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Original scientific paper

Performance of Self Compacting Concrete Using Bentonite

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Abstract: Supplementary Cementitious Materials (SCMs) have the potential to enhance the properties of self-compacting concrete (SCC) while reducing the pressure on natural reserves and CO_2 emissions. However, certain SCMs are not able to meet the needs in the construction industry. This research investigates the role of unheated bentonite (BN) clay and its synergistic effect with Ground Granulated Blast Furnace Slag (GGBS) as a partial substitute for cement on performance of SCC. Three different mixtures were prepared, each consisting of 0%, 15%, and 30% (by weight) BC as a replacement for cement, while GGBS remained constant to get the designed strength. Each mix was designed with two strength grades of 30 and 60 MPa by adjusting the compositional parameters and validating their 28 days compressive strength. Fresh Properties tests were conducted as per EFNARC standards. The ultrasonic pulse velocity of all tested specimens is greater than 4.5 km/s, indicating "good" and "excellent" quality concrete. The experimental results revealed that combining BC with GGBS concrete improved durability. The BC and GGBS made concrete more resistant to sulphate attack and chloride ingress. The concrete mixtures were found to be suitable and more durable for use in the construction industry.

Keywords: durability; self-compacting concrete; sustainability

1 INTRODUCTION

After water, concrete is the widely used commercial material on the planet; it is used nearly twice as compared to all other building materials [1, 2]. When it comes to issues like followability, easy placement in congested areas, and sustainability, conventional concrete is not always appropriate. Conventional concrete with high flowability properties may experience segregation, strength loss, and ultimately durability [3]. As a result, Self-Compacting Concrete (SCC) is now widely used due to its flowability, ease of placement in congested areas, and sustainability [1, 4].

Superplasticizers (SP) are used to achieve these properties while minimizing the risk of bleeding and segregation, as well as to easily distribute aggregate in congested sections [5]. Furthermore, the amount of cement required for paste in SCC is comparatively higher, which results in more heat of hydration in addition to allied aspects related to economic and environmental issues [5, 6]. As a result, the use of alternate materials like silica fumes (SF), fly ash (FA), is encouraged in the development of SCC, as they have a favourable effect on rheological, mechanical, and durability properties [5-10]. This is mainly because of pozzolanic action of these materials, which forms additional calcium silicate hydrate (C-S-H) when portlandite is present [11-15]. These SCMs offer better options for producing more durable, cost-effective, and eco-friendly concrete.

Calcined clays are becoming more popular and unlike cement, these can be activated with very little energy as a lot of energy is utilized in manufacturing cement. Calcined clays are widely available worldwide and can be obtained by using a high-temperature thermal process [16]. Many researchers have investigated the performance of concrete by using these materials at various replacement levels with cement and found it very effective in terms of various mechanical and durability properties [6, 17-26]. Approximately one-third of the whole world's energy is consumed by the construction industry and contributing around 30% of CO_2 into the atmosphere. There is approximately 0.15 tonne of greenhouse gas emissions per tonne of concrete and 1 tonne per tonne of cement produced [15].

It is a well-known fact that famous SCMs like SF and FA are not available in abundance in the world [16]. Coal power plants are banned in some parts of the world due to the global shift toward green energy, and as a result, FA production has fallen dramatically [17]. The production of these materials is considerably lower as compared to cement therefore its availability is locally imbalanced. As a result, there is need to explore and utilize new SCMs to meet the demand of construction industry with high-level Cement replacement [18]. The situation is exacerbated by the fact that changes in the manufacturing process, as well as alterations in the coal and steel industries, affect the quantity and quality of these widely used SCMs [19]. As a result, many studies are being carried out to discover new SCMs that can meet the rising demand for construction while also being environmentally friendly.

Bentonite is a natural clay that is found in many countries worldwide. It is mostly made up of montmorillonite and other minerals like volcanic glass, cristobalite, feldspar, and crystalline quartz [27, 28]. Effect of bentonite was focused in many studies on the properties of fresh and hardened conventional mortar, pastes, and concrete. Taylor-Lange et al. [29] found that substituting bentonite for cement and blending it with calcined kaolinite resulted in positive outcomes. To investigate the performance of concrete with Bentonite as an ingredient, Memon et al. [30] conducted a study and found that bentonite had reduced workability and water absorption, while increasing 56-days strength. Bentonite was studied by Darweesh and Nagieb [16] to see how it affected pozzolanic activity in cement paste and found an increase in setting time, consistency, compressive strength, and bulk density. A decrease in apparent porosity correlated with an increase in strength was also noted. Mirza et al.[31] examined the role of unheated as well as heated bentonite at various temperatures as a partial substitute for Cement in both mortar and concrete in another study where temperature effects were studied. Bentonite was heated to various temperatures before being incorporated into Cement at various percentage levels. According to the study, it is possible to utilize mortar and concrete that contains 25% heated bentonite and 20% unheated bentonite at a higher temperature without compromising on construction costs or environmental considerations. Similarly, Ahmad et al. [27] studied the use of Bentonite as a partial cement replacement in concrete. The bentonite was heated at high temperatures, and the strength index of bentonite in both states (heated and unheated) was studied and it was concluded that concrete made with 30% bentonite replaced cement would have ample compressive strength.

Zine et al. [26] carried out an experimental study on bentonite replacement; in light of these findings, the addition of nanoparticles in concrete mixtures has been proposed as a lucrative substitute to generally used SCMs as a long-lasting, environmentally friendly SCC.

