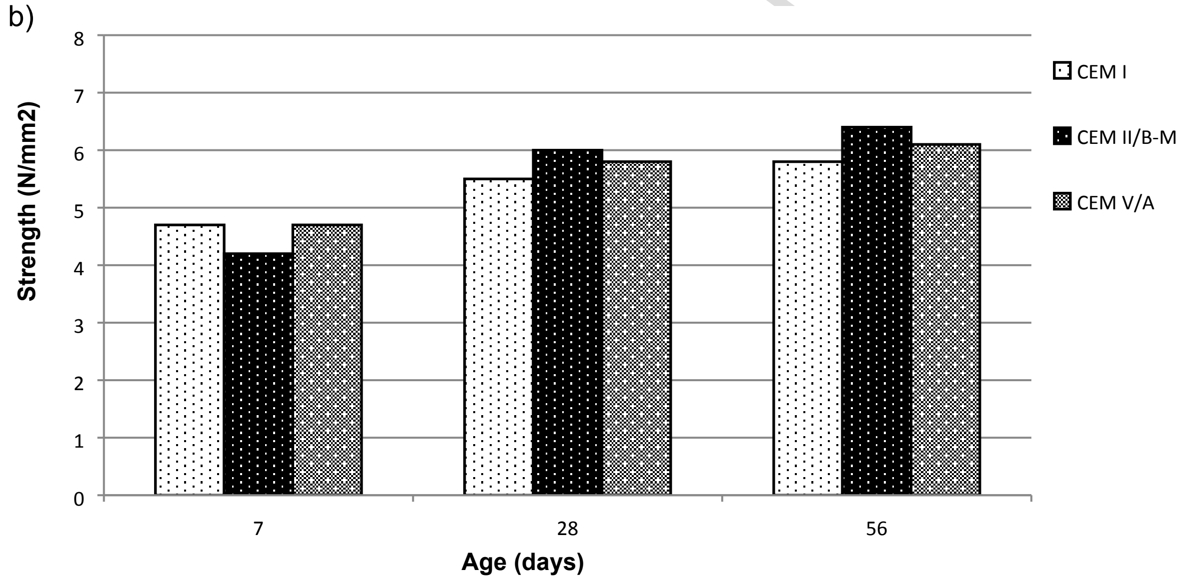


Figure 11. Flexural strengths of a) 40 N/mm^2 and b) 50 N/mm^2 design strength RAC mixes

3.4. Drying shrinkage

Drying shrinkage is a time-dependant incident and takes place when concrete is exposed to a dry atmosphere. This results in increase in tensile stress and lead to cracks, thereby reduces loadbearing capacity of reinforced concrete. Thus, it is an important property to determine from the structural point of view.

Drying shrinkage development over time up to 112 days are given in Figures 12(a) and 12(b) and 13(a) and 13(b) for 40 and 50 N/mm^2 design strength NAC and RAC mixes respectively.

In general, drying shrinkage was observed to decrease for CEM II/B-M and CEM V/A cement concretes for both NAC and RAC mixes. It is important to mention that water is known as the main contributor to drying shrinkage. Therefore, reduction in drying shrinkage development over time could be explained by reduction in free water content of CEM II/B-M and CEM V/A cement mixes as suggested by the BRE mix design. In addition, CEM II/B-M cement NAC mixes indicated higher drying shrinkage values at 7 days. This is in agreement with the previous research by Guneyisi [37] which stated SF incorporation increases drying shrinkage at early ages. At post 7-days, CEM II/B-M and CEM V/A cement mixes indicated lower drying shrinkage values than CEM I cement mixes at all ages. Even though CEM II/B-M mixes having higher w/c ratio compared to CEM I mixes achieved higher shrinkage values, CEM II/B-M cement RAC mixes provided lower drying shrinkage in comparison to conventional CEM I cement RAC mixes. Therefore, there is no relationship was observed between w/c ratio and drying shrinkage development. The results are in line with compressive and flexural strength results which suggests that pozzolanic reaction provided by SCMs triggers hydration at post 7-days. This is in contrast with existing study by Akcaozoglu [46] stating that drying shrinkage decreases at post 21-days for SMCs incorporated concretes.

There is no particular effect observed for RAC mixes at all ages, however early shrinkage development was declined for 50 N/mm2 design strength concretes. This is on the contrary with reported finding by Hui-sheng [39]. There are two different trends observed at post 21-days for RAC mixes. Initially, 40 N/mm^2 design strength concretes had higher whilst 50 N/mm^2 design strength concretes had lower drying shrinkage values. In addition, adverse effect of SF utilized CEM II/B-M mixes at early ages was diminished significantly with the contribution of recycled aggregates. However, 40 N/mm^2 design strength CEM II/B-M concrete mix showed higher drying shrinkage values at post 21-days.

