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2024-12

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Wiley

https://doi.org/10.1155/adce/3849110

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Wiley
Advances in Civil Engineering
Volume 2024, Article ID 3849110, 18 pages
https://doi.org/10.1155/adce/3849110

Review Article

Activated Bentonite for Physical, Mechanical, and Durability Properties of Concrete—A Review

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Received 16 July 2024; Accepted 15 November 2024

Academic Editor: Xing Wang

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Bentonite mostly exists in many counties and studies reported employment of activated bentonite in the concrete improves concrete performance more than using raw bentonite. However, it is not well-known which range of bentonite activation temperature and employment dose gives the best concrete performance for the sustainability of activated bentonite in construction materials. Therefore, the present study detail reviewed the effect of activated bentonite at different heating temperatures and replacement doses of bentonite on the durability, physical, mechanical, and microstructural properties of concrete. Also, environmental and economic beneficiary of employing activated bentonite in concrete is evaluated. As the review of various studies reveals, activation of bentonite between 201 and 800°C increases the pozzolanic reactivity of bentonite. Hence, the activated pozzolana can easily consume free calcium hydroxide to form a secondary C–S–H gel that can improve the mechanical, microstructural, and durability properties of activated bentonite blended concrete in addition to lessening energy consumption compared to conventional concrete. Besides these, adding 15%–20% of activated bentonite in concrete significantly improves the mechanical properties; specifically, most studies found the optimum activated bentonite dose is 15% by weight of cement in concrete. This replacement indicates lessened energy consumption by around 45% compared to the total employment of ordinary Portland cement in concrete production.

Keywords: activation; bentonite; concrete; ordinary portland cement; pozzolana

1. Introduction

Cement is the most produced construction material in the world; however, it requires a high amount of energy consumption due to its primary composition cement. Hence, every tone of ordinary Portland cement production releases the same amount of CO_2 to the environment [1–3]. Pozzolana is supplementary cementitious material and its use in a concrete mixture potentially enhances concrete performance and lessens the consumption of cement while significantly reducing CO_2 emission [4–13]. The enhancement of concrete performance on fresh and hardened properties like reducing acidic attack and porosity [14, 15], reduces permeability, lowers heat of hydration, improves durability, and ultimate strength [16–21]. These improvements in durability and mechanical properties of concrete are due to the reaction between pozzolanic material and the free calcium hydroxide in cement hydration [17, 22, 23]. Also, incorporation of pozzolana in concrete promises a potential chemical binding by providing less permeable concrete matrix [15, 24]. So, most concrete specimens that incorporate pozzolanic materials with cement exhibit lesser deformations and higher compressive strength [5, 18, 25–31].

This is due to pozzolanic reaction can actively react and consume $Ca(OH)_2$ to produce additional calcium aluminate silicate hydrates (C–A–S–H) and calcium silicate hydrates (C–S–H) that can lower heat of hydration and improve mechanical properties of concrete [6, 19, 32, 33].

Pozzolana can be categorized into artificial and natural pozzolana [34–36]. Artificial pozzolana is mostly from the combustion of various industrial furnaces, and from different waste that can be decomposed into ash, which potentially contains silica (SiO_2) like fly ash, rice husk ash, silica fume, and others. While natural Pozzolan is natural sedimented volcanic lava or ash which is rich in SiO_2 and alumina (Al_2O_3). Hence, employing natural pozzolana in concrete promises to mitigate alkali–SiO_2 reaction by enhancing secondary pozzolanic reactivity at the initial stage of cement setting and ultimately used for neutralizing the excessive alkalinity of cement [36, 37]. Besides these, raising the amount of natural pozzolana in concrete lessens chloride migration [24], enhances sulfuric acid resistance [38–42], and improves the long-term strength gain of cementing materials through reducing water absorption and permeability of the matrix [43–49].