Because of the abundant supply of raw material clay and the active components created by the disintegration of clay minerals owing to heat treatment, either naturally or artificially, nano-clay and calcined clay have shown to be promising, because of their same behaviour as SCMs. [19]. BC which can be found in large quantities in parts of Asia and Africa, is one of the most promising potential alternatives. Magnesium and potassium oxides are produced by the process, and they help concrete to harden [27]. BC is a smectite derived clay mineral with a high montmorillonite content. BC has a large surface area and high concentration of calcium and sodium. In the presence of water, a workable concrete mix can be created by binding the sand grains in concrete with bentonite to create a plastic paste [28]. As the bentonite has enriched in calcium, it has minimal capacity for swelling, in contrast to some forms of montmorillonite-rich bentonite that may swell when exposed to water [29]. According to estimations, natural resources can provide BC for 60 years. In the production of environmentally friendly concrete, BC is used as a partial replacement for cement [30, 31]. The compressive strength of concrete improved by 10% by the combination of BC and FA. Researchers discovered that compressive strength and tensile strength were improved with the replacement of BC, but chloride migration was found to be decreased. Furthermore, according to reports, the usage of BC can boost the economy of the construction industry in emerging nations [32]. In comparison to standard concrete, BC (up to a 20% substitution of Cement) in a blend with metakaolin or FA increased sulphate resistance, compressive strength, and microstructural characteristics. It is important to check the early-stage strength of this unconventional concrete before using it in construction [33]. BC clays are classified as low purity clays with a wide range of composition and mineralogy. As a result, a review of available studies cannot predict or assess its performance in cement or concrete [19].

Every type and source of BC should be studied separately for their use in place of cement while using with SCMs.

GGBS is a hydraulic material that, when exposed to water, hydrates to form a hardened compound. The reactivity index of GGBS is influenced by factors, like chemical composition and glass content, and this in turn affects the cementitious properties of the material. An ASTM C989 standard defines grades 80 (the least reactive) through 120 (the most receptive). Pozzolanic and cementitious properties in many studies have examined how GGBS affects different types of concrete and mortar's strength. Compressive strength of the mix is significantly improved by swapping Cement with GGBS, however durability properties still need to be investigated, while replacing GGBS with Cement. Slow strength development is bad for fresh concrete, but it is good for concrete, which has been in place for at least 28 days. When it comes to ageing, GGBS-containing concrete continues to gain strength at an earlier age than normal cement concrete [34].

Limestone filler is frequently used in the development of SCC to reduce segregation [35]. For precast concrete, industrial floors, and foundations that are vulnerable to chemical or sulfuric acid attack, SCC is increasingly being used in the form of SCC.

The durability of SCC in these areas must be evaluated because the mix design of SCC differs from that of conventional concrete. The sulfuric acid resistance of SCC is thought to be altered by varying the ratios of limestone filler and aggregate combinations. Because of this, bentonite is used to replace cement and limestone is used as a filler to increase the materials' long-term strength and durability.

Given the few previous studies on the production of SCC containing BC with GGBS, the purpose of this study is to investigate the effect of BC by replacing cement with GGBS and BC, and to investigate the durability properties. As a result, different grades of concrete were prepared, each with a different aggregate content, to produce more durable and eco-friendly concrete with optimal compositional parameters and durability properties with bentonite and GGBS.

2 MATERIALS

2.1 Cement

Ordinary Portland cement (OPC), conforming to ASTM specification C150-94 Type I, was used. The properties and chemical composition of OPC is given in Tab. 1.

2.2 Aggregate

Aggregates were obtained from Margalla (Taxila, Pakistan) which is a very commonly adopted source by the construction industry in the country. These aggregates are mainly composed of limestone and are basic in nature. Fine aggregates i.e., sand from Lawrencepur, Pakistan was used in this study. Tab. 2 shows the details.

2.3 Admixture

ViscoCrete-3110 [36] was used to increase the workability. It is a third generation polycarboxylate based superplasticizer that to refers ASTM C494. Suitable for use in concrete mixes containing micro silica and other pozzolanic materials such as GGBS and fly ash. Chemical Base Aqueous solution of modified polycarboxylates, co-polymers.

2.4 Bentonite

Chemical Properties of Bentonite (BN) used in this study are given in Tab. 1.

2.5 Mix Proportioning

Concrete with different strength grades of 30 MPa and 60 MPa was designed, and each grade was further classified based on different mortar paste to aggregate ratios. In all mix designs, 0%, 15% and 30% of OPC was replaced by BN. Finalized composition, after a number of trials, of all the materials used is given in Tab. 3.

Table 1 Physical and chemical properties of OPC and BN

Composition / %	OPC	BN	GGBS
SiO_2	17.5	50-65	35.0
Al_2O_3	10.4	15-25	12.0
Fe_2O_3	3.5	2-4	1.0
MgO	1.7	3-6	-
CaO	61.8	0.5-2	40.0
Na_2O	0.7	0.5-5	0.3
K_2O	1.3	0.2-1	0.4
TiO	-	0.2-0.5	-
SO_2	-	-	9.0
Moisture	-	5-8	-
Other content	-	0.5-2.5	-
PH in distilled water	-	9-10	-
Swelling	-	12-16 Time	-
Practical	-	98% Passing through 250 Mesh	-
Specific gravity of 6% mud	-	1.0-1.5	-
Specific gravity	3.06	2.4-2.5	2.94
Specific surface area / m^2/kg	-	-	400
Loss on ignition / %	0.94	10-16	1.0
Specific surface area / m^2/kg	320	220	238

Table 2 Properties of course and fine aggregate

Coarse Aggregate			Fine Aggregate		
Property	Reference	Values	Property	Reference	Values
Sieve analysis	ASTM C136	Well graded	Specific gravity	ASTM C128	2.72
Moisture content	ASTM C566	0.25%	Water absorption	ASTM C128	3.10%
Specific gravity	ASTM C127	2.66	Fine modulus	ASTM C136	2.84
Water absorption	ASTM C127	1.23%	Moisture content	ASTM C70	2.40%

Table 3 Mix proportioning

Material required for samples in kg									
Mix Design		OPC	BN	GGBS	WATER	SP	LP	FA	CA
0%	0BC30A	240	0	80	201.6	1.4	109	743	924
	0BC30B	240	0	80	201.6	1.6	156	764	840
	0BC30C	240	0	80	201.6	2.3	194	795	756
	0BC60A	315	0	105	197.5	2.3	94	677	924
	0BC60B	315	0	105	197.5	2.4	125	716	840
	0BC60C	315	0	105	197.5	2.8	172	735	756
15%	15BC30A	204	36	80	201.6	1.4	109	743	924
	15BC30B	204	36	80	201.6	1.6	156	764	840
	15BC30C	204	36	80	201.6	2.3	194	795	756
	15BC60A	267.75	47.25	105	197.5	2.3	94	677	924
	15BC60B	267.75	47.25	105	197.5	2.4	125	716	840
	15BC60C	267.75	47.25	105	197.5	2.8	172	735	756
30%	30BC30A	168	72	80	201.6	1.4	109	743	924
	30BC30B	168	72	80	201.6	1.6	156	764	840
	30BC30C	168	72	80	201.6	2.3	194	795	756
	30BC60A	220.5	94.5	105	197.5	2.3	94	677	924
	30BC60B	220.5	94.5	105	197.5	2.4	125	716	840
	30BC60C	220.5	94.5	105	197.5	2.8	172	735	756