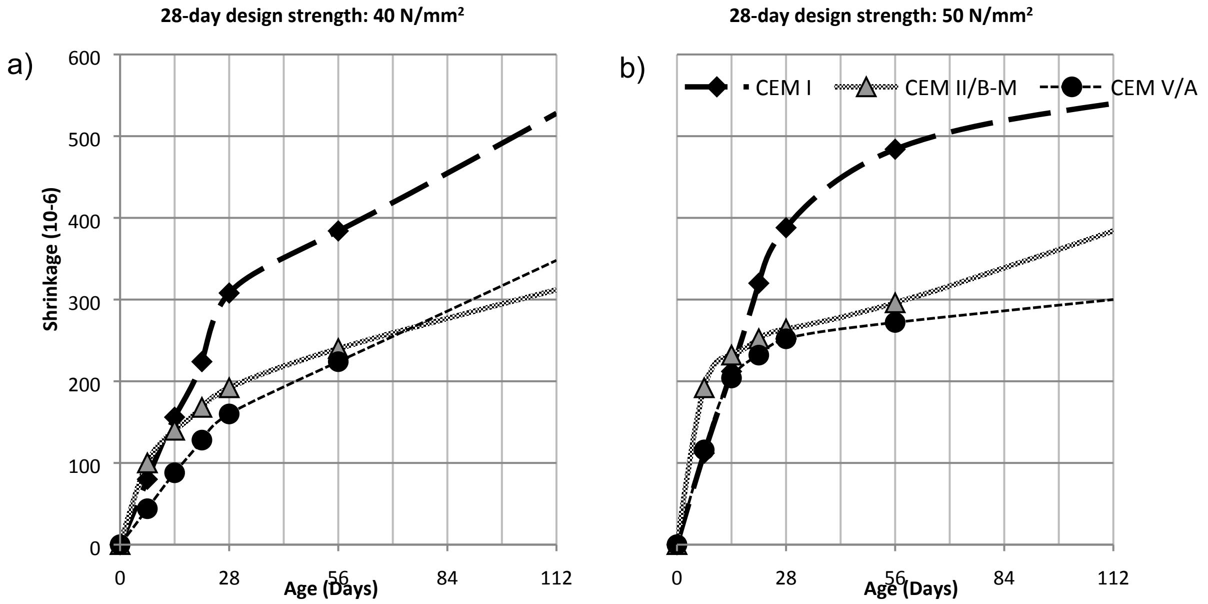


Figure 12. Drying shrinkage values of equal design strength NAC mixes

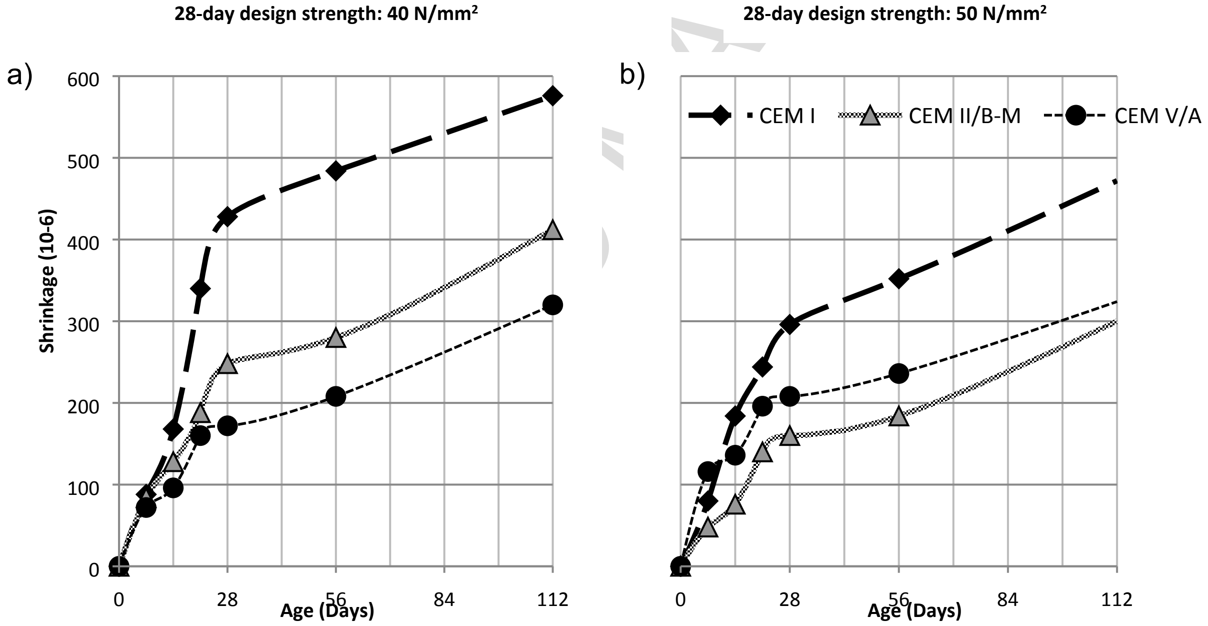


Figure 13. Drying shrinkage values of equal design strength RAC mixes

3.5. Initial surface absorption test

The ISAT-10 results and N-values for developed concrete are given in Tables 10 and 11 for NAC and RAC mixes respectively. In addition, Figures 14(a) and 14(b) show the relationship between ISAT-10 values and 28-days compressive cube strength for NAC and RAC mixes respectively. The results showed that use of CEM II/B-M and CEM V/A cements lead to significant reduction in ISAT-10 values compared to CEM I cement concretes and indicated closer or lower values to lower range of 0.25 ml/m^2/sec. This may be attributed to refinement of pore structure of the concrete provided by the pozzolanic reactions of the SCMs as stated previously [13, 25, 47]. Even though CEM II/B-M mixes, in particular, had the lowest total cementitious contents amongst all mixes, CEM II/B-M mixes reduced the ISAT-10 values due to extreme fineness of SF. CEM V/A with highest binder content amongst mixes formed an agglomerated matrix and reduced the ISAT-10 values significantly. In general, it is seen in figure 14 that ISAT-10 values increased for the same cement mixes as the 28-day target design strength increases except CEM II/B-M mixes which can be attributed to increase in the SF content provided dense matrix due to its extreme fineness as specified above which is in contrast with Ganjian [48] stating that GGBS and SF incorporated mixes resulted in more porous matrix. Moreover, there is no relationship observed between w/c ratio and the ISAT-10 results. This is due to all mixes were designed with various proportions of constituents in order to satisfy target design strength.

For RAC mixes, ISAT-10 results indicated the same trend as NAC mixes. CEM I mixes showed closer values to high range of 0.5 ml/m^2/sec specified earlier. However, recycled aggregate incorporation was observed to increase ISAT-10 values compared to NAC mixes. This increase cannot be linked with either RA or RGS only. Nevertheless, it is believed to be due to recycled aggregates incorporation lead to an increase in the porous matrix. This is coherent with previous studies by Thomas [49] and Zaharieva [50]. This slight increase could be attributed to porous characteristics of RA.