Bentonite is natural pozzolana mainly composed of montmorillonite compound and its substitution in cement is important for the reaction of montmorillonite with free portlandite to give extra C–S–H gel. Therefore, C–S–H gel is the sole cause for the strength development of cement in the production of cement-based concrete [50, 51]. Laidani et al. [52] studied the effect of partial replacement of activated bentonite by 0%, 5%, 10%, 15%, 20%, 25%, and 30% on the weight of ordinary Portland cement for concrete production using an activation temperature of 800°C for 3 h. So, the study reported that 10% and 15% replacement of activated bentonite significantly improved compressive strength, reduced chloride ion penetration, porosity, and gas permeability of concrete compared to the control mixture and also, compared to other sampled doses of activated bentonite used in the study.

Also, Adjei et al. [53] investigated Saudi-activated bentonite cement replacement for the uses of cement composite materials. Bentonite activated at 850°C for 3 h, then 10%–30% cement replacement doses were used. The study found the optimum replacement of activated bentonite sample is 20%, which has good pozzolanic reactivity that can enhance durability, mechanical, and microstructural properties of cementing materials. However, Chandrakanth and Rao [54] worked on the experimental study for the partial replacement of raw bentonite in concrete. The study used the replacement of bentonite by 0%, 5%, 10%, and 20% to the weight of cement in concrete and found adding 5% of raw bentonite to the concrete improves compressive, splitting tensile, and flexural strength. So, 5% replacement of raw bentonite is significantly lower than the result found by Adjei et al. [53] which is 20% replacement of activated bentonite in concrete. Hence, this indicates activation of bentonite is crucial to more replace in concrete while improving concrete properties compared to the raw bentonite. However, it is not well-known at what range of bentonite activation temperature and replacement doses most positively improve concrete properties. Therefore, the present study reviewed the effect of activated bentonite at different heating temperatures and replacement doses of bentonite on the durability, physical, mechanical, and microstructure properties of concrete. Also, environmental and economic beneficiary of employing activated bentonite in concrete is evaluated.

2. Method Adopted for Reviewing Process

The literature and information are gathered from Google scholar that include databases of Elsevier, Taylor & Francis, Springer, Wiley, etc., on full discussion and evaluation of the keywords, like raw bentonite, activated bentonite, activation temperature, optimum dose, natural pozzolana, supplementary cementitious materials, and sustainable concrete. Then, depending on the keywords gathered different articles, case studies, conference papers, and book sections, as shown in Figure 1. Hence, it has concluded the effect of different activated bentonite replacement doses and various bentonite activation temperatures on the physical, mechanical, durability, and microstructural properties of concrete. Also, it is evaluated the importance of replacing activated bentonite in the concrete for sustainable economy and green environment.

3. Bentonite

Bentonite is clay rich in Al_2O_3–siliceous minerals, mainly consisting of 87% earthen minerals with montmorillonite and mostly it can fulfill pozzolanic properties. Khaliq, Jamil, and Ullah [55] reported that bentonite is montmorillonite clay produced after volcanic ash through long term in the presence of water that can reflect pozzolanic properties. Hence, it has pozzolanic properties that can give a lot of benefits in the construction industries as a partial replacement of cement to form improved concrete properties. Furthermore, Al-Hammood, Frayyeh, and Abbas [56] also stated that bentonite is a rock mixture of different minerals, potentially consisting of montmorillonite and clay minerals such as illite, kaolinite, and palygorskite with nonclay minerals such as quartz, gypsum, and calcite that all in one support enhancement of concrete durability [57].

Bentonite can be categorized into sodium and calcium bentonite [33, 57]. Most natural pozzolanic materials need thermal treatment to accelerate the pozzolanic reaction and make denser microstructure of concrete [58, 59]. Especially calcium bentonite is the most abundant material that provides highly reactive pozzolanic properties when activated at the optimum temperature [53]. Hence, Adjei et al. [53] found that activated bentonite employment in concrete can highly enhance durability, mechanical, and microstructural properties of cementing materials.

