

Article

Partial Substitution of Binding Material by Bentonite Clay (BC) in Concrete: A Review

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Abstract: Concrete consumes millions of tons of cement, which causes global warming as cement factories emit huge amounts of carbon dioxide into the atmosphere. Thus, it is essential to explore alternative materials as a substitute of OPC, which are eco-friendly and at the same time cost-effective. Although there are different options available to use industrial waste instead of cement, such as waste glass, waste marble, silica fume fly ash, or agriculture waste such as rice husk ash, wheat straw ash, etc., but bentonite clay is also one of the best options to be used as a binding material. There are a lot of diverse opinions regarding the use of bentonite clay as a cement substitute, but this knowledge is scattered, and no one can easily judge the suitability of bentonite clay as a binding material. Accordingly, a compressive review is essential to explore the suitability of bentonite clay as a cementitious material. This review focuses on the appropriateness of bentonite clay as a binding material in concrete production. The attention of this review is to discuss the physical and chemical composition of BC and the impact of BC on the fresh and mechanical performance of concrete. Furthermore, durability performance such as water absorption, acid resistance and dry shrinkage are also discussed. The results indicate that bentonite clay increased the mechanical and durability performance of concrete up to some extent but decrease its flowability. The optimum proportion of bentonite clay varies from 15 to 20% depending on the source of bentonite clay. The overall study demonstrates that bentonite clay has the creditability to be utilized partially instead of cement in concrete.

Keywords: sustainable concrete; supplementary cementitious material; bentonite clay; strength; durability

1. Introduction

Concrete is widely utilized as a building material around the globe due to its exceptional stability and compressive strength [1–3]. The current practice of concrete construction is thought to be unsustainable as it consumes a huge amount of natural resources [4–6]. Cement factories face difficulties in minimizing carbon dioxide emissions, increasing the cost of energy rises, and the supply of raw materials (in particular maintaining a supply of raw materials of good quality) [7–9]. Demand for cement and concrete on a global scale has

expanded dramatically in recent years, owing to the fast development of nations and the continuation of population growth in many parts of the world [10–12]. According to the World Cement Association, Pakistan manufactures 85 million tons of cement, which refers to 2% of global cement production. The cost of cement increasing continuously (i.e., more than 150 percent in ten years) [13]. Therefore, it is essential to explore alternative materials instead of cement.

Sustainable development is a kind of evaluation that seeks to enhance the quality of life, while also meeting the fundamental requirements of future generations. Its goals are to provide basic requirements, raise living standards, and promote the protection and management of ecosystems, among other things [14–16]. In response to growing public concerns about environmental degradation, fossil fuel depletion, and sustainable growth, the reusing of various industrial waste shows a rapid increase on a global scale [17–20]. Overall, the creation of OPC, which is a key component in concrete [21–23], is a significant supply of emissions of harmful gases such as carbon dioxide [24,25].

Currently, our planet produces around 3.6 billion metric tons of cement each year [26]. It is anticipated, that by 2030 the amount of cement would rise to greater than 5 billion metric tons [27,28]. Although this trend may vary across countries, almost part of the global OPC is used to create 11 billion metric tons of concrete each year; the remaining part is utilized in mortars, soil stabilization, coatings, etc. [14,29]. As it is well known that the concrete industry is a significant consumer of natural resources on a worldwide level. Consequently, reused aggregates and natural cementitious materials may be employed in the building sector to conserve energy and increase the sustainability of the overall structure [30–32]. Bentonite clay corresponds to one of the best possible solutions of integration in concrete, as a partial replacement as a substitute of OPC in a variety of applications.

BC is a highly colloidal ductile clay that is generated by the modification of volcanic ash (or glass) in situ. It is sometimes referred to as smectite-rich clay due to the presence of smectite in the clay (mostly montmorillonite) [33]. United States, China, India, Greece, Mexico, Turkey, Iran, Russia, Japan, Brazil, and Germany are the world's leading BC manufacturers, listed in decreasing order of manufacture [34]. Recently, researchers described bentonite as calcined clays that are not derived from kaolin and that are economical supplemental cementitious materials [35,36].

Various researchers have determined the appropriateness of bentonite clay for use in the construction of concrete [37]. A common clay-bentonite was employed as an addition in concrete in one research. Apart from investigating the impact of such clay elements on the mechanical characteristics of concrete, the authors investigated the chemical resistance of concrete to sulphates, carbonation, and chloride exposure as well. They detected that the resistance to carbonation in the bentonite-bearing material may be lower than the resistance to carbonation in the reference plain Portland cement concrete [37]. The addition of bentonite in concrete can significantly improve the durability of concrete and helps to prevent it from shrinkage cracking once it has been allowed to dry. Concrete's performance, strength, and durability are all greatly affected by the presence of specific minerals in pozzolanic materials [38]. The use of bentonite clay may aid to increase the compressive strength of a material. The early-age compressive strength of the concrete with additional bentonite did not demonstrate a substantial improvement. However, it increases to a level that is much greater than that of the control concrete specimen when the specimen is aged longer. Apart from that, the water to binder percentage was increased to 55% and the OPC content was increased to 340 kg/m³, with the maximum bentonite replacement ratio set at 21%. Apart from compressive strength, other durability characteristics was studied. According to the findings, the specimens that had been treated with bentonite performed better in terms of acid corrosion resistance. A study conclude that the mechanical performance of concrete decreased with the substitution of bentonite clay [39]. The hydration process in a Portland cement mixture comprising metakaolin and sodium bentonite has been researched to determine the influence of pozzolanic elements on the final product. A combination of sodium bentonite and metakaolin enhanced the cement hydration, as measured by strength

development, portlandite utilization, and the calcium-silicate hydrate (C-S-H) phase, as well as other parameters. In addition, the decomposition of metakaolin is speeded up in the existence of BC [40]. A study claims that BC based concrete needs more curing time to obtain strength [41]. The silane-modified BC had a greater pozzolanic activity as compared to without treated BC [42].

Several research efforts focus on utilizing bentonite clay in concrete instead of cement. However, the knowledge of bentonite clay in concrete is scattered and no one can easily judge the importance of bentonite clay in concrete. Therefore, this review focus on the physical and chemical composition of BC, fresh properties, mechanical and durability performance of concrete with bentonite clay instead of cement. The optimum dose is also important for better performance. A successful review will also give the idea for a new researcher to choose and apply bentonite clay in concrete.

2. Physical Properties

The physical properties of bentonite clay, including grain size, specific gravity, and fineness, assist in determining their applicability and ability to utilize as a binding material in concrete. BC is usually accessible in several colors and types. Table 1 shows lists some of the physical properties of bentonite clay indicated by various researchers. The specific gravity of bentonite clay is slightly lower than cement (3.1 to 3.16). The particle size of bentonite (4.75 μm) is much lower than cement (75 μm). Blain's fineness of bentonite clay varies greatly ranging from 1730 to 4800 (cm^2/g). Almost all authors described distinct values. It is due to a change in the location source of BC.

Table 1. Physical properties of bentonite clay.

Property Name	Achyutha et al. [43]	Memom et al. [44]	Rao et al. [45]
Specific Gravity	3.12	2.79	2.82
Particle Size (μm)	-	4.32	4.75
Blains Fineness (cm^2/g)	1730	4800	4800

The scanning electron microscope (SEM) was utilized to define the grain size of BC, which was previously unknown. The scanning electron micrographs of BC was shown in Figure 1 which indicate that the bentonite clay is flaky and elongated which decreased the flowability of fresh concrete.

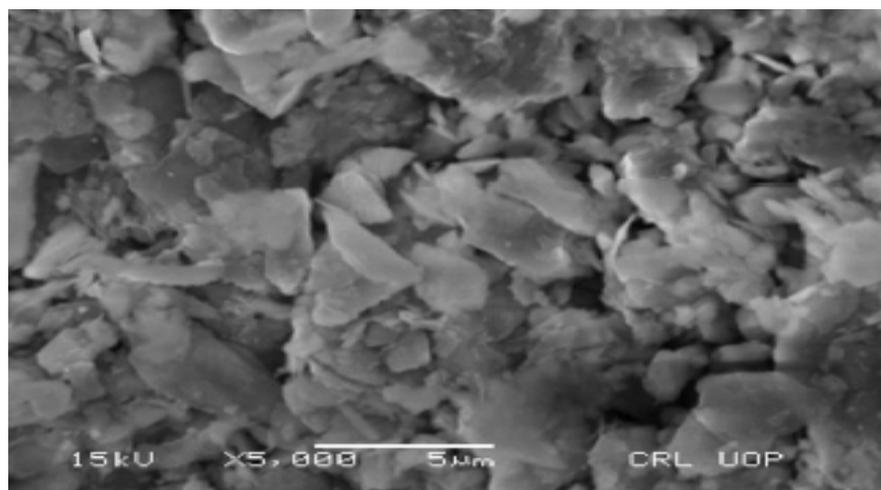


Figure 1. SEM of Bentonite Clay, reprinted from permission of Elsevier [44].

3. Chemical Composition of Bentonite Clay

Concrete made with bentonite clay has variable mechanical and durability characteristics depending on the number of different compounds contained in the bentonite clay.

According to one study, the chemical composition and particle size of SCM are the most important factors influencing its pozzolanic action [46]. According to previous investigations, the chemical makeup of bentonite clay is shown Table 2. It can be concluded that the primary constituent of bentonite clay is SiO_2 . Figure 2 depicts the XRD results of BC. The amorphous nature of the silicon dioxide (SiO_2) included in bentonite clay has a considerable influence on the performance of concrete, from the initial hydration through the ultimate development of strength. ASTM [47] states that the addition of a chemical (SiO_2 , CaO , Al_2O_3 , MgO , and Fe_2O_3) more than 70% can be used as pozzolanic materials as bentonite clay exceeds 70%.

Table 2. Chemical properties of BC.