Table 10. ISAT-10 and N value results of equal design strength NAC mixes

28-day design strength	**Cement**	**w/c ratio**	**ISAT-10 (ml/m^2/s) x 10^{-2}**	**N-value (10^{-2})**
40 N/mm^2	CEM I	0.51	42.8	57.9
	CEM II/B-M	0.55	24.0	31.9
	CEM V/A	0.40	19.7	26.1
50 N/mm^2	CEM I	0.41	44.4	60.2
	CEM II/B-M	0.41	19.2	22.2
	CEM V/A	0.38	23.5	29.4

Table 11. ISAT-10 and N value results of equal design strength RAC mixes

28-day design strength	Cement	w/c ratio	ISAT-10 (ml/m²/s) x 10^{-2}	N-value (10^{-2})
40 N/mm²	CEM I	0.51	45.4	60.9
	CEM II/B-M	0.55	28.2	36.7
	CEM V/A	0.40	24.5	36.2
50 N/mm²	CEM I	0.41	47.7	63.9
	CEM II/B-M	0.41	20.6	25.4
	CEM V/A	0.38	29.2	40.2

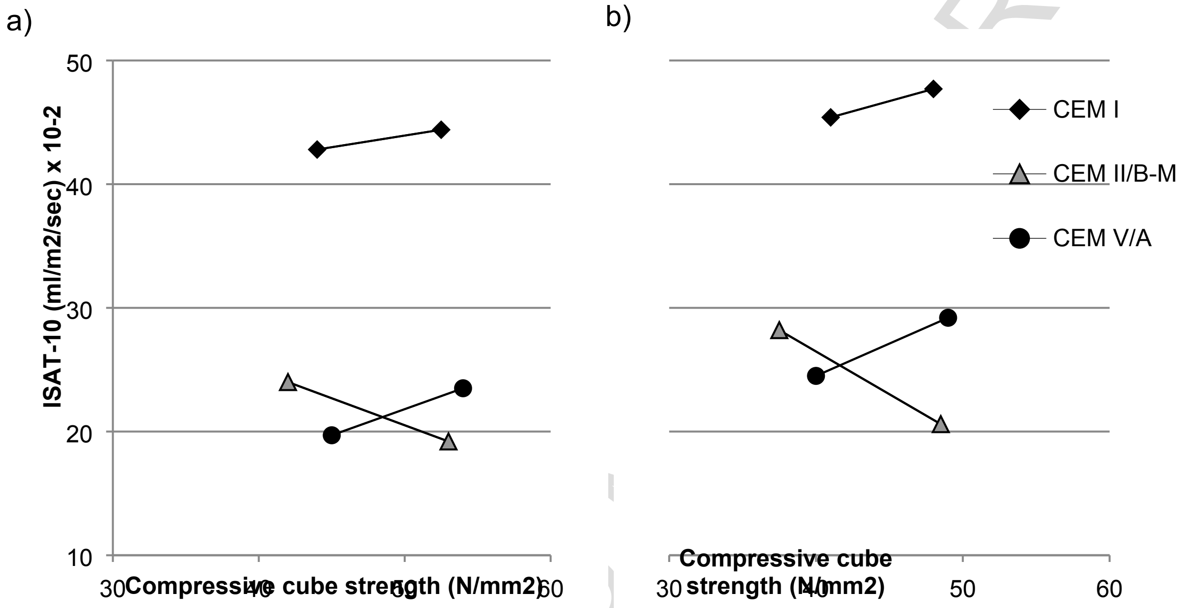


Figure 14. The relationship between ISAT-10 values and 28-day compressive cube strength for a) NAC and b) RAC mixes

3.6. Carbonation resistance

Carbonation penetration results are given in Figures 15(a) & 15(b) and Figures 16(a) and 16(b) for 40 N/mm² and 50 N/mm² design strength and NAC and RAC mixes respectively. It is clear from the results that carbonation penetration increases with time of exposure. CEM I cement mixes provided superior results compared to CEM II/B-M and CEM V/A mixes. For the same type of cement, carbonation depth decreases as the design strength increases. Thus, lower the w/c ratio resulted in denser structure and reduced carbonation depth for the same cement type mixes. Even though CEM

II/B-M and CEM V/A cement mixes showed superior permeation performance through ISAT-10 test, this reduction in carbonation resistance could be explained by the replacing of PC with GGBS, SF and FA lead to reduction in the calcium hydroxide (C-H) content of the mixes. This, then, changed the pore matrix and resulted in increased carbonation depth.

For RAC mixes, carbonation depths increase slightly in comparison to NAC mixes. As similar trend was observed for both NAC and RAC mixes, this increase for RAC mixes could be explained by rough characteristics and higher WA of RA increased porosity and enabled CO_2 to penetrate deeper.