SP: super-plasticizer, BN: Bentonite, GGBS: Ground Granulated Blast Furnace Slag, OPC: Cement, LP: lime powder ($CaCO_3$) < 125 µm, FA: Fine Aggregates < 2 mm, CA: coarse aggregate < 18 mm, A, B and C indicate reduction in coarse aggregate and relative increase in the paste volume for the same strength grade.

3 EXPERIMENTAL WORKS

3.1 Fresh Properties

Several tests to investigate the properties of fresh concrete were carried out as per procedures guided by EFNARC [37]. Slump flow test was performed to assess the filling ability of concrete. This ability to pass through confined areas was checked through L-box test, while viscosity of concrete was determined by the T500 and V-funnel time method. Proportioning of constituent materials was concluded by keeping fresh properties test results within limits as suggested by the EFNARC.

3.2 Compressive Strength

In case of hardened concrete, the compressive strength tests for 7, 14 and 28 days were carried out as per ASTM C39 for each sample. The tests were conducted to validate the designed strengths. For each assessment, three standard cubes (150 × 150 × 150 mm) and three cylinders (150 mm diameter and 300 mm height) were prepared and cured till the day of testing. Compressive strength achieved after 28 days is presented in Tab.4.

Table 4 Compressive strength

Mix Design	Achieved Compressive Strength (after 28 days curing) / MPa
0BC30A	30.5
0BC30B	29.5
0BC30C	29
0BC60A	60.5
0BC60B	59.5
0BC60C	59
15BC30A	32
15BC30B	31.5

Table 4 Compressive strength (continuation)

Mix Design	Achieved Compressive Strength (after 28 days curing) / MPa
15BC30C	31
15BC60A	63
15BC60B	62
15BC60C	61.5
30BC30A	30.5
30BC30B	29.5
30BC30C	28.5
30BC60A	58.5
30BC60B	59
30BC60C	59.5

3.3 Sorptivity

Sorptivity tests were conducted for all the mixes in accordance with ASTM C1585-20. The test method is used to determine the rate of absorption (sorptivity) of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time when only one surface of the specimen is exposed to water. The specimen is conditioned in an environment at a standard relative humidity to induce a consistent moisture condition in the capillary pore system. The exposed surface of the specimen is immersed in water and water ingress of unsaturated concrete is dominated by capillary suction during initial contact with water. Mass is recorded at each interval as mentioned in procedure. Absorption (I) is calculated by the formula mentioned in ASTM C1585-20 [38].

3.4 Chloride Migration Coefficient

Chloride Migration coefficient was measured for all mixes by following non-steady state migration test in accordance with NT BUILD 492. A two-cell arrangement was used as shown in Fig. 1.

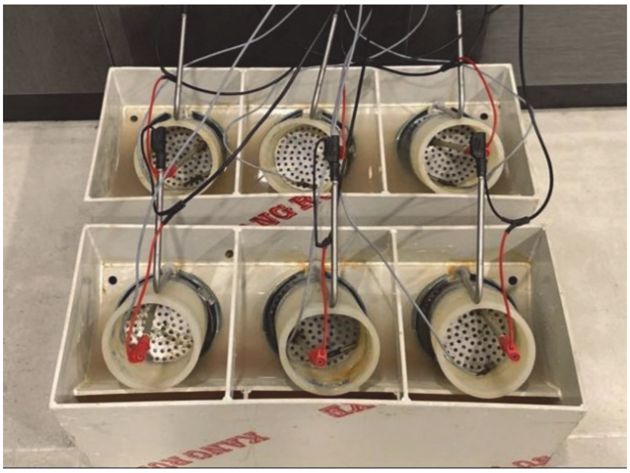

Figure 1 Non-steady state chloride migration test arrangement

Following steps were involved in performing Chloride migration test:

3.4.1 Preparation of Test Specimens

The test specimen for the non-steady state migration was concrete disc of 100 mm diameter and 50mm thickness. Three specimens were used in this test. The exact thickness of the specimens was measured using the Vernier callipers.

3.4.2 Sample Pre-Conditioning

After cutting, samples were vacuumed for 3 hours. The pressure in the vacuum chamber was less than 5 kPa (50 mbar). The saturated solution of $Ca(OH)_2$ was added to the container while the vacuum pump was still running, till the samples were completely immersed. For one hour, the samples were kept in the solution. The samples were submerged in the solution for further 18 + 2 hours while under atmospheric pressure after the vacuum was removed.

3.4.3 Sample Testing

The samples were pre-conditioned, then washed in deionized water, dried in air, and firmly packed in a rubber sleeve, both the top and bottom sides were exposed. The samples were set on an inclined support, with the top face exposed to a 0.3 molar NaOH anolyte solution and the bottom face exposed to a 10 percent (by mass) NaCl catholyte solution (Fig. 2). Anode and cathode connections for each sample were made, 60 volts were applied from power supply. The current was measured, and if necessary, the voltage was adjusted. The testing timeframe was also defined in the same procedure. The initial and final voltage, current, and temperature of the anolyte solution were all measured.