Chemical Name	Akbar et al. [48]	Vijay et al. [49]	Shabab et al. [50]
SiO_2	49.63	51.11	52.1
Al_2O_3	21.11	16.38	13.4
Fe_2O_3	3.23	7.65	7.5
MgO	12.56	7.57	2.64
CaO	3.59	7.12	12.0
K_2O	2.091	1.34	2.64
Na_2O	0.449	0.29	-
TiO_2	0.498	1.29	-
P_2O_5	0.119	0.29	-
LOI	-	6.75	8.61

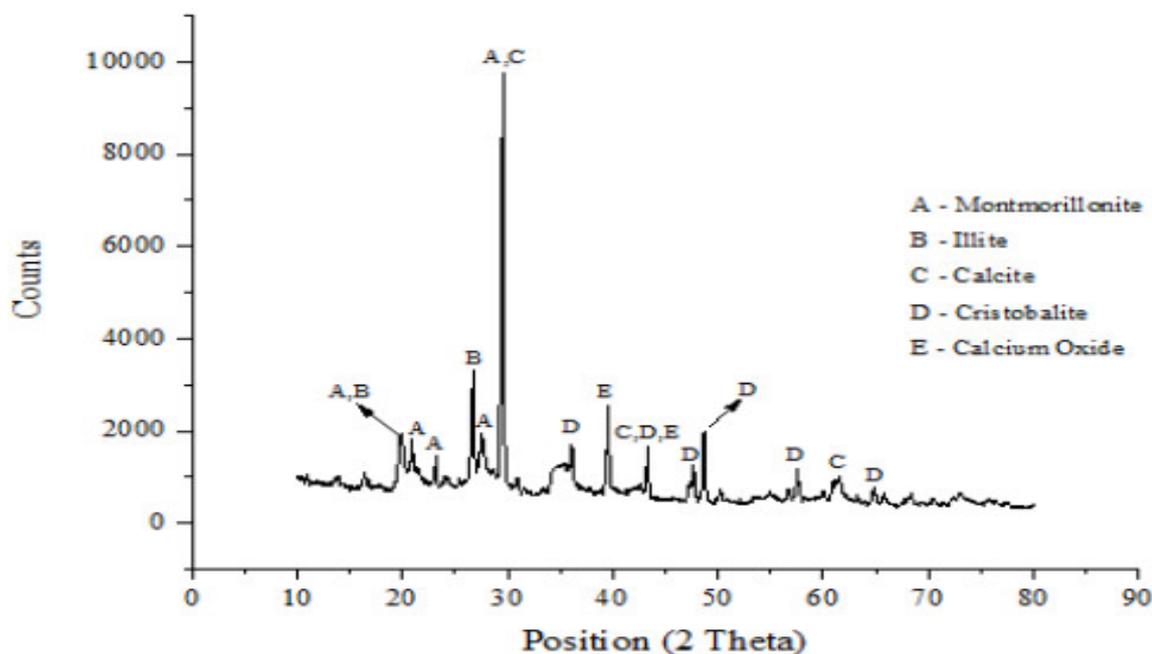


Figure 2. XRD Analysis of bentonite clay [43].

4. Fresh Properties

Workability and Fresh Density

The higher workable concrete in the construction sector results in ease of installation, increased filling ability, the use of dense reinforcement in highly congested concrete components, and a reduction in the cost of vibration in the building industry [51]. To produce highly workable concrete with exceptional segregation resistance, it is necessary to have

sufficient flowability and rheological qualities. The flowability with various percentages of bentonite clay is given in Figure 3. It can be observed that the flowability of concrete is reduced with bentonite clay. The tiny grain size and relatively large surface area of BC particles contribute to the decrease in slump value. As a result, it can be inferred that, while using the same water to cement ratio, the flowability of concrete made with BC is lower as compared to the blank mix [44]. According to one research, the flowability of concrete deteriorated when BC was used instead of Portland cement. The large surface area of the clay elements, as well as the subsequent adsorption of free water within the combination, is responsible for the decreased flowability of the mixture. As a result, lubrication of the solid particles is hindered, and internal friction is increased due to less cement paste [35]. In contrast, some study claimed that the pozzolanic materials results increase in the flowability of concrete due to the micro filling effect which results in less cavities in concrete ingredients and hence free water are available in more quantity for lubrication, causing more flowable concrete [52]. With the use of a superplasticizer, it is possible to achieve the necessary flowability of concrete [44]. A also reported that the flowability of concrete reduced with the substitution of BC due to a larger surface area [53]. The flaky and elongated shape of BC as shown in Figure 1 also causes to decrease in the flowability of concrete by increasing friction between aggregates. A study also claims that BC is from clay material having high water absorption [54]. Therefore, less water is available for lubrication to reduce the friction between concrete ingredients.

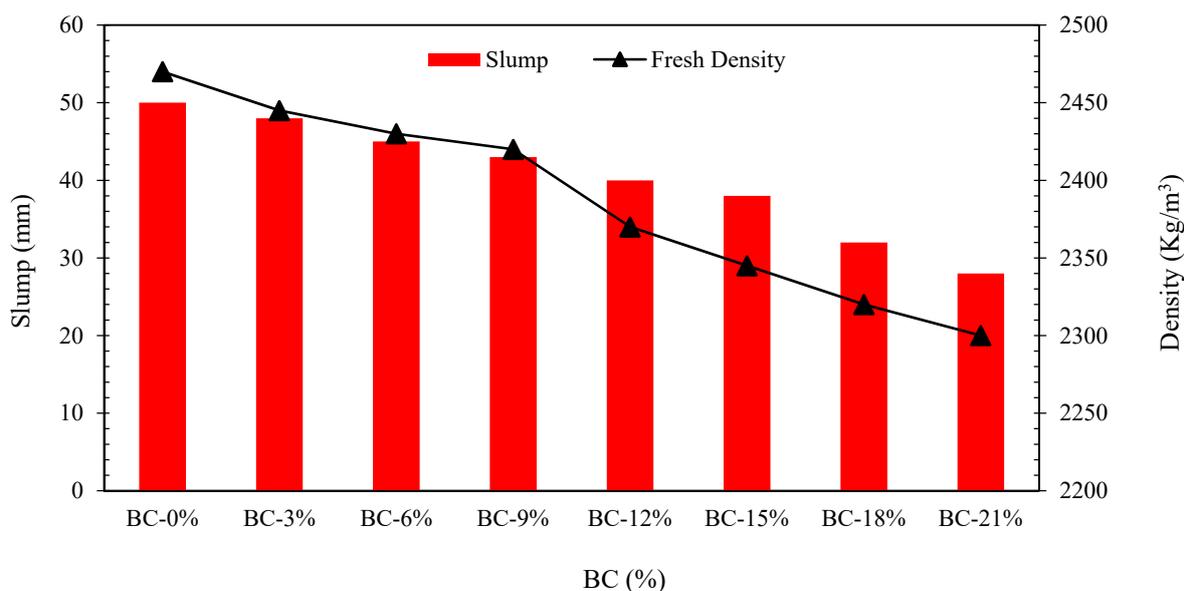


Figure 3. Workability and fresh density (data source [44]).

Figure 3 depicts the results of fresh density tests on various percentages of bentonite clay. Blank mix without bentonite clay shows the highest density (2470 kg/m^3), when it is in its fresh condition, as can be seen in Figure 3. The introduction of bentonite substitute resulted in a fall in density and the greater the bentonite percentage, the lower the density. This is due to the fact that density is a function of specific gravity. Since cement has higher specific gravity than bentonite, the density of the control mix (blank mix) is higher than that of the bentonite-based mixture [44].

With the inclusion of secondary cementitious materials (SCM), the density of concrete increases due to the micro-filling of gaps in the concrete components which results in a denser concrete mixture. Furthermore, the pozzolanic reaction of SCM improved the binding characteristics of cement paste, resulting in denser concrete [52]. However, some studies reported that a higher dose of SCM leads to a lower density of concrete due to lower workability [35,55]. A study also claimed that, as the BC in the concrete mix is increased, the

workability of the concrete mix decreased which increased compaction affords, resulting in the fresh density of the concrete mix decreased [53].

Figure 4 shows a correlation between slump values and the density of concrete. As stated earlier that workability and density are correlated to each other. The lower workability increased the compaction affords and increased the number of voids in hardened concrete, resulting in a decreased density of concrete. As a result, a strong correlation between slump values and concrete density has been observed, with an R^2 of greater than 90%.

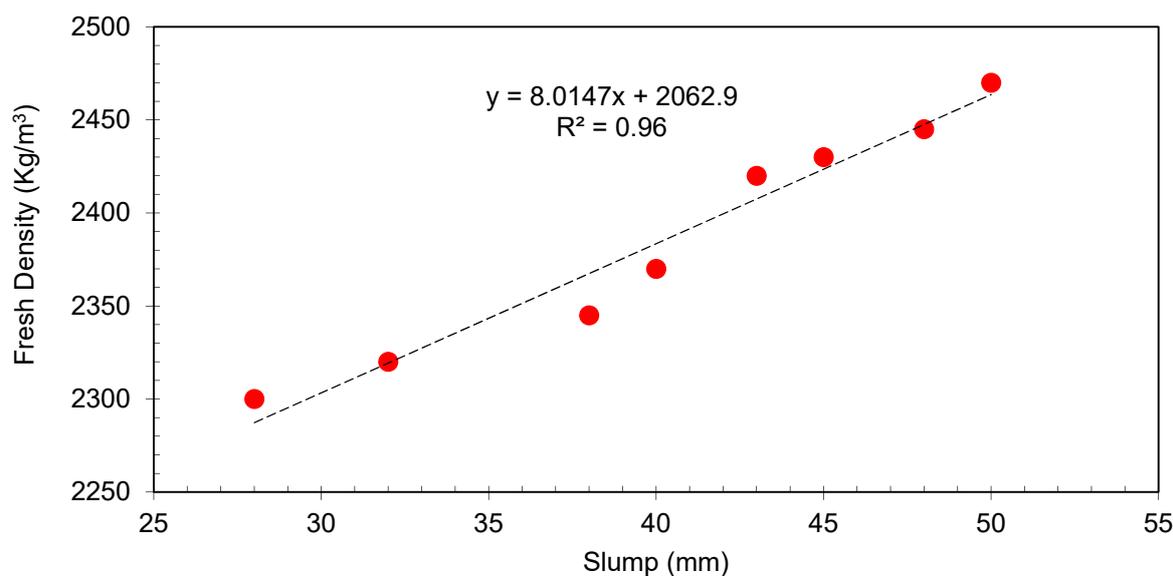


Figure 4. Correlation between slump and fresh density (data source [44]).

5. Mechanical Properties

5.1. Compressive Strength

The compressive capacity of concrete with varying doses of BC is given in Figure 5. It can be observed that the BC dose does not considerably affect the compressive capacity of concrete. All of the mixes of BC have a compressive capacity comparable to the reference concrete in terms of strength. Although no increase in compressive capacity was observed but the use of cement could be reduced up to 20%. Furthermore, the pozzolanic reaction of SCM proceeds slowly and the authors conduct compressive strength only up to 28 days. However, according to one research project, the compressive capacity of concrete reduced with the rise in the proportion of bentonite clay used as a cement substitute on all days of curing [56]. In contrast, according to the findings of the research. At 56 days, the proportion of improvement in strength was 0.9 percent, 1.5 percent, 1.8 percent, 2.7 percent, 2.5 percent, and 2.2 percent, respectively, when compared to the control group [44]. A researcher claim that the compressive capacity of concrete reduced with the rise in the proportion of BC used as a cement substitute at all ages of curing [56]. A study reported a considerable improvement in compressive strength with the substitution of BC [35]. One of the most important factors contributing to this improvement in compressive capacity is the pozzolanic reaction, which occurs at a slower rate than the rate of cement hydration and is combined with the filling voids in concrete ingredients effect induced by pozzolanic material [57]. These contrasting findings of bentonite clay will need to be investigated further in future research before being used practically.