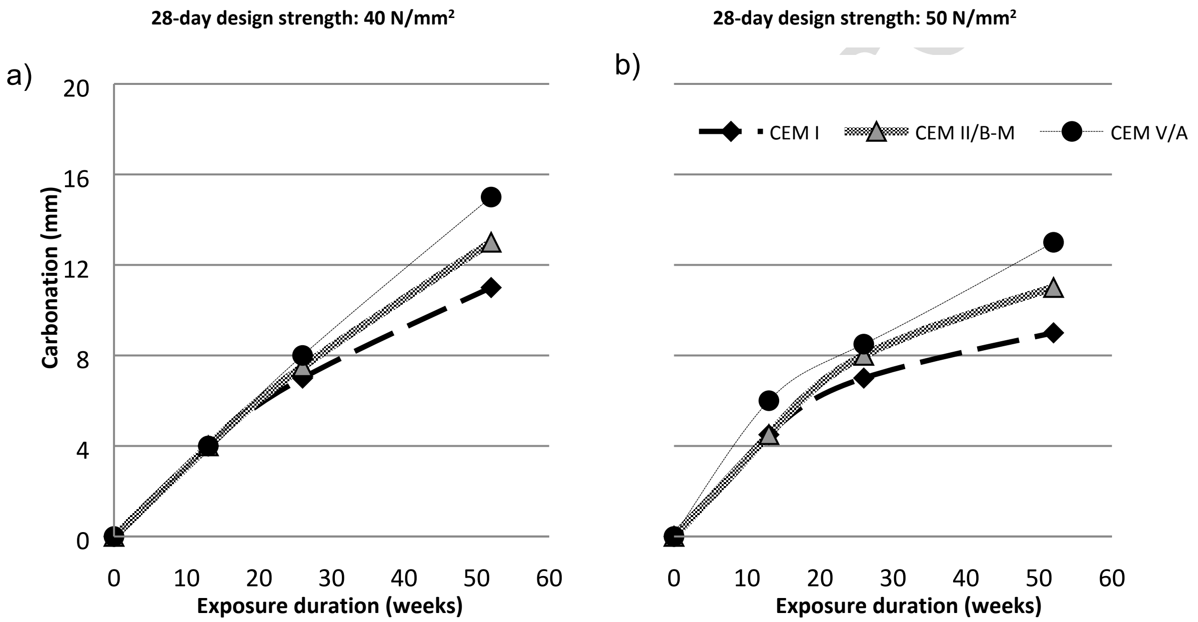


Figure 15. Carbonation penetration of equal design strength NAC mixes

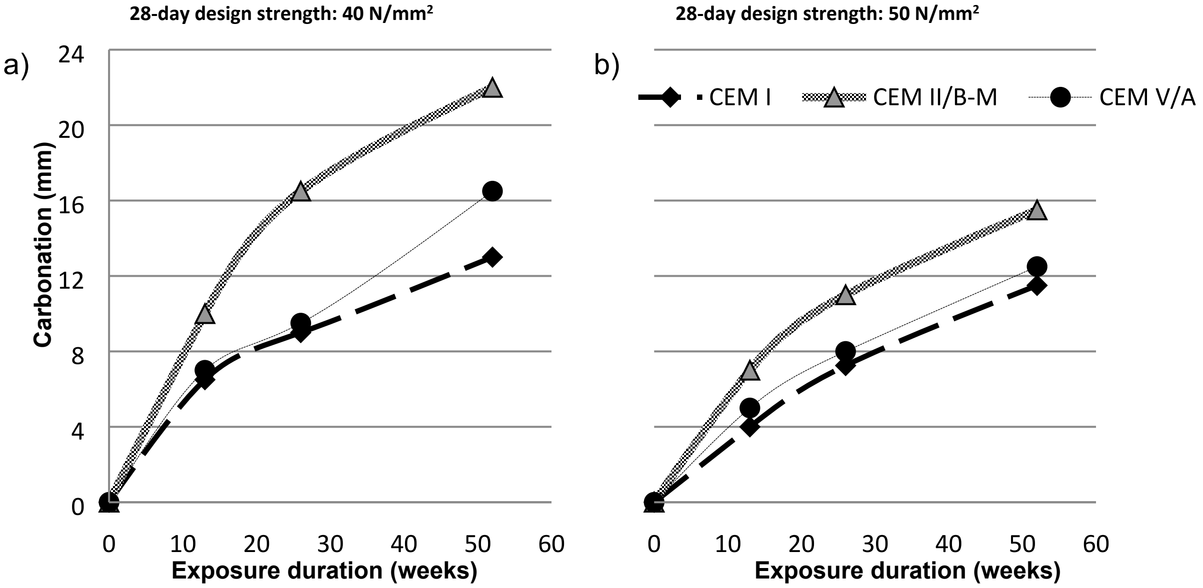


Figure 16. Carbonation penetration of equal design strength RAC mixes mixes

4. ECO_2 emissions and cost analysis

4.1. ECO_2 emissions

The ECO_2 emissions are given in Figures 17 and 18 for NAC and RAC mixes respectively. The results are in agreement with the previous studies [6-8] that the concrete ECO_2 emissions increase as the concrete design strength increase. This study has achieved to provide lower ECO_2 emissions for given design strengths of 40 and 50 N/mm2 than previous study carried out [6]. However, ECO_2 emissions of CEM I mixes were observed to be higher than previous study by Jones [7]. From the results, it is clear that PC is the main contributor of the concrete‟s environmental emissions and CEM I mixes indicated the highest ECO_2 emissions amongst all concrete mixes due to higher ECO2 emissions of PC. The results also demonstrated that ECO_2 reduction in the blended CEM II/B-M and CEM V/A mixes is proportional to the substituted amount of PC by the SCMs regardless of total cementitious content for a given design strength. The ECO_2 emissions of CEM I mixes were 154 and 177 kg ECO_2/tonne for 40 and 50 N/mm^2 design strength concretes respectively. The ECO_2 emissions of CEM II/B-M mixes ranged between 89 and 113 kg ECO_2/tonne which are equivalent to 42% and 36% reductions whilst the ECO_2 emissions of CEM V/A mixes ranged between 74 and 78 kg ECO_2/tonne which are equivalent to 51% and 56% reductions for 40 and 50 N/mm^2 design strength concretes respectively.

From the results, it can be seen that RAC mixes had quite similar ECO_2 emissions compared to NAC mixes. In general, the use of recycled aggregates resulted in an increment between 1 to 2 kg ECO_2/tonne. The results were observed as 155 and 178, 90 and 114 and 74 and 79 kg CO_2/tonne were calculated for CEM I, CEM I/B-S and CEM V/A cements and 40 and 50 N/mm^2 design strength concretes respectively for RAC mixes. However, the results were lower than the previous study reported [7] except CEM I cement NAC and RAC mixes. Even though SCMs has lower CO_2 emissions compared to PC, this similar ECO_2 emissions could be explained by higher ECO_2 emissions of both RA and RGS. Initially, the use of RGS results in increase in the ECO_2 emissions as its production requires reprocessing and transportation to the processor in differ from natural aggregates. In addition, the use of RA also had higher emissions due to extraction and production of recycled aggregate. The use of both RGS and RA requires reprocessing which generates higher electricity consumption, especially in the processing of waste glass into standard aggregate quality, and thus increases the ECO_2 emissions compared to natural aggregates.