Figure 2 Migration coefficient preconditioning and testing

3.4.4 Measurement of Chloride Penetration

After the test was finished, the samples were taken out of the device, cleaned, dried, and divided axially into two halves. A 0.1 molar silver nitrate solution was sprayed over a freshly split piece. After 15 minutes, the chloride penetration profile was clearly visible as a white silver chloride precipitate (Fig. 2). Chloride penetration was measured across the sample's 100 mm diameter. To accurately determine the non-steady-state migration coefficient, three measurements accurate to 0.1 mm were required

3.4.5 Determination of Migration Coefficient D_{nssm}

The non-steady-state migration coefficient, D_{nssm}, is determined using Eq. (1). The D_{nssm} is typically reported in 10-12 m²/sec.

$$D_{nssm} = \frac{RT}{zFE}\frac{x_d - \alpha\sqrt{x_d}}{t} \tag{1}$$

where,

$$E = \frac{U-2}{L} \tag{2}$$

$$\alpha = s\sqrt{\frac{RT}{zFE}}.erf^{-1}\left(1-\left(\frac{2c_d}{c_o}\right)\right) \tag{3}$$

3.5 Acid Attack

Acid Attack was performed in line with ASTM C1898-20 [39]. Weight loss of samples, exposed to acidic environment, was measured at different intervals of time. Specimens were examined after 1, 7, 14, 28, days of immersion to determine the rate of attack and weight loss was calculated.

3.6 Ultrasonic Pulse Velocity

UPVC test was performed according to ASTM C 597-02 [36]. The UPVC results can be used to determine whether concrete is uniform and to find concrete voids and cracks. By comparing results to similarly manufactured concrete, it is possible to regulate the quality of concrete and concrete products. Ultrasonic pulse velocity (UPVC), an indicator of concrete quality, was determined for cube specimens using a direct method, and the pulse transit time was measured. Pulse velocity was measured by multiplying the distance between the transducers by the time required for the wave to pass through the concrete.

4 RESULTS AND DISCUSSIONS
4.1 Fresh Properties

Fresh properties test results are shown in Tab. 5. The slump flow values of all mixes of SCC vary between 650 mm and 750 mm. Higher percentage replacement of BN with cement reduced the workability but still in the range to be called as self-compacting concrete. With the decreasing trend in the slump flow values it is clear that the workability decreased when OPC was partially replaced by the BN. To achieve the targeted slump for all the mixes, dosages of super plasticizers (SP) were adjusted. During adjustment dosage of SP in order to keep mixes within ranges guided by EFNARC, decrease in slump value was observed by the inclusion of BN, which can be explained by the fact that BN has a higher fineness and specific surface area than OPC, requiring more water to wet the particles. The same result was observed by Ahmed et al. [27]. Mirza et al. [31] also determined that very fine BN particles decreased the slump value, and its workability can be enhanced by adding SP. Memon et al. [30] reached similar conclusions that the finer the BN particles, the lower will be the slump value due to their higher surface area. In another study, Madandoust and Mousavi [22] observed that the slump flow of mixtures decreased with the partial replacement of calcined kaolin with OPC, but the dosage of super plasticizers utilized was high. This was because the added minerals partly mobilized the quantity of SP which were intended for the dispersing and deflocculation of cement grains. Fig. 3 and Tab. 5 illustrate various results of fresh properties.

Table 5 Fresh properties test results

Bentonite Percentage	Mix Designation	Slump flow test		V-Funnel test	J-Ring flow test	L-Box test
		mm	T500, s	TV-Funnel, s	mm	H_2/H_1
0%	0BC30A	720	3.5	8.5	710	0.90
	0BC30B	740	3	8	715	0.92
	0BC30C	750	2.5	7	730	0.93
	0BC60A	710	3.4	9	700	0.88
	0BC60B	730	3	8	710	0.89
	0BC60C	745	2.6	7.5	720	0.9
15%	15BC30A	670	4.5	9	660	0.85
	15BC30B	685	4.3	8.5	673	0.88
	15BC30C	690	4	8	685	0.89
	15BC60A	665	4.6	9.5	660	0.83
	15BC60B	670	4.4	9	665	0.84
	15BC60C	675	4.3	8.6	670	0.86
30%	30BC30A	655	4.9	10	650	0.81
	30BC30B	658	4.8	11	651	0.82
	30BC30C	660	4.6	11.5	653	0.83
	30BC60A	653	5	11	651	0.8
	30BC60B	657	4.9	11.5	653	0.81
	30BC60C	665	4.8	12	656	0.82

From Tab. 5, it can be noted that the T500 value increased with the addition of BN and hence it can be stated that BN increased the viscosity of the concrete mixture.

The results obtained from V-funnel flow time for different concrete mixes can show that the flow time values are ranging between 7 and 12 seconds, hence falling in category of VF2 as suggested by EFNARC. With the addition of BN in the concrete, the V-funnel flow time value increased, the same trend is found in T500 flow time method. Also, this range was selected and achieved to be in accordance with the EFNARC VS2. It should be noted that up to 15% of BN replacement, there was enhancement in the V-funnel flow time of the concrete, which means that the concrete made of this percentage was more viscous demanding more amount of SP to meet the criteria necessary for SCC.

Tab. 5 depicts the L-box test results trend of various SCC samples with and without BN. To minimize risk of blocking, the H2/H1 ratio must not be less than 0.8. The results indicate that this ratio remained in the limits and was considered as L-box class PA1 as per EFNARC. 28-days compressive strength of SCC produced with various percentages of BN are validated as mix design was performed.

4.2 Compressive Strength

The compressive strength results for all of the mixes are shown in Tab. 5. The incorporation of BN improved the compressive strength after the 28 curing periods. After 28 days, the compressive strength of the mixes 15BC30A & 15BC60A improved by 3%, compared to the control mix (0BC30A & 0BC60A). The increase in compressive strength of SCM concrete mixtures can be attributed to the production of supplementary cementitious products due to the pozzolanic reaction and filler effect of SCMs that results in a more compact and refined microstructure of concrete [39-41]. Although previous research [27, 31] demonstrated the positive effect of BN on the compressive strength of concrete mixtures, it can be observed from the compressive strength results of the current study that BN can also be incorporated up to 15% replacement of cement to obtain comparable compressive strength. In this study replacement of BN up to 30% has no positive impact on compressive strength.

Figure 3 Various tests for fresh properties of SCC

4.3 Sorptivity

Sorptivity test results are presented in Figs. 4 to 6. It can be observed that water absorption is less in case of binary (with unheated BN) mixes of SCC than as observed in control mixes of same strength. Furthermore, water absorption is greater in the mix with less coarse aggregate content than in the mix with more coarse aggregate content. Less water absorption in samples in which BN was replaced could be due to the fact that BN can impart physical and chemical effects on the microstructure of concrete. The particle of BN is finer in size compared to cement and exhibits a filler effect by filling up micro voids in the concrete mix whereas pozzolanic reaction due to the presence of SCMs produces supplementary CSH gel which enhances the homogeneity of the concrete matrix thus reducing sorptivity [39, 40].