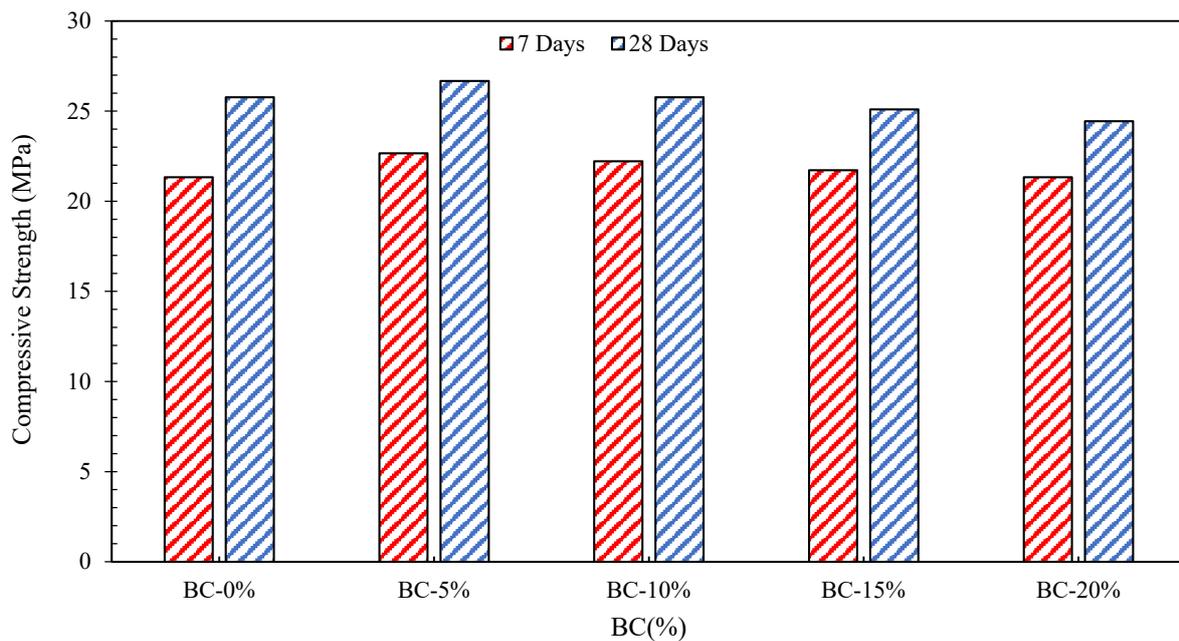


Figure 5. Compressive strength(data source [58]).

An analysis of compressive capacity gain with various days of curing is also provided in Figure 6, in which the compressive capacity of control concrete is used as a reference concrete. At seven days of curing, concrete compressive capacity is less than 14% from the blank mix at 10% substitution of BC while 20% substitution of BC shows 18% lower than blank mix. At 28 days, compressive capacity is just 4% more than blank mix at 5% substitution of BC while 20% substitution shows 6% lower than the reference strength. It has been established that BC could not improve the compressive capacity effectively but the strength is approximately equal to the reference concrete.

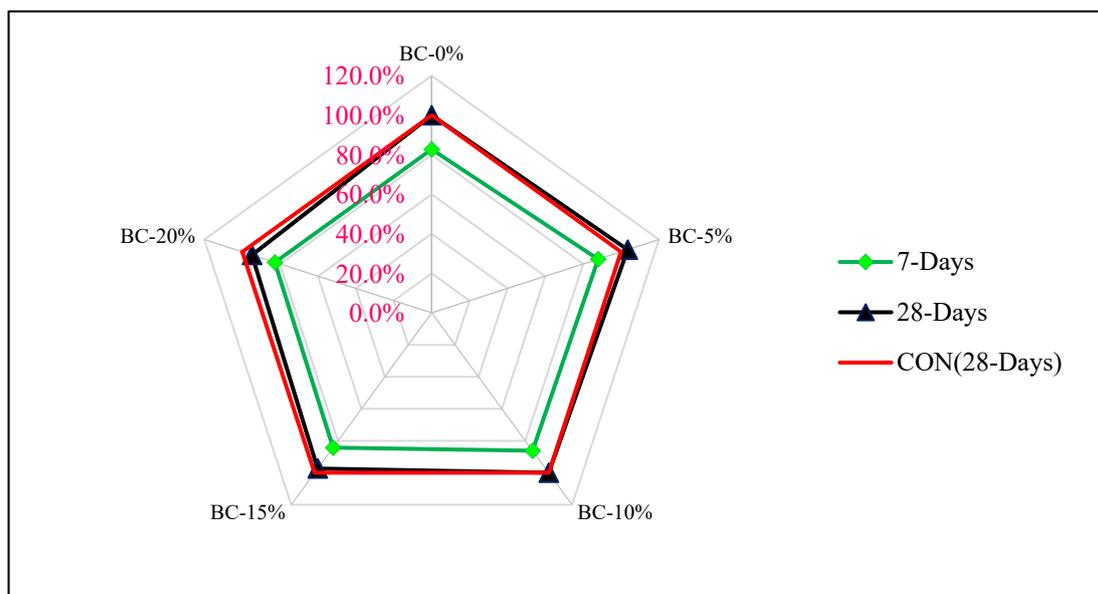


Figure 6. Relative analysis of compressive strength (data source [58]).

5.2. Split Tensile Strength

The split tensile capacity of mix with various doses of BC shows similar trends to the compressive capacity of concrete i-e the split tensile capacity of the mix is not enhanced

with the substitution of BC; nonetheless, all of the BC mixes have split tensile strengths that are about equivalent to the reference concrete as indicated in Figure 7. Additionally, it has been shown that increasing the bentonite content of concrete degrades its performance, resulting in a significant reduction in both tensile strength and compressive strength (tensile strength) [39]. Based on the research, it was determined that the best bentonite replacement ratio by weight of cement in the concrete is 2.7 percent, which produces a satisfactory compressive and tensile strength. The concrete is appropriate for usage in low-rise buildings [59]. Using bentonite clay as a binding substance, A researcher discovered that split tensile strength decreased when the bentonite clay was substituted. It can be determined that the poor bond formation between the bentonite and cement particles is responsible for the decreased split tensile strength [43]. However, according to one research, the split tensile strength improved due to the replacement of BC. The pozzolanic reaction enhanced the binding qualities of the cement paste and thus raised the split tensile strength. Additionally, the presence of micro-filling gaps of BC also leads to increased split tensile strength. Overall, the combination of pozzolanic and micro-filling gaps in BC has a good effect on split tensile strength. Aside from that, the increased dosage of BC resulted in a drop in split tensile strength as a consequence of a lack of workability [35]. Almost all authors reported different values. The reason behind this attribute to changes in the location of the source.

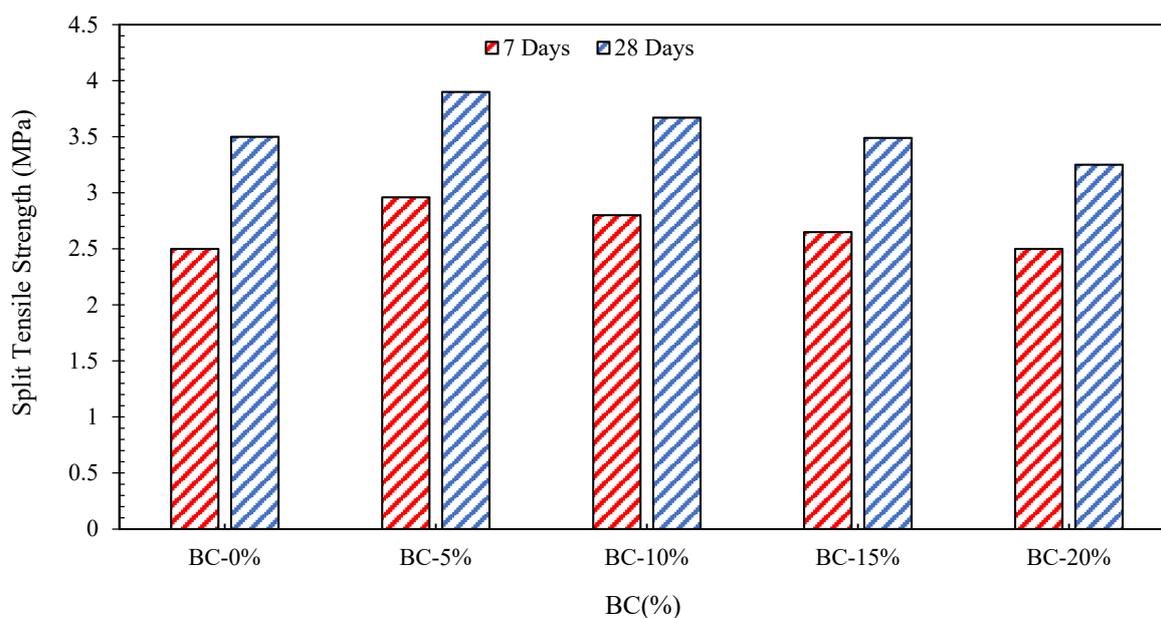


Figure 7. Split tensile strength (data source [58]).

A relative analysis of tensile strength with various days of curing is also shown in Figure 8. The 28 days tensile strength of the blank mix is taken as a reference strength. At seven days, the tensile capacity of concrete is less than 20% from the reference mix at 10% substitution of BC while 20% substitution of BC shows 29% lower split tensile strength than reference strength. At 28 days, tensile capacity is just 9% more than reference strength at 5% substitution of BC while 20% substitution shows 8% less tensile capacity than the reference strength. It has been noted that concrete with a partially substituted BC is still weak in tension.

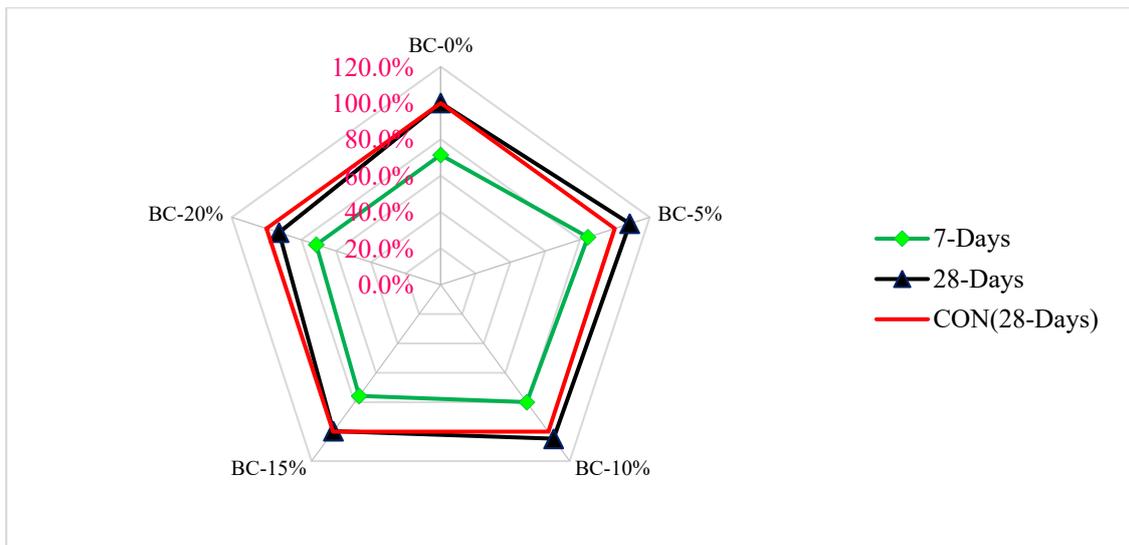


Figure 8. Relative analysis of split tensile strength (data source [58]).