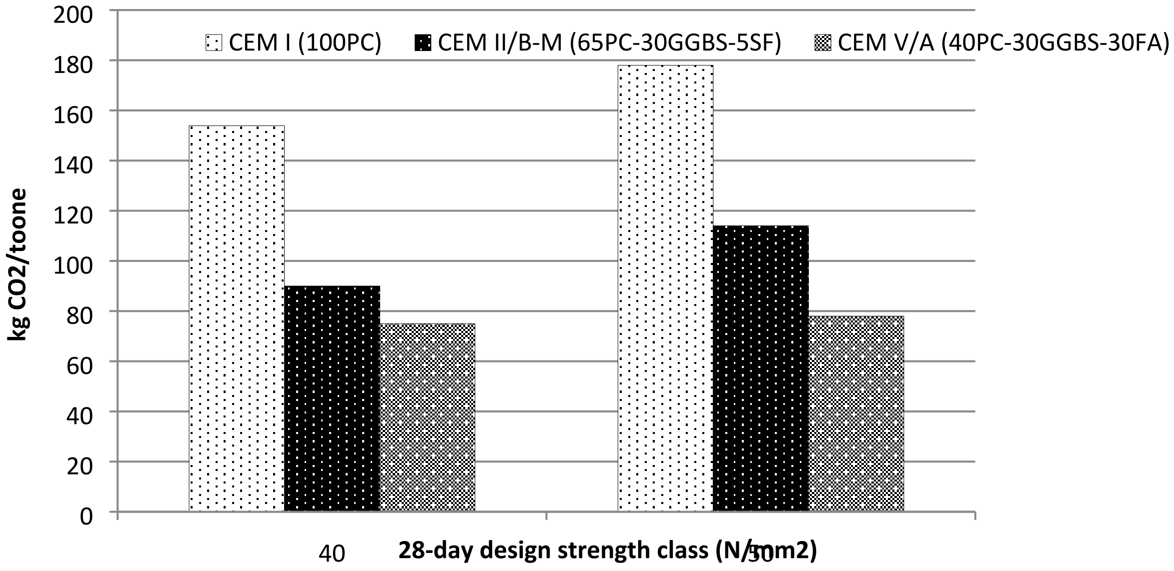


Figure 17. The ECO_2 emissions of NAC mixes

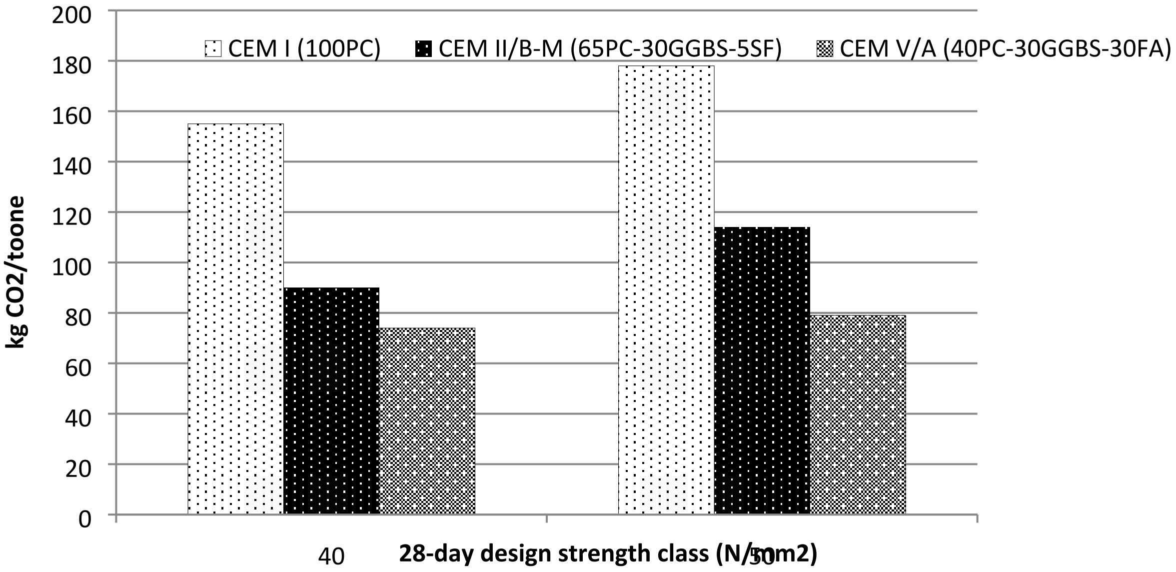


Figure 18. The ECO_2 emissions of RAC mixes

4.2. Cost Analysis

The cost of developed NAC and RAC mixes are given in Tables 12. CEM II/B-M and CEM V/A mixes were observed to be more cost efficient compared to conventional mixes. In comparison to CEM I mixes, cost reductions achieved were 17% and 13 % for CEM II/B-M mixes whilst up to 23% and 27% for CEM V/A mixes for 40 and 50 N/mm^2 design strength concretes respectively. Moreover, the cost of all concretes increased with the increasing design strengths due to more cementitious materials were required to achieve the desired strength. The reduction in cost was proportional to the substituted amount of PC by the SCMs, even though SF had the highest price amongst cementitious materials. This can be attributed to the local availability of both FA and GGBS in the UK. This is also in line with the industry`s sustainability approach to encourage suppliers to use as much as SCMs and waste materials in concrete production.

As can be seen from the results, the use of recycled aggregates increased the cost of concretes slightly. For both strength classes, an increase of between 3% and 6% was observed, equivalent to £3/tonne and £4/tonne respectively. Considering the price of RGS has the same price as natural sand, the increase in cost due to higher cost of RA compared to natural gravel. The higher cost for recycled aggregates was expected reprocessing of RA involves collection of the materials and crushing to get the aggregates to the appropriate standard quality.

Table 12. Cost of NAC and RAC mixes

Concretes	Cements	Cost (£/tonne)	
		40 N/mm^2 design strength concretes	50 N/mm^2 design strength concretes
NAC	CEM I	86.0	94.0
	CEM II/B-M	71.3	82.6
	CEM V/A	66.8	68.7
RAC	CEM I	88.7	96.7
	CEM II/B-M	73.7	84.6
	CEM V/A	70.5	72.9

4.3. Impact on the concrete performance

Lower carbon and cost concretes were investigated to require more SP to achieve target slump value. As a consequence, the ECO$_2$ emissions by the SP contribution were higher for CEM II/B and CEM V mixes than CEM I mixes. Similar trend was observed for RAC mixes compared to NAC mixes. Loss of workability of lower carbon concretes, CEM II/B and CEM V, was found to decrease as the PC content in these mixes was reduced. Therefore, it could be more difficult to compact these concrete in comparison to CEM I mixes. Similar to this, RAC mixes with having either comparable or slightly higher ECO$_2$ emissions than NAC mixes were observed to reduce workability over time.