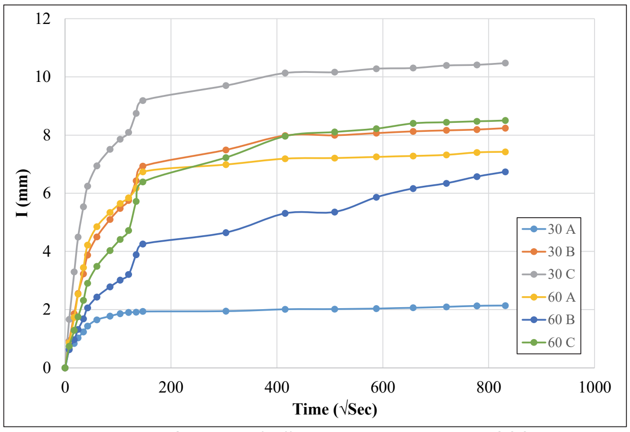

Figure 4 Sorptivity of different strength control mix SCC

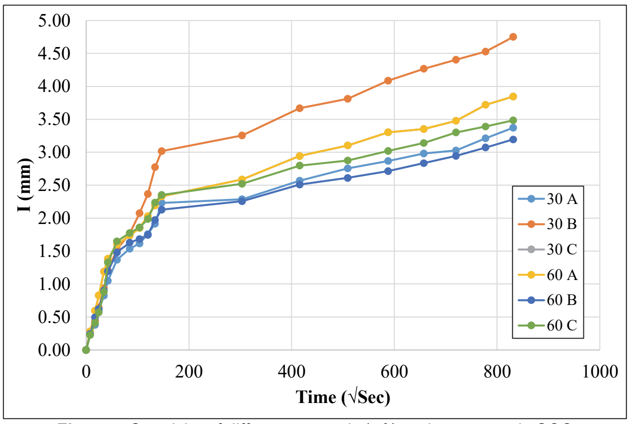

Figure 5 Sorptivity of different strength 15% replacement mix SCC

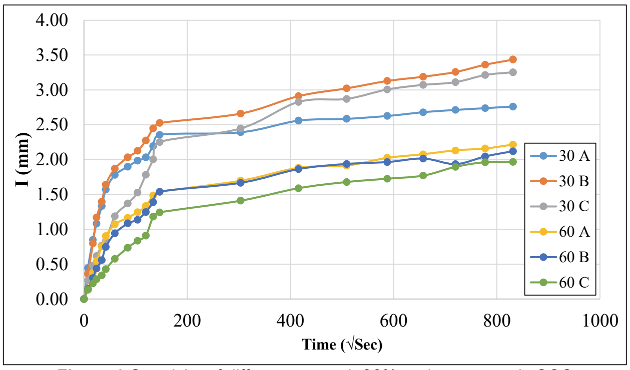

Figure 6 Sorptivity of different strength 30% replacement mix SCC

4.4 Chloride Migration Coefficient

This behaviour of higher resistance to chloride-ions penetration is due to the reduction in porous system due to pozzolanic reaction between OPC and CB. This finding is consistent with the findings of Gill et al. [33], who discovered that self-compacting concrete containing up to 15% metakaolin and 10% rice husk ash would resist chloride penetration by 14-44 percent after 28 days of curing. Kavitha et al. [34] reported a long-lasting SCC with improved resistance to chloride ion penetration that contained 10% metakaolin. Burgos et al. [35] used volcanic material to evaluate chloride ion penetration in SCC, concluding that SCC incorporating natural pozzolanic material would have more resistance to chloride migration than SCC made with simple OPC.

Chloride migration coefficient was measured for different bentonite percentages and found for the 15% bentonite the durability was in very high range as compared to the other sample in which 0% and 30% bentonite was replaced with cement. However, the durability of the latter two was also in very good range. Figs. 7 and 8 shows the results of chloride migration and penetration depth.