Figure 9 shows a correlation between compressive and tensile capacity of mix with different replacement ratios of BC. Tensile strength depends on the compressive strength of concrete. It is estimated that the tensile capacity of concrete is around 10 to 15 percent of compressive capacity. A high link is existing between the compressive capacity of concrete and its split tensile capacity, even when the BC substitution ratios are varied. The regression model shows an R^2 value greater than 90%.

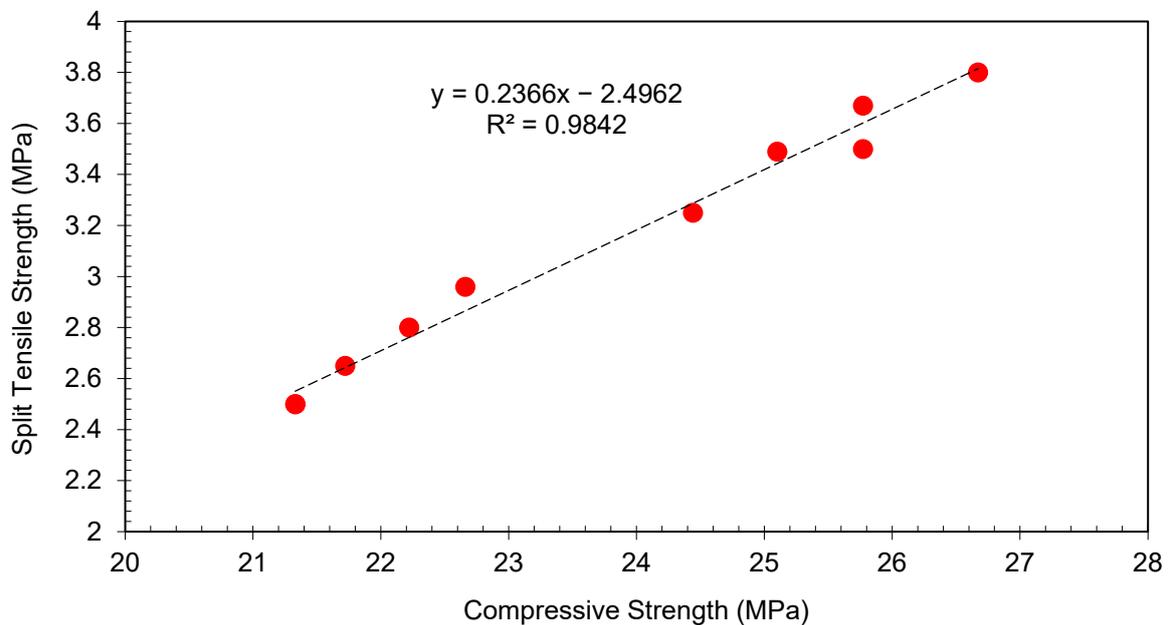


Figure 9. Correlation between compressive and split tensile strength (data source [58]).

5.3. Flexure Strength

The flexural capacity of concrete when treated with various doses of BC is displayed in Figure 10. Similar to the compressive capacity of concrete, the flexure capacity of the mix is not enhanced by the addition of BC, but all of the BC mixes have flexure strengths that are nearly equivalent to the reference concrete. Flexural strength of BC mixtures was shown to be lowered than from blank concrete, particularly at a higher dose of BC. In concrete, the flexural strength is inversely related to the amount of bentonite blended (after 20 percent)

and the water to cement ratio (W/C). It may be linked to the creation of a weak connection between bentonite and cement particles during the manufacturing process [43]. After 28 days of curing, concrete beams with dimensions of 150 mm × 150 mm × 750 mm were cast to assess the modulus of rupture, commonly known as flexural strength of the concrete. The results show that the modulus of rupture reduced as the degree of cement substitution rate rise as a result of the addition of bentonite. However, the decrease was not significant. These results were almost the same for concrete beams containing 20 percent and 25 percent bentonites, respectively. Web shear cracks are developed in the same direction as flexural fractures. Final results showed that after being loaded, the control and bentonite-containing concrete beams failed at ten and eight tones, respectively [13]. A study suggests that, for high-strength concrete, it is important to add fiber with secondary cementitious materials (SCM) [52]. As compared to the reference concrete, when basalt fiber and bentonite clay were combined, the flexure strength of the concrete improved significantly, according to the researchers. Furthermore, the use of 10% bentonite replacement and 1.5 percent basalt fiber provided the best results possible [60]. However, less studies consider flexure strength in their research.

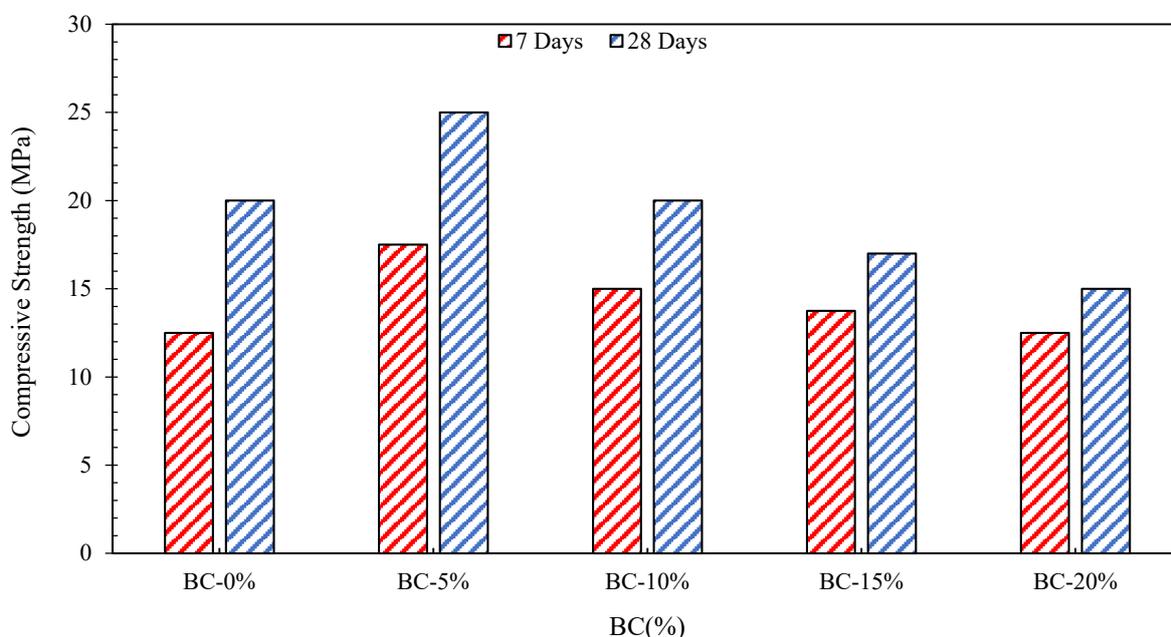


Figure 10. Flexure strength [58].

Figure 11 shows the strength age relation of flexure strength with various percentages of BC. The 28 days of reference concrete flexure capacity of concrete was taken as a benchmark flexure strength. At seven days of curing, flexure capacity of 5% replacement of BC is 13% lower than the reference flexure strength (28 days control concrete flexure strength) while 10% substitution of BC shows 25% less than flexure strength to the benchmark flexure strength (28 days blank concrete flexure strength). At 28 days, the flexure capacity of concrete is 25% more than the benchmark flexure strength. The increased flexure strength with the substitution of BC is due to the chemical reaction of BC which increased the binding characteristics of concrete and filling the cavities in concrete components, leading to more dense concrete [35].

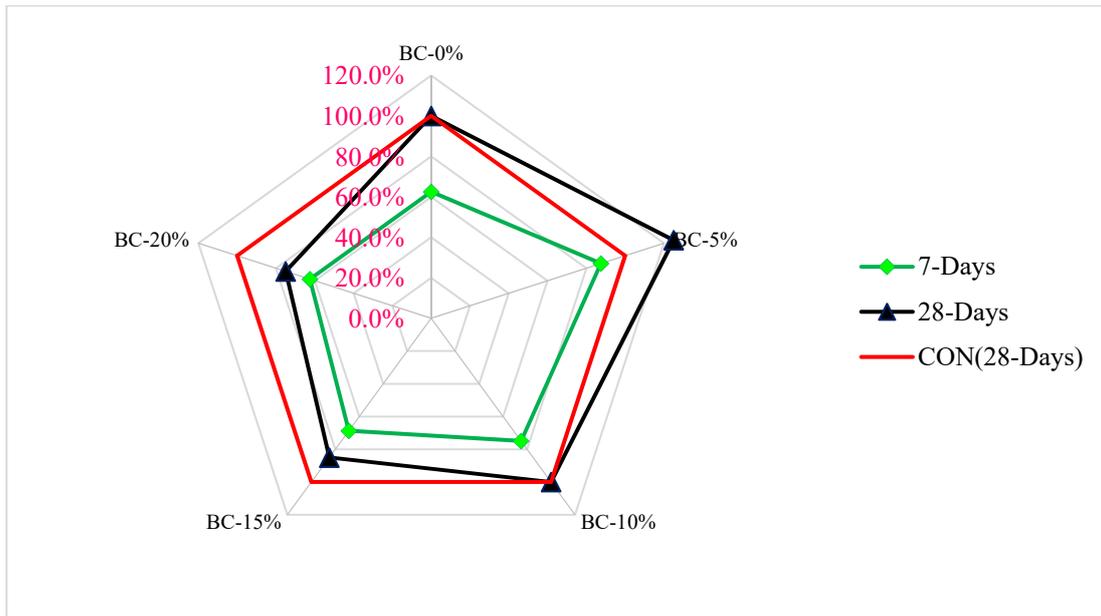


Figure 11. Relative analysis of flexure strength (data source [58]).

Figure 12 shows the correlation between compressive and flexure strength on different days of curing. It can be noted that a strong correlation exists between compressive and flexure strength having an R^2 value approximately equal to 90% (78%).