In summary, CEM I mixes with the highest environmental impact performed better performance in terms of fresh properties than CEM II/B-M and CEM V/A mixes. This is due to reducing PC, with the highest ECO$_2$ contributor, with lower impact SCMs reduced the flowability of concrete mixes and resulted in harsher matrix. Thus, reducing PC content with SCMs in order to produce sustainable concrete might have negative effect on the concrete fresh properties.

The strength results of concrete mixes showed that environmentally friendly and cost efficient CEM II/B and CEM V mixes indicated lower strengths than CEM I mixes due to reduction in the higher environmental impact PC content in these mixes. The reduction was more dramatic for CEM V mixes which had remarkably lower PC content in their mix proportions. Replacing PC content with SCMs could reduce ECO_2 emissions of concrete but it could also lead to reduction in Calcium oxide (CaO) content as expected and as a consequence, it delays the formation of Calcium silica hydrate (C-S-H) gel. However both mixes performed better than CEM I mixes at post 28 days with the contribution of pozzolanic reactions. RAC mixes with slightly higher costs indicated slightly lower strength values compared to NAC mixes. Replacing natural aggregates with higher impact and cost recycled aggregates weakened the bond between the cement paste and aggregates thereby reduced the concrete strength slightly.

The use of low carbon SCMs in CEM II/B and CEM V mixes reduced drying shrinkage values of concretes remarkably compared to CEM I mixes. However, SF inclusive CEM II/B-M mixes indicated higher shrinkage at early ages but performed lower shrinkage values than conventional CEM I mixes. RAC mixes was observed to provide similar shrinkage values as NAC mixes. In general, low carbon sustainable concrete mixes were observed to reduce concrete shrinkage.

From the durability performance point of view, low carbon CEM II/B and CEM V mixes showed lower resistance to carbonation and therefore higher risk for corrosion compared to CEM I mixes. Reducing higher impact PC with lower carbon footprint SCMs in aiming to reduce ECO_2 emission of concrete is believed to reduce C-H content therefore reduced resistance to carbonation. However, the use of recycled aggregates also reduced resistance to carbonation. On the contrary, the use of more environmentally friendly SCMs with their finer particle sizes was investigated to reduce concrete permeation significantly.

To conclude, low carbon sustainable concretes made with CEM II/B and CEM V cements along with recycled aggregates had negative effect on the concrete fresh properties. CEM II/B and CEM V mixes with lower carbon footprint and lower cost indicated lower early strengths but improved strength performance at 28 days and onwards. The utilization of recycled aggregates to promote sustainability reduced concrete strength slightly. In addition, low carbon sustainable concrete mixes were observed to reduce drying shrinkage considerably. Moreover, low carbon sustainable concretes indicated remarkably lower resistance to carbonation compared to conventional concrete but improved ISAT values significantly and reduced concrete permeability dramatically.

5. Practical implications

The use of CEM II/B and CEM V cements has a strong potential to use in concrete production as far as ECO_2 emissions and cost developed concretes is concerned. The results indicated that the use of CEM II/B and CEM V cements could practically produce cost-efficient concrete. Even though, the utilization of recycled aggregates slightly increased the cost of concretes, the use of CEM II/B-M and CEM V/A cements with particular replacement levels of recycled aggregates would be a practical approach when higher cost of CEM I cement NAC is taken into account.

From the environmental point of view, the use of CEM II/B and CEM V cements has a strong potential to reduce the ECO_2 emissions of concrete. As the current sustainability tools encourage higher rating construction materials with lower environmental impact, the use of CEM II/B and CEM V cement could be a practical approach to achieve better rating when used in the projects as far as the environmental tools are considered. The use of SF is believed to be an effective approach in improving the environmental performance since its incorporation provides improved strength and thus reduces the total cementitious content in other words PC content for a given design strength. Similar to that, GGBS usage has a potential to lower the ECO_2 of concrete as its incorporation improves the engineering performance of concrete due to its similar chemical composition as PC, and reduces the need for PC for a given design strength. Even though FA has the lowest emissions amongst all SCMs, slow strength gain of FA requires more PC to trigger necessary pozzolanic reaction which increases the ECO_2 emissions. However, FA use in concrete could still practically applicable for the production of low carbon concrete.

The use of recycled aggregates increased the concrete ECO_2 emissions, thus the use of recycled aggregates could be applicable in reducing environmental impact of concrete if used with CEM II/B-M and CEM V/A cements. As mentioned previously, it should also be considered that the UK government is setting highly approaches to promote the use of recycled aggregates in link with international and national agreements. The cost of natural resources is likely to increase in the future. Therefore, the use of recycled aggregates may be more cost-effective option in the near future.

6. Conclusions and Recommendations

The results obtained in this study could provide technical data on the general performance of CEM II/B-M and CEM V/A cement NAC and RAC mixes including ECO_2 emissions and cost analysis, fresh and engineering performances for the promotion of low carbon and economically viable concrete production. In this regard, the main conclusions drawn are defined below;

- The use of more environmentally friendly CEM II/B-M and CEM V/A cements and recycled aggregates showed higher loss of workability over time. The loss was observed to increase with replacement of PC by SCMs. The inclusion of SF and FA in CEM II/B-M and CEM V/A mixes increased viscosity of concrete mixes. In addition, the loss of workability over time increased for RAC mixes due to higher WA of both RA and RGS.