3.1. Chemical Composition of Activated Bentonite. Bentonite clay has different types, which varies by physical properties, and chemical composition [56]. But its primary constituents are silicon dioxide and aluminum oxide. The ratios of Si to Al increase by increasing the temperature from 600 to 1000°C of bentonite activation [60], which is due to a pozzolanic reaction in replacement of activated bentonite highly favors the formation of silicate phases [61]. Setina, Gabrene, and

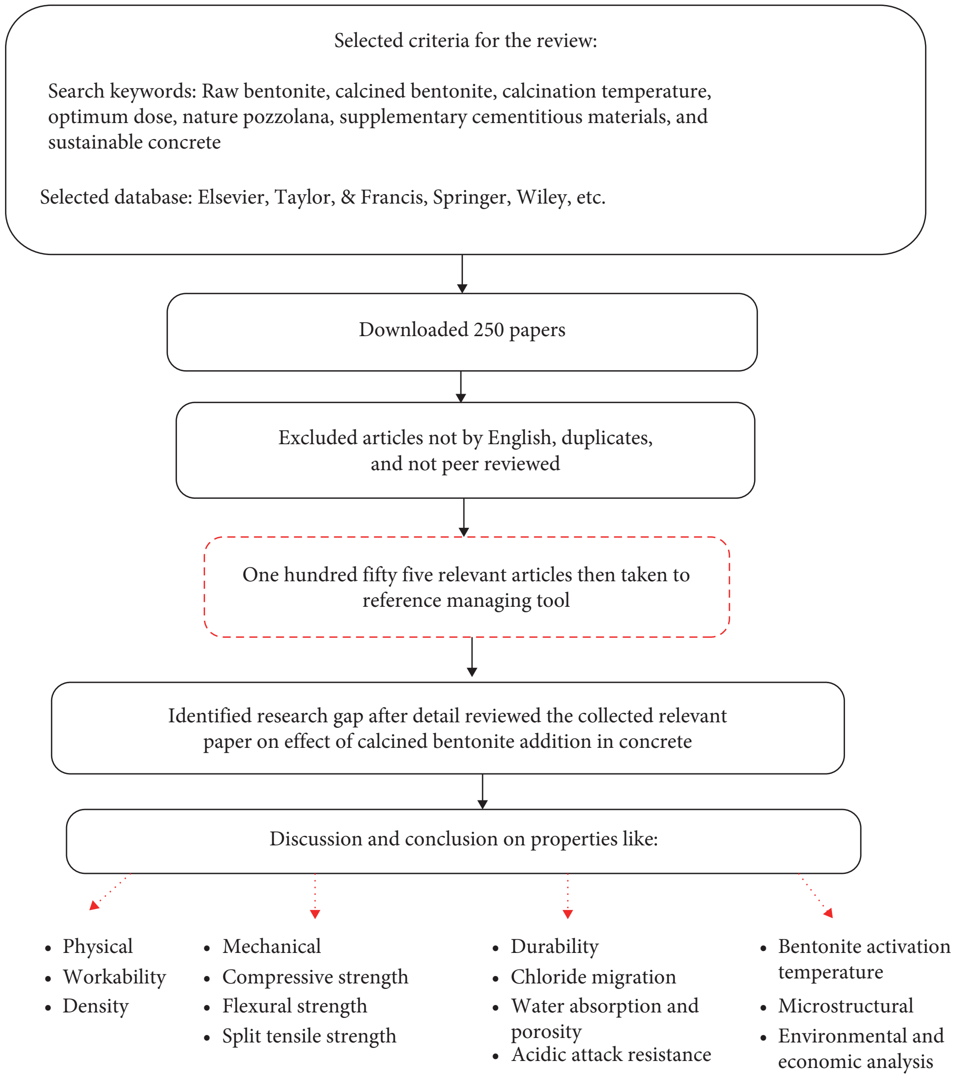

Figure 1: Method of reviewing process.

Juhnevica [62] found that the chemical composition especially, the amounts of reactive SiO_2 is mainly used to predict the pozzolanic material reaction. Also, the addition of three oxides SiO_2, Al_2O_3, and Fe_2O_3 have to be more than 70% of the total compositions as per ASTM C618 [63]. As presented in Table 1, all the studies by different authors on bentonite have the addition of SiO_2, Al_2O_3, and Fe_2O_3 (SAF) more than 70% fulfill the requirement of N-type pozzolana as per ASTM C618 [63]. Also, as shown in Figure 2, the activation of bentonite significantly increases those three oxides compared to the same raw bentonite sample, which is mainly due to dehydration ion of water through activation. This means activation increases the ratio of Si–Al, which can actively react with free lime to form crucial compound C–S–H/C–A–S–H gels. However, as shown in Figure 3, there is a limited number of studies on the employment of activated bentonite in cementitious materials, which indicates the importance of using activated bentonite in concrete is not well-known.