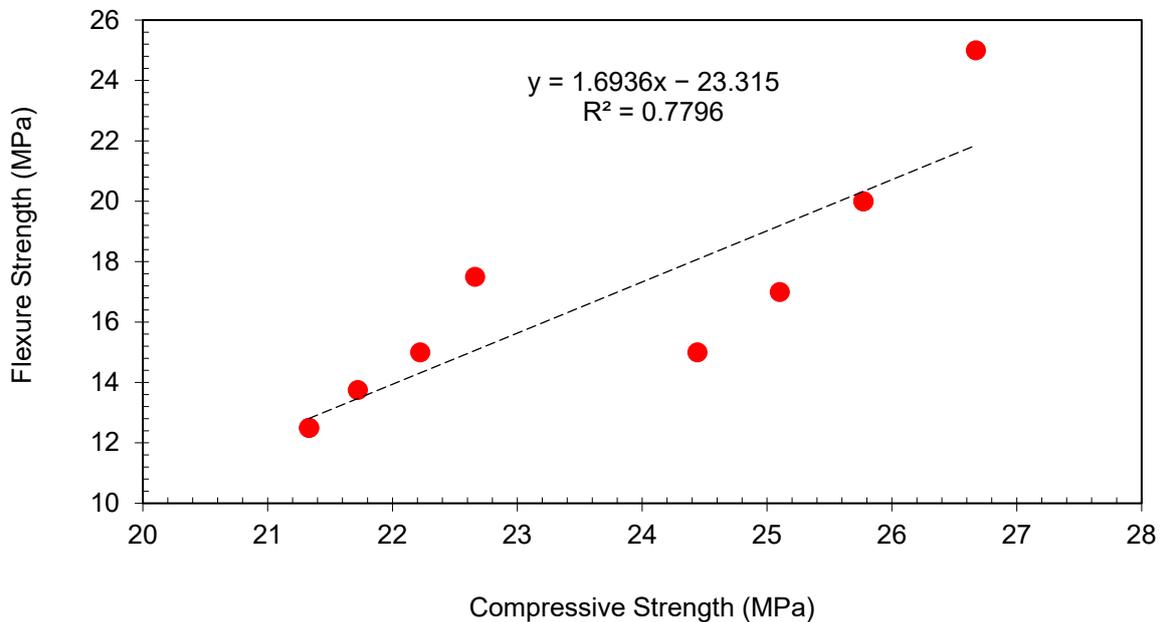


Figure 12. Correlation between compressive and flexure strength (data source [58]).

Load Deflection Curve and Ductility Ratio

Third point loading of 5.4 and 3.8 tons was observed at breaking of the control and BC beams, respectively, compared to design capacities of 4.1 and 4.0 tons. This fracture formed from the middle bottom region of the structure and was deflected by 3 mm. The crack width widened when the load increments were increased. Flexural fractures were observed by web shear cracks in the same direction. Ultimately, the control and BC concrete beams collapsed at 10 and 8 tons, respectively, when the loads were increased. Figure 13 displays the load versus deflection curves for the two beams for the third point loading,

which were plotted against each other. The yield of steel reinforcement was exhibited in the control and bentonite concrete beams, which were loaded with 7.8 and 6.0 tons, respectively. Furthermore, the considerable deflection of the bentonite-containing concrete beam was observed in Table 3 which demonstrates the more ductility ratio. The high ductility important attribute in earthquakes since it allows energy to be dissipated quickly. An increase in area under the curve is associated with a higher ductility ratio, which enhances the ability to disperse force during an earthquake, which might have major ramifications for human life. Table 4 reveals the summary of slump, compressive, flexural and split tensile strength of mix with different doses of BC as per past researchers.

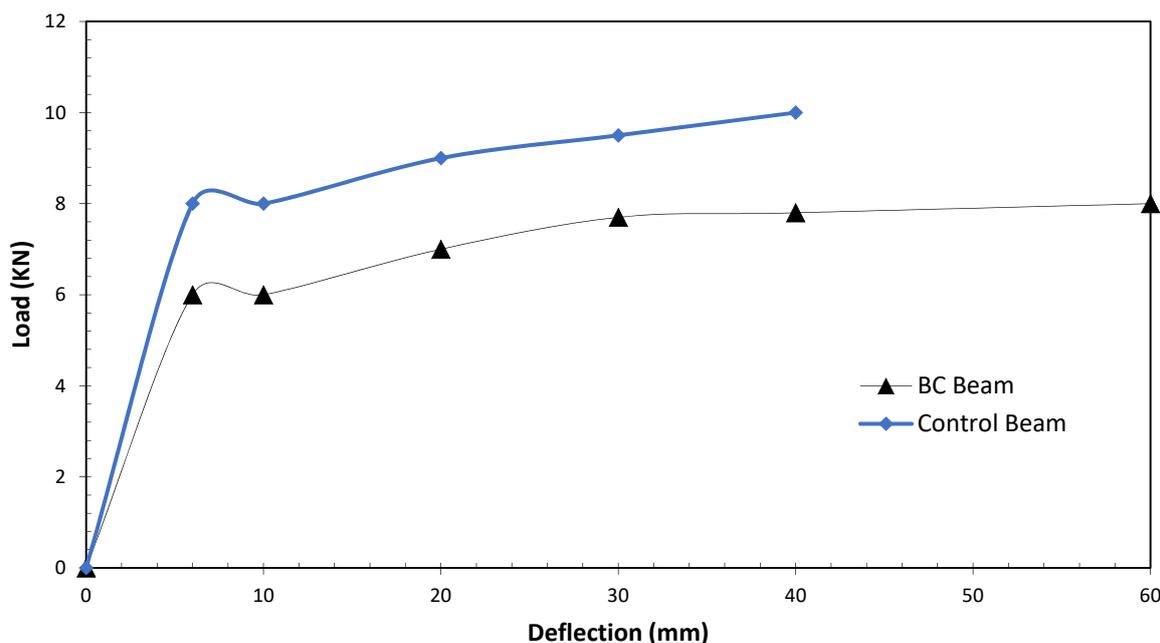


Figure 13. Load deflection curve [13].

Table 3. Ductility concrete with and without BC [13].

Beam Type	Deflection at Ultimate Point	Deflection at Yield Point	Ductility Ratio *
Control Beam	37.00	4.87	7.61
25% Bentonite Clay	56.83	5.66	10.05

* Ratio of the deflection at the ultimate point to the deflection at the yield point.

Table 4. Summary of mechanical performance of concrete with bentonite clay.

Authors	Remarks	Bentonite Clay (%)	Tensile Strength (MPa)	Compression Strength (MPa)	Flexure Strength (MPa)
Ahmad et al. [35]			14 days, 28 days	14 days, 28 days	
		BC-5%	2.6, 3.5	20, 30	
		BC-10%	2.7, 3.6	21, 32	-
		BC-15%	3, 4	24, 34	
Sumitha et al. [61]	Silica Fume 10%		7 days, 28 days	7 days, 28 days	7 days, 28 days
		0%	2.4, 3.3	38, 48	6, 8
		5%	2.5, 3.3	28, 42	5, 7
		10%	1.6, 2	25, 42	4.5, 5.5
		15%	1.4, 1.8	22, 35	3, 4.2

Table 4. Cont.

Authors	Remarks	Bentonite Clay (%)	Tensile Strength (MPa)	Compression Strength (MPa)	Flexure strength (MPa)
Liu et al. [62]	-	Ca-bent = 0%, 2%, 4%, 6%, 8%, 10%	-	28 days 11, 12, 12.2, 14, 15, 16	28 days 2.7, 2.8, 3, 3.5, 3.4, 3.7
		Na-bent = 0%, 2%, 4%, 6%, 8%, 10%		11 13, 14, 17, 17, 18	2.7, 2.8, 3, 3.5, 3, 6, 3.7
		Mg-bent = 0%, 2%, 4%, 6%, 8%, 10%.		12, 13, 14, 16, 17	2.7, 3.5, 3.4, 3.6, 3.7, 4
Akbar et al. [48]	Plasticizer (%) 1.5	0%, 20%	-	7 days 25, 30 14 days 32, 40 28 days 20, 22 56 days 24, 32	-
Rao et al. [45]	-	Control 10% WSA 10% BC (H) 10% BC (R)	-	7 days, 28 days 55, 65 52, 68 50, 60 45, 50	7 days, 28 days 16, 18 15, 19 14, 16 10, 12
Kumar et al. [63]	Fly Ash		7 days, 28 days	7 days, 28 days	
	0%	0%	1.9, 2.3	45, 90	
	5%	5%	1.4, 2	25, 50	-
	7.5%	7.5%	1.6, 2	40, 70	
	12.5%	12.5%	1.5, 1.5	30, 60	
	15%	15%	1.3, 1.3	40, 65	
Chandrakanth et al. [58]			7 days, 28 days	7 days, 28 days	7 days, 28 days
		0%	2.5, 3.5	21.33, 25.77	12.5, 20
		5%	2.96, 3.8	22.66, 26.67	17.5, 25
		10%	2.8, 3.67	22.22, 25.77	15, 20
		15%	2.65, 3.49	21.72, 25.10	13.75, 17
	20%	2.5, 3.25	21.33, 24.44	12.5, 15	
Mirza et al. [13]				7 days, 28 days	
		0%		16, 23	
		20%		15, 19	
		25%		15, 19	-
		30%	-	14, 16	
		40%		13, 14	
	50%		8, 10		
	100%		4, 2		
Khaliq et al. [64]			28 days	28 days	
		0%	2.1	23.44	
		5%	2.0	22.4	-
		10%	2.2	22	
		15%	2.1	17.2	
	20%	2.0	13.7		
Adeboje et al. [65]	Rubber		28 days	28 days	
	0	0	1.9	27	
	0.75	0.25	1.7	25	-
	0.50	0.50	1.8	26	
	0.25	0.75	1.7	25	

6. Durability

6.1. Water Absorption (WA)

The outcomes of the WA test are shown graphically in Figure 14. The results of the tests revealed that the water absorption reduced as the quantity of cement substituted by BC improved. Due to the chemical reaction among natural pozzolans and CH in hydrated cement paste consuming lime rather than lime producing calcium silicate hydrates (CSH) gel, the binding property of cement paste is increased, resulting in a more compact mass which decreased water absorption of concrete. Secondly, since the grain size of BC is smaller than OPC, it can give more compact mass by micro-filling voids and, as a result, a reduction in water absorption [57,66]. Additionally, research revealed that WA was reduced with BC substitutions of up to 30% [56]. Additionally, according to one research, SCM reduced water absorption due to micro filling, which improved the density of concrete, resulting in lower water absorption. However, with greater doses of BC, an increase in WA was found owing to a lack of flowability, which increased the compaction afforded, resulting in porous concrete, which eventually increased the water absorption of concrete [52].