- The lower carbon inert SCMs incorporation was observed to reduce the concrete strength at early ages (< 7 days). However, this was observed to be compensated at 28 days and onwards. The pozzolanic reactions start taking place at 14 days and onwards. This hypothesis is supported by the drying shrinkage results. Recycled aggregates incorporation was observed to have adverse effect on compressive cylinder strength. In addition, none of the mixes except 50 N/mm^2 design strength CEM II/B-M cement NAC mix at particular age satisfied design factor ratio of 0.8 defined by BS EN 206 0.8 for $f_{c,cyl}/f_{c,cube}$.

- SCMs incorporation was observed to reduce drying shrinkage which may reduce internal stresses and suggests developed concrete mixes to be used in structural members except cylindrical column members. From engineering point of view, there is no significant trend observed for flexural strength and drying shrinkage values between NAC and RAC mixes.

- Durability properties of developed lower carbon concrete indicated two different trends for ISAT and carbonation resistance tests respectively. Concrete permeability through ISAT test showed superior results for CEM II/B-M and CEM V/A cement mixes compared to CEM I mixes. However, CEM I mixes showed much higher resistance to carbonation in comparison to other two mixes. In addition, incorporation of recycled aggregates was observed to lower the concrete performance slightly except CEM II/B-M mixes which indicated significantly increased carbonation depth over time.

- There is a great potential to produce carbon efficient and cost effective concrete through the use of CEM II/B and CEM V/A cements and recycled aggregates regardless total cementitious contents. In this matter, SF was observed to be the most effective SCM to reduce the binder content needed to achieve total cementitious content and lead to reduction in concrete ECO_2 emissions. Recycled aggregates incorporation showed a negligible amount of increase in cost of concretes.

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References

1. Department for Environment, Food and Rural Affairs (2004) *Scientific and technical aspects of climate change, including impacts and adaptation and associated costs*. London: Department for Environment, Food and Rural Affairs (Report).

2. Environmental Data Interactive Exchange (2014) *edie – environmental news, environmental jobs, suppliers and technical info for sustainability* [online]. UK: Faversham House Group [cited 1st March 2014]. <http://www.edie.net/library/view_article.asp?id=6455&title=A+constructive+look+at+tackling+building+emissions>

3. Mineral Products Association (2015) *Concrete Industry Sustainability Performance Report 8th report: 2014 performance data.* UK: The Concrete Centre.

4. British Standard Institution. BS EN 197-1 Cement. (2011) *Composition, specifications and conformity criteria for common cements*. BSI. London.

5. The Concrete Centre (2013) *Embodied carbon dioxide (CO2 e) of concretes used in buildings*. UK: MPA The Concrete Centre.

6. University of Bath (2011) *Inventory of Carbon and Energy.* UK: University of Bath, Sustainable Energy Research Team.

7. Jones, R., McCarthy, M. and Newlands, M. (2011) Fly Ash Route to Low Embodied CO2 and Implications for Concrete Construction. *In* American Coal Association and the University of Kentucky Center for Applied Energy *Proceedings: World of Coal Ash conference: May 9-12, 2011 in Denver, USA.*

8. Purnell, P. and Black, L. (2012) Embodied carbon dioxide in concrete: Variation with common mix design parameters. *Cement and Concrete Research*. **42**, pp.874-77.

9. Concrete Industry Sustainable Construction Forum (2008) *Sheet C1 – Embodied CO2 of Concrete and Reinforced Concrete.* UK: MPA The Concrete Centre.

10. Flower, D. and Sanjayan, J. (2007) Green house gas emissions due to concrete manufacture. *International Journal of Life Cycle Assessment*, **12** (5), pp.282-88.

11. Knoeri, C., Sanye-Mengual, E., Althaus, H-J. (2013) Comparative LCA of recycled and conventional concrete for structural applications. *International Journal of Life Cycle Assesment*. **18**(June(5)), pp.909-18.

12. Limbachiya, M.C. (2009) Bulk engineering and durability properties of washed glass sand concrete. *Construction and Building Materials*. **23**. pp.1078-83.

13. Megat Johari, M.A., Brooks, J.J., Kabir, S. and Rivard, P. (2011) Influence of supplementary cementitious on engineering properties of high strength concrete. *Construction and Building Materials.***25** (5), pp.2639-2648.

14. Kou, S.C. and Poon, C.S. (2009) Properties of self-compacting concrete prepared with recycled glass aggregate. *Cement & Concrete Composites*. **31**, pp.107-113.

15. Kuder, K., Lehman, D., Berman, J., Hannesson, G. and Shogren, R. (2012) Mechanical properties of self consolidating concrete blended with high volumes of fly ash and slag. *Construction and Building Materials.* **34**, pp. 285-95.

16. Bernal, S.A., de Gutiérrez, R.M., Pedraza, A.L., Provis, J.L., Rodriguez, E.D. and Delvasto, S. (2011) Effect of binder content on the performance of alkali-activated slag concretes. *Cement and Concrete Research.* **41**, pp.1-8.

17. Benli, A., Karataş, M. & Bakir, Y. (2017) An experimental study of different curing regimes on the mechanical properties and sorptivity of self-compacting mortars with fly ash and silica fume. *Construction and Building Materials*. **144**. pp.552-62.

18. Concrete construction (2012) *Concrete Construction: Resources for contractors and specifiers including construction methods, materials and equipment*. [online]. Washington: Hanley Wood Media. <http://www.concreteconstruction.net/aggregates/global-demand-for-construction-aggregates-to-exceed-48-billion-metric-tons-in-2015.aspx>

19. Jones, M.R., McCarhty, A. and Dhir, R.K. (2005) *Recycled and Secondary Aggregates in Foamed Concrete*. Oxon: The Waste & Resources Action Programme. ISBN: 1-84405-184-6. p.29.