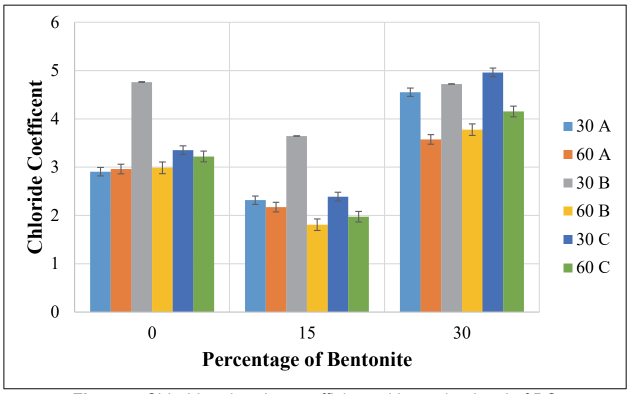

Figure 7 Chloride migration coefficient with varying level of BC

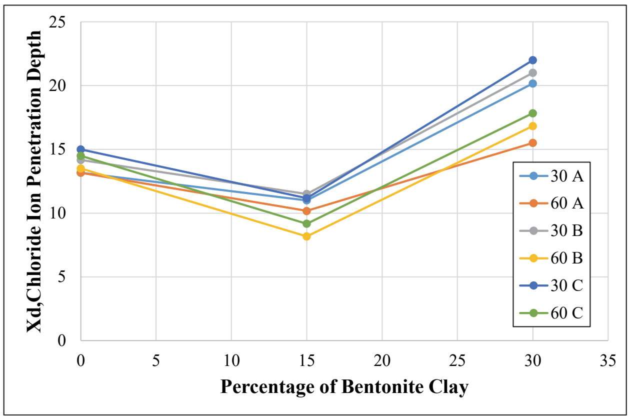

Figure 8 Chloride ion penetration depth with varying level of BC

4.5 Acid Attack

From Figs. 9 to 11 it can be seen that weight loss in control samples and 30% bentonite is more than the 15% bentonite samples. It can be concluded that replacement of bentonite up to 15% shows more resistance against acid attack as compared to 0% and 30% bentonite. The acid attack test causes weight loss and, as a result, strength loss. Concrete has numerous applications in field and especially when it contacts with water this can create an acidic environment; containing acids (most notably sulfuric acid) can ingress in concrete, resulting in the formation of sulphate ions. The reaction between these ions and the portlandite produces gypsum [42]. The calcium aluminate hydrate (CAH) reacts with the gypsum to produce ettringite. Ettringite is a primary cause of structural degradation because of its expansion [17, 19]. The mass loss due to sulphate ion exposure was quantified using the developed concrete mixes, and the results are shown in Fig. 9. Pore system refinement prevents further ion diffusion, so weight loss decreases as BN proportion in the mixture rises as shown in Fig. 10. In this current study it was also observed that the weight loss is quite significant when BN replacement is more than 15%, even the weight loss is more than control mix when 30% replacement of BN with OPC was carried out.

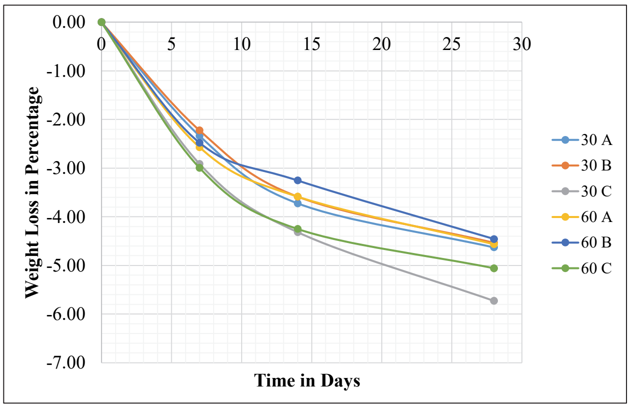

Figure 9 Acid test results of different strength control mix SCC

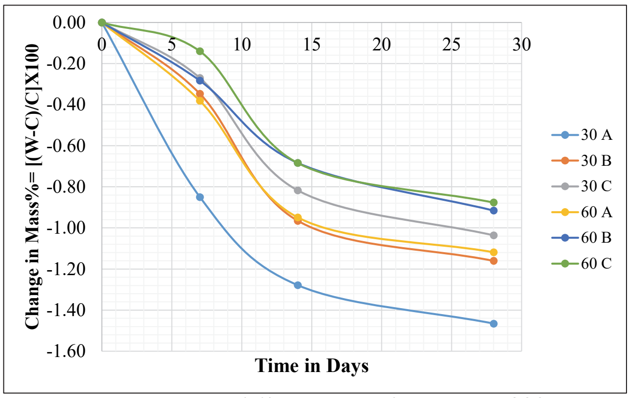

Figure 10 Acid test 15% replacement of bentonite mix SCC

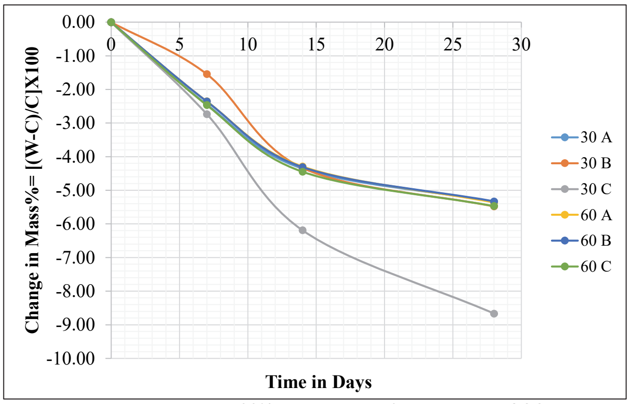

Figure 11 Acid test 30% replacement of bentonite mix SCC

4.6 Ultrasonic Pulse Velocity

The results of the UPVC test are shown in Fig. 12. Velocity is increased with 15% BN making it excellent concrete while 30% and control mix shows good quality concrete. BN incorporated up to 15 % mixtures exhibited higher UPV as SCM incorporation can offer a more compact and refined microstructure of concrete matrix due to supplementary CSH gel and filler effect of SCMs [39, 40].

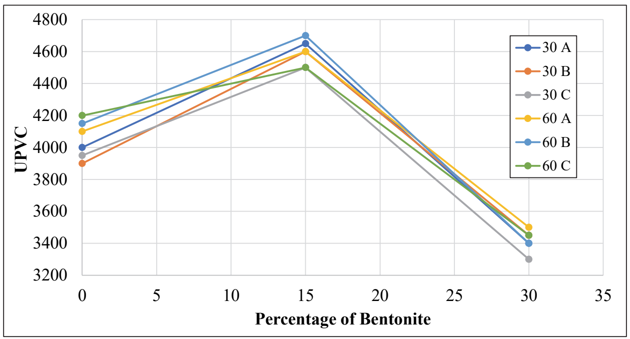

Figure 12 UPVC values with varying percentage of BC

5 CONCLUSIONS

The main objective of this research was to assess the symbiotic impact of (GGBS) and (BN) on the development and durability of self-compacting concrete. For this purpose, concrete mixtures of different strength grades using empirical formulation were developed and validated. Mixture contains 0%, 15% and 30% BC as replacement of OPC was developed keeping GGBS constant. GGBS was kept constant for specific strength in order to get the designed strength. Based on experimental results, it was concluded:

1. The durability is influenced positively by percentage of bentonite. The average Sorptivity value for the mixes with 15% BN is slightly higher in comparison with 30% BN. However, this effect is quite significant when compared to 0% BN (Control) mixes. It showed an improvement of about 100% in Sorptivity when compared to control mix.
2. The durability properties are also impacted by the coarse aggregate volume. Concrete is more durable when there is more aggregate. When comparing mixtures of the same strength, those with more CA (Coarse Aggregate) volume labelled as A, are more durable than those with less CA volume labelled as B & C. Their durability is 12% more when compared to the samples labelled as C.
3. The chloride coefficient is significantly affected by the percentage of BC and can range up to 86%, which lowers the concrete's durability. The density and resistance to chloride ingress were improved by substituting up to 15% of BN in replacement of OPC. SCC made with (15% BC) replacement is 29% more durable in terms of chloride migration coefficient when compared to control mix (0% BN). This trend is more significant when compared to (30%) replacement, and durability is 86% increased.
4. The same trend is observed in chloride depth penetration. 38% more penetration of silver nitrate solution in control samples in comparison with (15% BN), and depth penetration is 45% more in mix (30% BN) when compared with the mix (15% BN).
5. The mixture containing 15% BC showed overall more durability than control mix (0% and 30% BC).