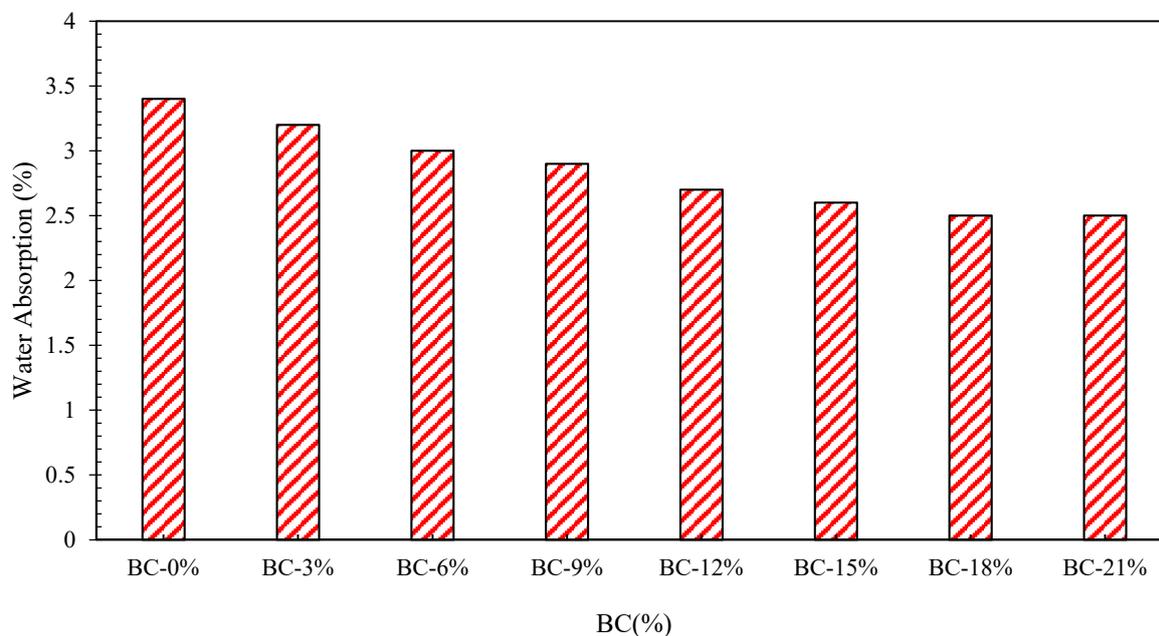


Figure 14. Water absorption (data source [44]).

6.2. Acid Resistance

The outcomes of the acid attack test with various replacement ratio of BC are shown in Figure 15. In the laboratory tests, it was discovered that the amount of weight loss experienced by blank mix was greatest in both sulfuric acid (H_2SO_4) and hydrochloric acid (HCL) solutions. The lower acid resistance of blank mix against acid attack may be attributed that it includes a big quantity of lime and during hydration emits a significant amount of free CH, which interacts with the acid and leaves a soft and mushy material behind. For bentonite mixes, the CH combines with the SiO_2 available in BC to produce CSH gel, resulting in a small quantity of CH and improved acid resistance capacity of BC concrete. When comparing the two acid solutions, the weight loss pattern was identical. Sulfuric acid, on the other hand, was shown to cause greater degradation than HCL. The greater degradation of H_2SO_4 is due to a product known as calcium sulfaluminate (Ettringite) is created, which expands and produces rupture of the set cement paste [67]. In the case of hydrochloric acid, no such product is generated. An investigation into Pozzolanic reaction and micro filling SCM resulted in a reduction of cavities, which inhibited the rapid entry of acid. The dissolving of calcium aluminate and calcium hydroxide in concrete due to H_2SO_4 is the primary cause of erosion [68]. The concrete erosion is determined by the rate

at which H_2SO_4 penetrates into the concrete body and the time it takes to achieve calcium hydroxide and calcium aluminate. As a consequence, a reduction in the voids of concrete due to the replacement of bentonite clay leads to a denser concrete mixture. It is anticipated that increased density will lead to a reduction in the rate of H_2SO_4 penetration into the concrete. However, higher acid resistance was examined at a higher substitution ratio of bentonite clay due to loss of flowability which results in porous concrete. The acid may readily permeate concrete via cavities, resulting in the destruction of the concrete structure. Further, bentonite is one of the most essential ingredients utilized in the construction of plastic concrete, where it serves to stabilize the concrete. It is made of clay components that have strong water absorption and swelling characteristics of 300 percent even after being in touch with water [54]. Swelled BC slurry will fill the voids and these water-saturated BC can block the further water absorption and permeability, thus decreasing the water absorption of water and increasing the acid resistance.

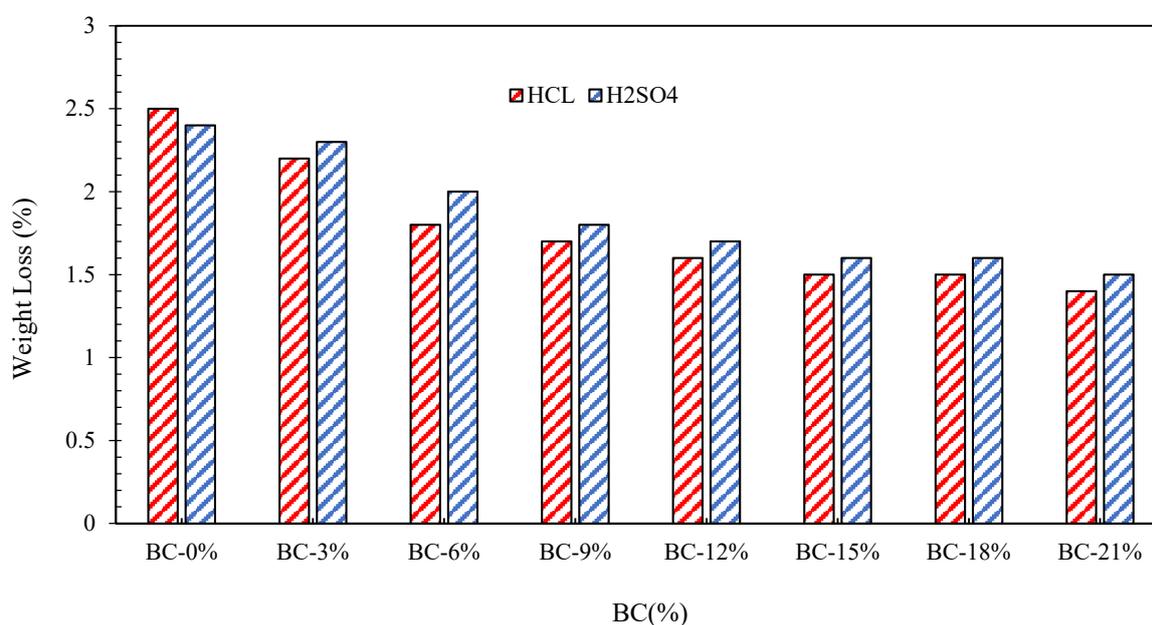


Figure 15. Acid resistance (data source [44]).

6.3. Dry Shrinkage

The shrinking of concrete is induced by the loss of moisture as a result of the drying process. To decrease cracking and the structural movement caused by drying shrinkage in concrete, shrinkage compensating concrete is utilized in its construction. It is dependent on the component materials, mixture proportions, curing time, drying environment, and constraint that the degree of drying shrinkage that happens in concrete buildings is determined. A study claims that the shrinkage of concrete is due to the movement of cement paste while aggregate restricts the movement of cement paste [55]. The findings of dry shrinkage of the five samples evaluated for initial days of hardening are assessed for evaluation. These specimens are the reference concrete, 5% BC, 10% BC, 15% BC, and 20% BC, respectively. Results indicate that the reference concrete experienced a large shrinkage when compared to the total amount of shrinkage experienced by all of the bentonite mixes. The maximal value of autogenous shrinkage strain obtained by the control mix was 135 macro strains. The shrinkage in B-5 and B-10 was 40 macro strain or 31 percent and 11 percent, respectively, but the shrinkage in B-15 and B-20 was 14 percent and 14 percent, respectively (Figure 16). The B-10 specimen produced the best results in terms of autogenous shrinkage strain. These findings are quite encouraging in terms of the decrease in linear shrinkage that may be obtained with the substitution of bentonite. The overall testing duration for the concrete beams was ten days, and no substantial fluctuation in autogenous strain was recorded

beyond that time. The combined pozzolanic reaction and micro filling of mineral admixture improved the cement paste binding properties and density which ultimately decreased the dry shrinkage of concrete [57]. A study noted that the reduction of cement content in cement pastes results in a decrease in drying shrinkage of cement pastes [69]. In addition, the research found that the mineral additive lowered the heat of hydration which prevented the quick evaporation of water from the concrete surface and decreased the formation of dry shrinkage cracks [70]. It has also been observed that fly ash may significantly minimize drying shrinkage in concrete by plugging micropores in the concrete and hence increasing the internal compactness of the concrete mix [19].

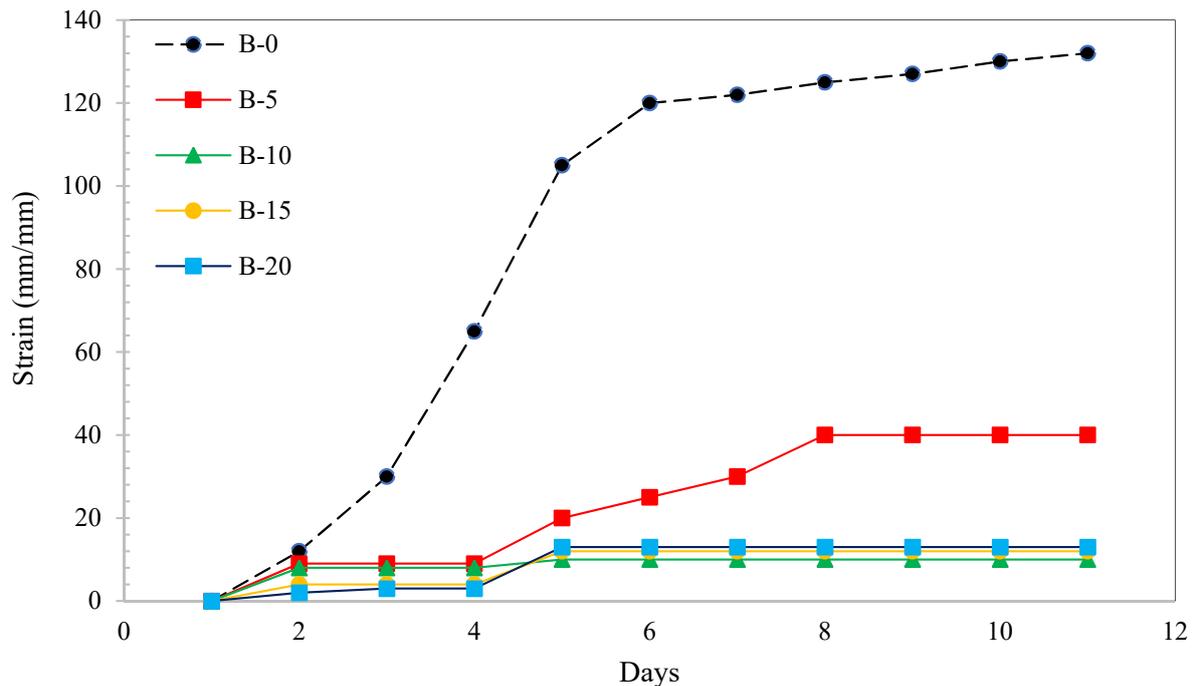


Figure 16. Dry shrinkage of concrete [71].