20. British Standard Institution. BS EN 12620 Aggregates for concrete (2013) BSI. London.

21. Sustainable Concrete Forum (no date) *Home Page*. [online]. UK: MPA The Concrete Centre. <http://www.sustainableconcrete.org.uk/top_nav/uk_construction_industry/aggregate_levy.aspx>

22. Mineral Products Association (no date) *Mineral Products Association (MPA) – the trade association for the aggregates, asphalt, cement, concrete, lime, mortar and silica sand industries*. [online]. London: Mineral Products Association. <http://www.mineralproducts.org/prod_agg_recy01.htm>

23. University of Dundee (2005) *www.greenconcrete.dundee.ac.uk.* [online] Scotland: University of Dundee. <http://www.greenconcrete.dundee.ac.uk/RecycledGlass.htm>

24. Gönen, T. and Yazıcıoğlu, S. (2007) The influence of mineral admixtures on the short and long-term performance of concrete. *Building and Environment*. **42**. (8), pp.3080-85.

25. Limbachiya, M., Meddah, M.S. and Ouchagour, Y. (2012) Use of recycled concrete aggregate in fly-ash concrete. *Construction and Building Materials*. **27**, pp.439-449.

26. Sim, J. and Park, C. (2011) Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. *Waste Management*. **31** (11), pp.2352-2360.

27. Song, H. and Saraswathy, V. (2006) Studies on the corrosion resistance of reinforced steel in concrete with ground granulated blast-furnace slag – an overview. *Journal of Hazardous Materials*. **B138**, pp. 226-33.

28. Abbas, A., Gholamreza, F., Isgor, O.B. and Razaqpur, A.G. (2009) Durability of recycled aggregate concrete designed with equivalent mortar volume method. *Cement & Concrete Composites*. **31**, pp.555-563.

29. British Standard Institution. BS EN 15167-1 Ground granulated blast furnace slag for use in concrete, mortar and grout. (2006) *Definitions, specification and conformity criteria.* BSI. London.

30. British Standard Institution. BS EN 450-1 Fly ash for concrete. (2012) *Definition, specifications and conformity criteria.* BSI. London.

31. British Standard Institution. BS EN 13263-1 Silica fume for concrete. (2009) *Conformity evaluation.* BSI. London.

32. British Standard Institution. BS EN 934-2: 2009+A1:2012 Admixtures for concrete mortar and grout (2009) *Concrete admixtures. Definitions, requirement, conformity, marking and labelling.* BSI. London.

33. Building Research Establishment Ltd. (1997) *Design of normal concrete mixes.* 2nd Ed., London: Construction Research Communications Ltd.

34. British Standard Institution. BS EN 12390-2 Testing hardened concrete (2009) *Making and curing specimens for strength tests.* BSI. London.

35. British Standard Institution. BS 1881-208 Testing Concrete (1996). *Recommendations for the determination of the initial surface absorption of concrete.* BSI. London.

36. Mineral Products Association (2015) *Fact Sheet 18 Embodied* CO_2*e of UK cement, additions and cementitious material.* UK: Mineral Products Association.

37. Gesoglu, M., Guneyisi, E., Ozbay, E. (2009) Properties of self-compacting concretes made with binary, ternary and quaternary cementitious blends of fly ash, blast furnace slag and silica fume. *Construction and Building Materials*. **23** (5), pp.1847-54.

38. Guneyisi, E., Gesoglu, M, and Ozbay, E. (2010) Strength and drying shrinkage properties of self-compacting concretes incorporating multi-system blended mineral admixtures. *Construction and Building Materials.* **24**, pp. 1878-87.

39. Hui-sheng, S., Bi-wan, X. and Xiao-chen, Z. (2009) Influence of mineral admixtures on compressive strength, gas permeability and carbonation of high performance concrete. *Construction and Building Materials.* **29**, pp.1985-90.

40. McCarthy, M.J. and Dhir, K. (2005) Development of high volume fly ash cements for use in concrete construction. *Fuel.* **84** (11), pp.1423-32.
41. Tu, T.Y., Chen, Y.Y. and Hwang, C.L. (2006) Properties of HPC with recycled aggregates. *Cement and Concrete Research.* **36**, pp.943-50.

42. Limbachiya, M., Meddah, M.S., Fotiadou, S. (2012) Performance of granulated foam glass concrete. *Construction and Building Materials*. **28**, pp.759-68.

43. Ling, T.C., Poon, C.S. and Kou, S.C. (2012) Influence of recycled glass content and curing conditions on the properties of self-compacting concrete after exposure to elevated temperatures. *Cement & Concrete Composites.* **34**. Pp. 265-72.

44. Nikbin, I.M., Dehestani, M., Beygi, M.H.A. and Rezvani, M. (2014) Effects of cube size and placement direction on compressive strength of self-consolidating concrete. *Construction and Building Materials.* **59**, pp.144-150.

45. Bhanja, S. and Sengupta, B. (2002) Investigations on the compressive strength of silica fume concrete using statistical methods. *Cement and Concrete Research*. **32**, pp. 1391-94.

46. Akçaözoglu, S. and Atis, C.D. (2011) Effect of Granulated Blast Furnace Slag and fly ash addition on the strength properties of lightweight mortars containing waste PET aggregates. *Construction and Building Materials.* **25** (10), pp.4052–4058.

47. Abdul Razak, H., Chai, H.K. and Wong, H.S. (2004) Near surface characteristics of concrete containing supplementary cementing materials. *Cement & Concrete Composites*. **26**, pp.883-89.

48. Ganjian, E. & Pouya, H.S. (2009) The effect of Persian Gulf tidal zone exposure on durability of mixes containing silica fume and blast furnace slag. *Construction and Building Materials*. **23**. pp.644-652.

49. Thomas, C., Setien, J., Alaejos, P. And de Juan, M.S. (2013) Durability of recycled aggregate concrete. *Construction and Building Materials*. **40**. Pp.1054-65.

50. Zaharieva, R., Buyle-Bodin, F., Skoczylas, F. and Wirquin, E. (2003) Assessment of the surface permeation properties of recycled aggregate concrete. *Cement & Concrete Composites*. **25**. Pp.223-32.

Highlights:

$f_{c,cyl}/f_{c,cube}$ ratios indicated lower ratios than BS EN 206-1 design factor (0.8).

Drying shrinkage results showed that pozzolanic reactions takes place after 14 days.

SCMs recycled aggregate concretes improved permeability compared to control mix.

Recycled aggregates could slightly increase the ECO_2 emissions and cost of concretes.