4. Results and Discussion

The results of different reviewed literature on the employment of calcined bentonite effects on the concrete physical properties like fresh density and workability, mechanical properties like compressive, flexural, and splitting tensile strength, durability like water absorption and porosity, chloride ion migration, and sulfuric acid resistance have been detail discussed. Also, the effect of activated bentonite on the microstructural properties of concrete and the assessment of environmental and economic beneficiaries has been highlighted in the following subsections.

4.1. Uses of Bentonite in Concrete. The main uses of most pozzolanic materials in concrete are to enhance long-term mechanical properties, durability, and reduction of carbon emissions in the cement production [67, 76, 87–89]. Replacing bentonite in the mixture of concrete can decrease the amounts of portlandite, due to the hydration reaction between cement and bentonite. Also, adding bentonite to

Table 1: Bentonite chemical composition of reported by different researchers.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	Cl	LOI	SAF	A/R	References
63.04	17.15	3.17	1.93	1.53	0.38	2.64	1.47	—	—	—	0.00	83.36	A	[64]
49.17	14.55	7.37	0.75	2.23	—	3.25	0.68	0.22	—	—	—	71.09	R	[60]
48.80	15.54	6.44	5.22	3.50	—	2.19	0.75	0.49	0.13	—	15.73	70.78	R	[65]
64.25	15.60	4.60	1.63	2.50	0.00	2.80	3.86	0.60	0.21	—	0.24	84.45	R	[48]
49.17	14.55	7.37	0.75	2.23	—	3.25	0.68	0.22	—	—	—	71.09	A	[60]
70.70	13.80	1.49	2.30	2.26	0.29	2.56	0.33	0.20	0.05	0.00	5.12	85.99	R	[66]
60.53	17.41	2.06	0.86	7.63	0.09	9.62	0.23	0.10	0.03	—	0.05	**80**	**R**	[67]
64.23	19.39	5.19	3.79	1.81	0.08	1.49	1.52	0.09	0.02	—	1.12	**88.81**	**A**	[67]
67.03	16.31	1.76	2.81	7.15	0.05	3.10	1.43	0.13	0.09	0.04	—	85.1	R	[68]
52.80	16.40	5.80	4.60	1.40	—	0.62	0.70	—	—	—	9.6	75	R	[69]
56.63	19.86	14.89	1.16	1.79	—	1.51	1.56	2.20	—	—	—	**91.38**	**A**	[53]
57.98	19.70	12.46	1.11	1.71	—	1.25	1.51	1.62	—	—	—	**90.14**	**R**	[53]
52.80	16.40	5.80	4.60	1.40	—	0.62	0.70	—	—	—	9.60	75	R	[47]
56.13	21.20	3.23	3.16	4.32	—	4.14	1.01	0.55	0.12	—	6.11	80.56	R	[33]
76.17	14.38	3.17	1.88	1.11	0.91	1.06	0.54	0.60	0.04	—	4.86	93.72	R	[70]
55.70	20.10	13.50	2.20	3.50	—	0.13	2.50	2.54	—	—	—	89.3	R	[71]
62.00	17.20	6.51	0.95	7.35	0.20	5.03	0.07	0.22	—	0.18	—	85.71	R	[72]
51.01	24.36	2.78	1.13	1.14	0.80	1.58	0.66	0.17	0.05	—	20	78.15	A	[73]
70.12	12.19	5.12	3,52	3.16	—	5.06	0.56	0.15	0.11	—	—	87.43	R	[74]
67.10	15.44	2.56	3.86	4.32	—	0.18	0.33	—	—	—	7.20	85.1	R	[49]
62.62	16.46	3.26	5.92	3.54	0.05	6.31	1.24	—	———	———	—	82.34	R	[75]
65.16	19.63	5.25	4.00	1.67	0.02	0.45	2.65	0.86	0.09	——	—	90.04	R	[76]
52.80	16.40	5.80	4.60	1.40	—	0.62	—	—	—	——	9.60	75	R	[69]
54.62	20.35	4.05	1.02	0.10	—	2.92	0.19	—	—	——	15.00	**79.02**	**R**	[77]
65.61	24.44	4.86	1.23	0.12	—	3.51	0.23	—	—	———	—	**94.91**	**A**	[77]
58.84	17.15	2.73	1.51	4.93	0.83	2.24	1.28	—	—	———	9.21	78.72	R	[78]
70.75	9.67	1.80	1.13	0.00	—	1.47	0.76	—	—	—	11.24	82.22	R	[5]
63.20	15.60	7.60	8.70	3.70	1.60	1.20	0.60	—	0.90	—	—	**86.4**	**A**	[79]
57.60	13.60	6.30	7.40	3.20	1.30	1.10	0.50	—	0.87	—	—	**77.5**	**R**	[79]
72.58	14.46	1.94	3.90	3.30	—	0.50	1.83	0.07	—	—	1.42	88.98	A	[80]
60.53	17.41	2.06	0.82	7.63	—	9.62	1.23	—	—	—	—	80	R	[81]
57.83	13.55	5.94	3.97	2.44	0.08	—	1.59	—	—	—	10.17	77.32	R	[82]
53.20	18.50	10.80	3.10	1.90	—	—	0.60	2.60	—	—	7.80	82.5	A	[6]
65.00	15.00	3.00	2.66	6.50	—	0.12	027	—	—	—	6.00	83	R	[83]
56.62	19.81	0.02	1.16	0.55	0.69	—	0.96	—	0.05	—	10.12	76.45	R	[84]
68.70	17.20	0.90	0.40	1.60	—	3.70	2.30	0.13	—	—	—	86.8	R	[85]
65.00	18.50	1.43	1.00	1.73	0.19	3.20	0.95	0.27	0.13	0.09	4.98	84.93	R	[86]
71.2	13.00	0.75	1.62	2.71	—	—	1.01	0.1	—	—	7.38	84.95	A	[48]