7. Conclusions

In a general sense, the incorporation of bentonite as pozzolan appears to be an environmentally friendly possibility. Technically and economically, BC presents various benefits to be used as a cement replacement in concrete. This review highlights the current research progress on bentonite clay in concrete. The main properties such as the physical and chemical composition of bentonite clay, fresh properties, and hardened properties of concrete with varying doses of bentonite clay are the main focus of this review. Also, load deflection and ductility were discussed. Furthermore, the durability of concrete with varying doses of bentonite clay was also a major concern of this review. The fundamental conclusions are as follows:

- Physical properties of bentonite clay show that the particle nature of bentonite clay is a rough and larger surface area than cement which negatively impacts the flowability of concrete.
- The chemical compounds of bentonite clay shows that it has the creditability to be utilized as a cement substitute.
- The flowability of concrete decreased with bentonite clay due to the larger surface area of bentonite clay which needed additional mortar to cover them and thus workability of concrete decreased.
- The fresh density was also noted to reduce with bentonite clay. The reduction in the fresh density is due to the lower specific gravity of bentonite clay as compared to cement.

- A reduction in mechanical performance was noted with bentonite clay. However, the decrease in strength was not significantly but approximately equal to the control. In contrast, some studies claim that strength was improved with bentonite clay due to pozzolanic reaction and micro filling voids, but more research is required in this regard.
- The load-deflection curve shows that the ductility of concrete is considerably improved with bentonite clay.
- Increased acid resistance and decreased dry shrinkage were observed with the substitution of bentonite clay instead of cement but still less studies are available on acid resistance and dry properties of concrete with substations of bentonite clay.

8. Future Perspective/Scope of BC

Although the overall review shows that bentonite clay has the creditability to be used as cement replacement in concrete up to some extent, less research focused on bentonite clay to be used as cement replacement in concrete as compared to other pozzolanic materials such silica fume, fly ash, etc. Furthermore, information on the long-term durability properties of concrete with bentonite clay is still scarce. No information is available on the alkali-silica reaction associated with bentonite clay. Therefore, this review recommends a detailed study on the durability aspects such as freezing and thawing action, dry shrinkage properties, and risk of alkali-silica reaction. Also, no information is available on microstructure analysis such as thermogravimetric analysis, and Fourier transforms infrared spectroscopy (FTIR). This review recommends a detailed study on microstructure analysis. Furthermore, the review also recommends fibers into bentonite clay-based concrete for high-strength concrete.

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References

1. Sankh, A.C.; Biradar, P.M.; Naghathan, S.J.; Ishwargol, M.B. Recent Trends in Replacement of Natural Sand with Different Alternatives. In Proceedings of the International Conference on Advances in Engineering and Technology, Singapore, 29–30 March 2014; pp. 59–66.
2. Svintsov, A.P.; Shchesnyak, E.L.; Galishnikova, V.V.; Fediuk, R.S.; Stashevskaya, N.A. Effect of Nano-Modified Additives on Properties of Concrete Mixtures during Winter Season. *Constr. Build. Mater.* **2020**, *237*, 117527. [[CrossRef](#)]
3. Fediuk, R. Reducing Permeability of Fiber Concrete Using Composite Binders. *Spec. Top. Rev. Porous Media Int. J.* **2018**, *9*, 79–89. [[CrossRef](#)]
4. Isler, J.W. *Assessment of Concrete Masonry Units Containing Aggregate Replacements of Waste Glass and Rubber Tire Particles*; University of Colorado at Denver: Denver, CO, USA, 2012; ISBN 1267297336.
5. Taskin, A.; Fediuk, R.; Grebenyuk, I.; Elkin, O.; Kholodov, A. Effective Cement Binders on Fly and Slag Waste from Heat Power Industry of the Primorsky Krai, Russian Federation. *Int. J. Sci. Technol. Res.* **2020**, *9*, 3509–3512.
6. Nassar, R.-U.-D.; Soroushian, P. Green and Durable Mortar Produced with Milled Waste Glass. *Mag. Concr. Res.* **2012**, *64*, 605–615. [[CrossRef](#)]

7. Benhelal, E.; Zahedi, G.; Shamsaei, E.; Bahadori, A. Global Strategies and Potentials to Curb CO₂ Emissions in Cement Industry. *J. Clean. Prod.* **2013**, *51*, 142–161. [[CrossRef](#)]
8. Oh, D.-Y.; Noguchi, T.; Kitagaki, R.; Park, W.-J. CO₂ Emission Reduction by Reuse of Building Material Waste in the Japanese Cement Industry. *Renew. Sustain. Energy Rev.* **2014**, *38*, 796–810. [[CrossRef](#)]
9. Agency, I.E.; Agency, I.E. *Tracking Industrial Energy Efficiency and CO₂ Emissions*; OECD: Paris, France, 2007; ISBN 9789264030169.
10. Berriel, S.S.; Favier, A.; Domínguez, E.R.; Machado, I.R.S.; Heierli, U.; Scrivener, K.; Hernández, F.M.; Habert, G. Assessing the Environmental and Economic Potential of Limestone Calcined Clay Cement in Cuba. *J. Clean. Prod.* **2016**, *124*, 361–369. [[CrossRef](#)]
11. Kou, S.C.; Poon, C.S. Properties of Self-Compacting Concrete Prepared with Coarse and Fine Recycled Concrete Aggregates. *Cem. Concr. Compos.* **2009**, *31*, 622–627. [[CrossRef](#)]
12. Si, R.; Dai, Q.; Guo, S.; Wang, J. Mechanical Property, Nanopore Structure and Drying Shrinkage of Metakaolin-Based Geopolymer with Waste Glass Powder. *J. Clean. Prod.* **2020**, *242*, 118502. [[CrossRef](#)]
13. Mirza, J.; Riaz, M.; Naseer, A.; Rehman, F.; Khan, A.N.; Ali, Q. Pakistani Bentonite in Mortars and Concrete as Low Cost Construction Material. *Appl. Clay Sci.* **2009**, *45*, 220–226. [[CrossRef](#)]
14. Smith, R.A.; Kersey, J.R.; Griffiths, P.J. The Construction Industry Mass Balance: Resource Use, Wastes and Emissions. *Construction* **2002**, *4*, 680.
15. Jiang, Y.; Ling, T.-C.; Mo, K.H.; Shi, C. A Critical Review of Waste Glass Powder—Multiple Roles of Utilization in Cement-Based Materials and Construction Products. *J. Environ. Manag.* **2019**, *242*, 440–449. [[CrossRef](#)] [[PubMed](#)]
16. Anwar, A. The Influence of Waste Glass Powder as a Pozzolanic Material in Concrete. *Int. J. Civ. Eng. Technol.* **2016**, *7*, 131–148.
17. Zhang, T.; Yang, Y.-L.; Liu, S.-Y. Application of Biomass by-Product Lignin Stabilized Soils as Sustainable Geomaterials: A Review. *Sci. Total Environ.* **2020**, *728*, 138830. [[CrossRef](#)]
18. Park, S.B.; Lee, B.C.; Kim, J.H. Studies on Mechanical Properties of Concrete Containing Waste Glass Aggregate. *Cem. Concr. Res.* **2004**, *34*, 2181–2189. [[CrossRef](#)]
19. Rahma, A.; El Naber, N.; Issa Ismail, S. Effect of Glass Powder on the Compression Strength and the Workability of Concrete. *Cogent Eng.* **2017**, *4*, 1373415. [[CrossRef](#)]
20. Somasri, M.; Kumar, B.N. Graphene Oxide as Nano Material in High Strength Self-Compacting Concrete. *Mater. Today Proc.* **2021**, *43*, 2280–2289. [[CrossRef](#)]
21. Siddique, R.; Singh, G.; Singh, M. Recycle Option for Metallurgical by-Product (Spent Foundry Sand) in Green Concrete for Sustainable Construction. *J. Clean. Prod.* **2018**, *172*, 1111–1120. [[CrossRef](#)]
22. Idir, R.; Cyr, M.; Tagnit-Hamou, A. Use of Waste Glass As Powder and Aggregate in Cement-Based Materials. In Proceedings of the SBEIDCO-1st International Conference on Sustainable Built Environment Infrastructures in Developing Countries, Oran, Algeria, 12–14 October 2009; pp. 109–116.
23. Kumar, R.; Goel, P.; Mathur, R. Suitability of Concrete Reinforced with Synthetic Fiber for the Construction of Pavements. In Proceedings of the 3rd International Conference on Sustainable Construction Materials and Technologies, Kyoto, Japan, 18–21 August 2013; pp. 18–22.
24. Amin, S.K.; Allam, M.E.; Garas, G.L.; Ezz, H. A Study of the Chemical Effect of Marble and Granite Slurry on Green Mortar Compressive Strength. *Bull. Natl. Res. Cent.* **2020**, *44*, 19. [[CrossRef](#)]
25. Jani, Y.; Hogland, W. Waste Glass in the Production of Cement and Concrete—A Review. *J. Environ. Chem. Eng.* **2014**, *2*, 1767–1775. [[CrossRef](#)]
26. Humphreys, D. Long-Run Availability of Mineral Commodities. *Miner. Econ.* **2013**, *26*, 1–11. [[CrossRef](#)]
27. Müller, N.; Harnisch, J. *How to Turn Around the Trend of Cement Related Emissions in the Developing World*; WWF: Gland, Switzerland, 2008.
28. Imbabi, M.S.; Carrigan, C.; McKenna, S. Trends and Developments in Green Cement and Concrete Technology. *Int. J. Sustain. Built Environ.* **2012**, *1*, 194–216. [[CrossRef](#)]
29. McEwan, A.E. From Cottages to ‘Skyscrapers’: The Architecture of AE & ES Luttrell in Tasmania and New Zealand. Master’s Thesis, University of Canterbury, Christchurch, New Zealand, 1988.
30. Okeke, K.L.; Adediji, A.A. A Review on the Properties of Concrete Incorporated with Waste Glass as a Substitute for Cement. *Epistem. Sci. Eng. Technol.* **2016**, *5*, 396–407.
31. Idir, R.; Cyr, M.; Tagnit-Hamou, A. Use of Fine Glass as ASR Inhibitor in Glass Aggregate Mortars. *Constr. Build. Mater.* **2010**, *24*, 1309–1312. [[CrossRef](#)]
32. Rashad, A.M. Recycled Waste Glass as Fine Aggregate Replacement in Cementitious Materials Based on Portland Cement. *Constr. Build. Mater.* **2014**, *72*, 340–357. [[CrossRef](#)]
33. Pusch, R. *Bentonite Clay: Environmental Properties and Applications*; CRC Press: Boca Raton, FL, USA, 2015; ISBN 148224344X.
34. Arslan, M.; Abdioğlu, E.; Kadir, S. Mineralogy, Geochemistry, and Origin of Bentonite in Upper Cretaceous Pyroclastic Units of the Tirebolu Area, Giresun, Northeast Turkey. *Clays Clay Miner.* **2010**, *58*, 120–141. [[CrossRef](#)]
35. Ahmad, J.; Tufail, R.F.; Aslam, F.; Mosavi, A.; Alyousef, R.; Faisal Javed, M.; Zaid, O.; Khan Niazi, M.S. A Step towards Sustainable Self-Compacting Concrete by Using Partial Substitution of Wheat Straw Ash and Bentonite Clay Instead of Cement. *Sustainability* **2021**, *13*, 824. [[CrossRef](#)]
36. Fernandez, R.; Martirena, F.; Scrivener, K.L. The Origin of the Pozzolanic Activity of Calcined Clay Minerals: A Comparison between Kaolinite, Illite and Montmorillonite. *Cem. Concr. Res.* **2011**, *41*, 113–122. [[CrossRef](#)]