However, a detailed parametric and leachate analysis could be conducted for the development of more durable concrete for its wide application. Based on the findings, it is possible to conclude that the combination of GGBS and BC is effective in developing sustainable, durable, and eco-friendly concrete that can be easily used in construction.

6 REFERENCES

[1] Cui, W., Yan, W.-s., Song, H.-f., & Wu, X.-l. (2018). Blocking analysis of fresh self-compacting concrete based on the DEM. *Construction and Building Materials*, *168*, 412-421. https://doi.org/10.1016/j.conbuildmat.2018.02.078
[2] Wang, S. R., Zhao, J. Q., Wu, X. G., Yang, J. H., & Liu, A. (2021). Meso-Scale Simulations of Lightweight Aggregate Concrete under Impact Loading. *International Journal of Simulation Modelling*, *20*(2), 291-302. https://doi.org/10.2507/IJSIMM20-2-558
[3] Boukhelkhal, A., Azzouz, L., Belaïdi, A. S. E., & Benabed, B. (2016). Effects of marble powder as a partial replacement of cement on some engineering properties of self-compacting concrete. *Journal of adhesion science and Technology*, *30*(22), 2405-2419. https://doi.org/10.1080/01694243.2016.1184402
[4] Long, W.-J., Gu, Y., Liao, J., & Xing, F. (2017). Sustainable design and ecological evaluation of low binder self-compacting concrete. *Journal of Cleaner Production*, *167*, 317-325. https://doi.org/10.1016/j.jclepro.2017.08.192
[5] Sharma, R. & Khan, R. A. (2018). Influence of copperslag and metakaolin on the durability of self compacting concrete. *Journal of Cleaner Production*, *171*, 1171-1186. https://doi.org/10.1016/j.jclepro.2017.10.029
[6] Mohammed, S. (2017). Processing, effect and reactivity assessment of artificial pozzolans obtained from clays and claywastes: A review. *Construction and Building Materials*, *140*, 10-19. https://doi.org/10.1016/j.conbuildmat.2017.02.078
[7] Şahmaran, M., Yaman, İ. Ö., & Tokyay, M. (2009). Transport and mechanical properties of self consolidating concrete with high volume fly ash. *Cement and concrete composites*, *31*(2), 99-106. https://doi.org/10.1016/j.cemconcomp.2008.12.003
[8] Juenger, M. C. & Siddique, R. (2015). Recent advances in understanding the role of supplementary cementitious materials in concrete. *Cement and concrete research*, *78*, 71-80. https://doi.org/10.1016/j.cemconres.2015.03.018
[9] Yang, K.-H., Jung, Y.-B., Cho, M.-S., & Tae, S.-H. (2015). Effect of supplementary cementitious materials on reduction of CO_2 emissions from concrete. *Journal of Cleaner Production*, *103*, 774-783.
[10] https://doi.org/10.1016/j.jclepro.2014.03.018
[11] Pelisser, F., Vieira, A., & Bernardin, A. M. (2018). Efficient self-compacting concrete with low cement consumption. *Journal of Cleaner Production*, *175*, 324-332. https://doi.org/10.1016/j.jclepro.2017.12.084
[12] Mardani-Aghabaglou, A., Sezer, G. İ., & Ramyar, K. (2014). Comparison of flyash, silica fume and metakaolin from mechanical properties and durability performance of mortar mixtures view point. *Construction and Building Materials*, *70*, 17-25. https://doi.org/10.1016/j.conbuildmat.2014.07.089
[13] Paiva, H., Velosa, A., Cachim, P., & Ferreira, V. (2012). Effect of metakaolin dispersion on the fresh and hardened state properties of concrete. *Cement and Concrete Research*, *42*(4), 607-612. https://doi.org/10.1016/j.cemconres.2012.01.005
[14] Sabir, B., Wild, S., & Bai, J. (2001). Metakaolin and calcined clays as pozzolans for concrete: a review. *Cement and concrete composites*, *23*(6), 441-454. https://doi.org/10.1016/S0958-9465(00)00092-5
[15] Tironi, A., Trezza, M. A., Scian, A. N., &Irassar, E. F. (2014). Thermal analysis to assess pozzolanic activity of