37. Andrade, C.; Martínez-Serrano, A.; Sanjuán, M.Á.; Tenorio Ríos, J.A. Reduced Carbonation, Sulfate and Chloride Ingress Due to the Substitution of Cement by 10% Non-Precalcined Bentonite. *Materials* **2021**, *14*, 1300. [[CrossRef](#)]
38. Ramezani-pour, A.A.; Pourkhorshidi, A.R. Durability of Concretes Containing Supplementary Cementing Materials under Hot and Aggressive Environment. *Spec. Publ.* **2004**, *221*, 633–646.
39. Reddy, G.V.K.; Rao, V.R.; Reddy, M.A.K. Experimental Investigation of Strength Parameters of Cement and Concrete by Partial Replacement of Cement with Indian Calcium Bentonite. *Int. J. Civ. Eng. Technol.* **2017**, *8*, 512–518.
40. Wei, J.; Gencturk, B. Hydration of Ternary Portland Cement Blends Containing Metakaolin and Sodium Bentonite. *Cem. Concr. Res.* **2019**, *123*, 105772. [[CrossRef](#)]
41. Ashraf, M.; Iqbal, M.F.; Rauf, M.; Ashraf, M.U.; Ulhaq, A.; Muhammad, H.; Liu, Q. Developing a Sustainable Concrete Incorporating Bentonite Clay and Silica Fume: Mechanical and Durability Performance. *J. Clean. Prod.* **2022**, *337*, 130315. [[CrossRef](#)]
42. Khandelwal, S.; Rhee, K.Y. Evaluation of Pozzolanic Activity, Heterogeneous Nucleation, and Microstructure of Cement Composites with Modified Bentonite Clays. *Constr. Build. Mater.* **2022**, *323*, 126617. [[CrossRef](#)]
43. Reddy, M.A.K.; Rao, V.R.; Chaitanya, K.N.; Khed, V.C. Optimization of Bentocrete Parameters Using Response Surface Methodology (RSM). *AIMS Mater. Sci.* **2021**, *8*, 221–247. [[CrossRef](#)]
44. Memon, S.A.; Arsalan, R.; Khan, S.; Lo, T.Y. Utilization of Pakistani Bentonite as Partial Replacement of Cement in Concrete. *Constr. Build. Mater.* **2012**, *30*, 237–242. [[CrossRef](#)]
45. Khushnood, R.A.; Rizwan, S.A.; Memon, S.A.; Tulliani, J.-M.; Ferro, G.A. Experimental Investigation on Use of Wheat Straw Ash and Bentonite in Self-Compacting Cementitious System. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 832508. [[CrossRef](#)]
46. Ahmad, J.; Martínez-García, R.; De-Prado-Gil, J.; Irshad, K.; El-Shorbagy, M.A.; Fediuk, R.; Vatin, N.I. Concrete with Partial Substitution of Waste Glass and Recycled Concrete Aggregate. *Materials* **2022**, *15*, 430. [[CrossRef](#)]
47. ASTM D6868; Specification for Biodegradable Plastics Used as Coatings on Paper and Other Compostable Substrates. ASTM International: West Conshohocken, PA, USA, 2017.
48. Akbar, J.; Alam, B.; Ashraf, M.; Afzal, S.; Ahmad, A.; Shahzada, K. Evaluating the Effect of Bentonite on Strength and Durability of High Performance Concrete. *Int. J. Adv. Struct. Geotech. Eng.* **2013**, *2*, 1–5.
49. Vijay, C.; Reddy, M.A.K. Optimization of Bentonite Modified Cement Mortar Parameters at Elevated Temperatures Using RSM. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2021; Volume 1197, p. 12040.
50. Shabab, M.E.; Shahzada, K.; Gencturk, B.; Ashraf, M.; Fahad, M. Synergistic Effect of Fly Ash and Bentonite as Partial Replacement of Cement in Mass Concrete. *KSCE J. Civ. Eng.* **2016**, *20*, 1987–1995. [[CrossRef](#)]
51. Mousavi, S.S.; Dehestani, M.; Mousavi, S.M. Bond Strength and Development Length of Glass Fiber-Reinforced Polymer Bar in Unconfined Self-Consolidating Concrete. *J. Reinf. Plast. Compos.* **2016**, *35*, 924–941. [[CrossRef](#)]
52. Ahmad, J.; Zaid, O.; Shahzaib, M.; Abdullah, M.U.; Ullah, A.; Ullah, R. Mechanical Properties of Sustainable Concrete Modified by Adding Marble Slurry as Cement Substitution. *AIMS Mater. Sci.* **2021**, *8*, 343–358. [[CrossRef](#)]
53. Waqas, R.M.; Butt, F.; Danish, A.; Alqurashi, M.; Mosaberpanah, M.A.; Masood, B.; Hussein, E.E. Influence of Bentonite on Mechanical and Durability Properties of High-Calcium Fly Ash Geopolymer Concrete with Natural and Recycled Aggregates. *Materials* **2021**, *14*, 7790. [[CrossRef](#)] [[PubMed](#)]
54. Fadaie, M.A.; Nekooei, M.; Javadi, P. Effect of Dry and Saturated Bentonite on Plastic Concrete. *KSCE J. Civ. Eng.* **2019**, *23*, 3431–3442. [[CrossRef](#)]
55. Ahmad, J.; Aslam, F.; Martinez-Garcia, R.; De-Prado-Gil, J.; Qaidi, S.M.A.; Brahmia, A. Effects of Waste Glass and Waste Marble on Mechanical and Durability Performance of Concrete. *Sci. Rep.* **2021**, *11*, 21525. [[CrossRef](#)] [[PubMed](#)]
56. Ahmad, S.; Barbhuiya, S.A.; Elahi, A.; Iqbal, J. Effect of Pakistani Bentonite on Properties of Mortar and Concrete. *Clay Miner.* **2011**, *46*, 85–92. [[CrossRef](#)]
57. Ahmad, J.; Aslam, F.; Martinez-Garcia, R.; El Ouni, M.H.; Khedher, K.M. Performance of Sustainable Self-Compacting Fiber Reinforced Concrete with Substitution of Marble Waste (MW) and Coconut Fibers (CFs). *Sci. Rep.* **2021**, *11*, 23184. [[CrossRef](#)]
58. Chandrakanth, M.; Rao, N.P.C.; Rao, K.S. Experimental Studies on Concrete with Bentonite as Mineral Admixture. *GRD J.* **2016**, *1*, 7–10.
59. Taklymi, S.M.Q.; Rezaifar, O.; Gholhaki, M. Investigating the Properties of Bentonite and Kaolin Modified Concrete as a Partial Substitute to Cement. *SN Appl. Sci.* **2020**, *2*, 2023. [[CrossRef](#)]
60. Ashish, P.; Srinivasarao, C. Influence of Bentonite as Partial Replacement of Cement in Basalt Fiber Concrete. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2021; Volume 1185, p. 12015.
61. Sumitha, Y.; Abraham, R. Experimental Study on Bentonite Clay Powder with Silica Fume and GGBS as Partial Replacement of Cement in M40 Grade Concrete. *Int. J. Eng. Res. Technol.* **2016**, *5*. [[CrossRef](#)]
62. Liu, M.; Hu, Y.; Lai, Z.; Yan, T.; He, X.; Wu, J.; Lu, Z.; Lv, S. Influence of Various Bentonites on the Mechanical Properties and Impermeability of Cement Mortars. *Constr. Build. Mater.* **2020**, *241*, 118015. [[CrossRef](#)]
63. Kumar, B.P.; Rao, V.R.; Reddy, M.A.K. Effect on Strength Properties of Concrete by Partial Replacement of Cement with Calcium Bentonite and Fly Ash. *Technology* **2017**, *8*, 450–455.
64. Khaliq, S.U.L.; Jamil, I.; Ullah, H. Evaluating Permeability and Mechanical Properties of Waste Marble Dust Mix Concrete and Bentonite Mix Concrete. In *Proceedings of the International Structural Engineering and Construction, Brisbane, Australia, 3–5 December 2018*. [[CrossRef](#)]
65. Adeboje, A.O.; Kupolati, W.K.; Sadiku, E.R.; Ndambuki, J.M.; Kambole, C. Experimental Investigation of Modified Bentonite Clay-Crumb Rubber Concrete. *Constr. Build. Mater.* **2020**, *233*, 117187. [[CrossRef](#)]

66. Shannag, M.J. High Strength Concrete Containing Natural Pozzolan and Silica Fume. *Cem. Concr. Compos.* **2000**, *22*, 399–406. [[CrossRef](#)]
67. Rawal, P. Development of Durable Concrete from Pulverized Fly Ash and Pozzolan Derived from Agricultural Wastes. Master's Thesis, Asian Institute of Technology, Bangkok, Thailand, 2003.
68. Fediuk, R.; Pak, A.; Kuzmin, D. Fine-Grained Concrete of Composite Binder. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2017; Volume 262, p. 12025.
69. Bheel, N.; Abbasi, S.A.; Awoyera, P.; Olalusi, O.B.; Sohu, S.; Rondon, C.; Echeverría, A.M. Fresh and Hardened Properties of Concrete Incorporating Binary Blend of Metakaolin and Ground Granulated Blast Furnace Slag as Supplementary Cementitious Material. *Adv. Civ. Eng.* **2020**, *2020*, 8851030. [[CrossRef](#)]
70. Ahmad, J.; Zaid, O.; Siddique, M.S.; Aslam, F.; Alabduljabbar, H.; Khedher, K.M. Mechanical and Durability Characteristics of Sustainable Coconut Fibers Reinforced Concrete with Incorporation of Marble Powder. *Mater. Res. Express* **2021**, *8*, 075505. [[CrossRef](#)]
71. Afzal, S.; Shahzada, K.; Fahad, M.; Saeed, S.; Ashraf, M. Assessment of Early-Age Autogenous Shrinkage Strains in Concrete Using Bentonite Clay as Internal Curing Technique. *Constr. Build. Mater.* **2014**, *66*, 403–409. [[CrossRef](#)]