calcined kaolinitic clays. *Journal of Thermal Analysis and Calorimetry*, *117*(2), 547-556. https://doi.org/10.1007/s10973-014-3816-1
[16] Uchima, J. S., Restrepo, O. J., & Tobón, J. I. (2015). Pozzolanicity of the material obtained in the simultaneous calcination of biomass and kaolinitic clay. *Construction and Building Materials*, *95*, 414-420. https://doi.org/10.1016/j.conbuildmat.2015.07.104
[17] Darweesh, H. & Nagieb, Z. (2007). Hydration of calcined bentonite Portlandblended cement pastes.
[18] Said-Mansour, M., Kadri, E.-H., Kenai, S., Ghrici, M., & Bennaceur, R. (2011). Influence ofcalcined kaolin on mortarproperties. *Construction and building Materials*, *25*(5), 2275-2282. https://doi.org/10.1016/j.conbuildmat.2010.11.017
[19] Fernandez, R., Martirena, F., & Scrivener, K. L. (2011). The Origin of the Pozzolanic Activity of Calcined Clay Minerals: A Comparison Between Kaolinite, Illite and Montmorillonite. *Cement and concrete research*, *41*(1), 113-122. https://doi.org/10.1016/j.cemconres.2010.09.013
[20] Habert, G., Choupay, N., Escadeillas, G., Guillaume, D., & Montel, J. (2009). Claycontentofargillites: Influence on cement basedmortars. *Applied Clay Science*, *43*(3-4), 322-330. https://doi.org/10.1016/j.clay.2008.09.009
[21] Garg, N. & Skibsted, J. (2016). Pozzolanic reactivity of a calcined interstratified illite/smectite (70/30) clay. *Cement and Concrete Research*, *79*, 101-111. https://doi.org/10.1016/j.cemconres.2015.08.006
[22] Hirono, T. & Tanikawa, W. (2011). Implications of the thermal properties and kinetic parameters of dehydroxylation of mica minerals for fault weakening, frictional heating, and earthquake energetics. *Earth and Planetary Science Letters*, *307*(1-2), 161-172. https://doi.org/10.1016/j.epsl.2011.04.042
[23] Madandoust, R. & Mousavi, S. Y. (2012). Fresh and hardened properties of self-compacting concrete containing metakaolin. *Construction and building materials*, *35*, 752-760. https://doi.org/10.1016/j.conbuildmat.2012.04.109
[24] Mohammed, S., Elhem, G., & Mekki, B. (2016). Valorization of pozzolanicity of Algerian clay: Optimization of the heat treatment and mechanical characteristics of the involved cement mortars. *Applied Clay Science*, *132*, 711-721. https://doi.org/10.1016/j.clay.2016.08.027
[25] Chikouche, M. A., Ghorbel, E., & Bibi, M. (2016). The possibility of using dredging sludge in manufacturing cements: Optimization of heat treatment cycle and ratio replacement. *Construction and Building Materials*, *106*, 330-341. https://doi.org/10.1016/j.conbuildmat.2015.12.128
[26] Mikhailenko, P., Cassagnabère, F., Emam, A., & Lachemi, M. (2018). Influence of physico-chemical characteristics on the carbonation of cement paste at high replacement rates of metakaolin. *Construction and building materials*, *158*, 164-172. https://doi.org/10.1016/j.conbuildmat.2017.10.021
[27] El-Abidine Laidani, Z., Benabed, B., Abousnina, R., Gueddouda, M. K., & Kadri, E.-H. (2020). Experimental investigation on effects of calcined bentonite on fresh, strength and durability properties of sustainable self-compacting concrete. *Construction and Building Materials*, *230*, 1-11. https://doi.org/10.1016/j.conbuildmat.2019.117062
[28] Ahmad, S., Barbhuiya, S., Elahi, A., & Iqbal, J. (2011). Effect of Pakistani bentonite on properties of mortar and concrete. *Clay Minerals*, *46*(1), 85-92. https://doi.org/10.1180/claymin.2011.046.1.85
[29] Sakizci, M., ErdoğanAlver, B., & Yörükoğullari, E. (2009). Thermal behavior and immersion heats of selected clays from Turkey. *Journal of Thermal Analysis and Calorimetry*, *98*(2), 429-436. https://doi.org/10.1007/s10973-009-0294-y
[30] Taylor-Lange, S. C., Lamon, E. L., Riding, K. A., & Juenger, M. C. (2015). Calcined kaolinite–bentonite clay blends as supplementary cementitious materials. *Applied Clay Science*, *108*, 84-93. https://doi.org/10.1016/j.clay.2015.01.025
[31] Memon, S. A., Arsalan, R., Khan, S., & Lo, T. Y. (2012). Utilization of Pakistani bentonite as partial replacement of cement in concrete. *Construction and building materials*, *30*, 237-242. https://doi.org/10.1016/j.conbuildmat.2011.11.021
[32] Mirza, J., Riaz, M., Naseer, A., Rehman, F., Khan, A., & Ali, Q. (2009). Pakistani bentonite in mortars and concrete as low cost construction material. *Applied Clay Science*, *45*(4), 220-226. https://doi.org/10.1016/j.clay.2009.06.011
[33] Khayat, K. & Manai, K. (1996). *Lesbetonsautonivlants: proprietes, charcterisation et applications, colloque sur les betonsautonivlants*. Universite de Sherbroke, Canada, 8.
[34] Gill, A. S. & Siddique, R. (2018). Durability properties of self-compacting concrete incorporating metakaolin and rice husk ash. *Construction and Building Materials*, *176*, 323-332. https://doi.org/10.1016/j.conbuildmat.2018.05.054
[35] Kavitha, O., Shanthi, V., Arulraj, G. P., & Sivakumar, V. (2016). Microstructural studies on eco-friendly and durable Self-compacting concrete blended with metakaolin. *Applied Clay Science*, *124*, 143-149. https://doi.org/10.1016/j.clay.2016.02.011
[36] Burgos, D. M., Guzmán, Á., Torres, N., & Delvasto, S. (2017). Chloride ion resistance of self-compacting concretes incorporating volcanic materials. *Construction and Building Materials*, *156*, 565-573. https://doi.org/10.1016/j.conbuildmat.2017.09.017
[37] Norma, A. (2002). C597, Standard Test Method for Pulse Velocity Through Concrete, 100 Barr Harbor Drive, West Conshohocken, PA 19429, United States. American Society for Testing and Materials.
[38] Concrete, S.-C. (2005). *The European guidelines for self-compacting concret*e. BIBM, 22, 563.
[39] ASTM, A. (2020). C1585-20 Standard Test Method for Measurementof Rate ofAbsorptionof Water byHydraulic-Cement Concretes. West Conshohocken, PA: ASTM International.
[40] Amini, K., Ceylan, H., & Taylor, P. C. (2019). Effect of curing regimes on hardened performance of concrete containing slag cement *Construction and Building Materials*, *211*, 771-778. https://doi.org/10.1016/j.conbuildmat.2019.03.273
[41] Leung, H. Y., Kim, J., Nadeem, A., Jaganathan, J., & Anwar, M. (2016). Sorptivity of self-compacting concrete containing fly ash and silica fume. *Construction and Building Materials*, *113*, 369-375. https://doi.org/10.1016/j.conbuildmat.2016.03.071
[42] Akram, T., Memon, S. A., & Iqbal, K. (2007). Utilization of bag asseash as partial replacement of cement. *International Conference on Advancesin Cement Based Materials and Applications in Civil Infrastructure ACBM-ACI.*
[43] Zhang, C. & Liu, Q. (2022). Coupling Erosion of Chlorides and Sulfates in Reinforced Concrete - A Review. *Materials Reports*, *36*(1), 20100075.

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