Note: "Bold" signifies raw and activated bentonite having the same source.
Abbreviations: A, activated; R, raw.

concrete significantly consumes a higher amount of portlandite compared with kaolin replacement in concrete mixtures [72]. Therefore, using bentonite in concrete is beneficial for the improvement of mechanical properties and durability of concrete by increasing the resistance of the concrete structure to acidic attacks [40, 76, 87, 90, 91]. Besides these, using bentonite in concrete improves bleeding and cohesiveness of concrete in a low-intensity level [92]. Generally, utilizing bentonite in construction work is a better option for the improvement of environmental problems, financial, and technical aspects [89, 93–97].

4.2. Effects of Bentonite Activation Temperature. Activation by heating is the firing of a material at a specified temperature mainly carried out in industries by a fixed bed or fluid bed of calciner and in rotary kilns which is most effective in terms of heat distribution and thermal homogeneity of the activated material [98]. The process of preparing raw bentonite to the activation is shown in Figure 4, which starts from raw extracted bentonite, grinding, and heating. However, the activation temperature may vary from material to material, especially different for diverse clay depending on chemical composition, structural order, crystallography,

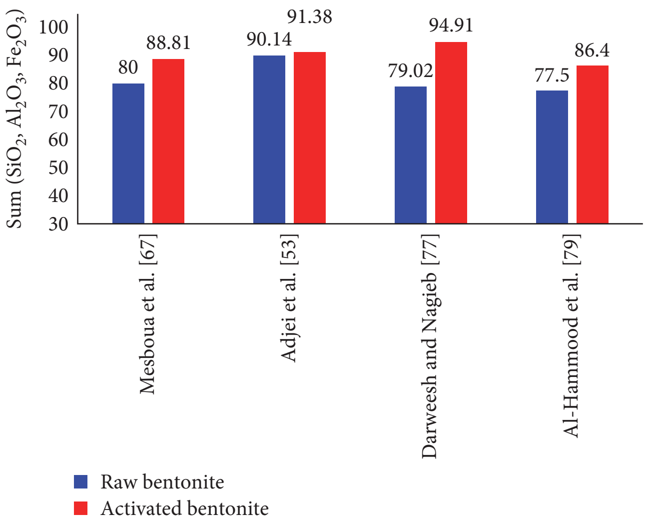

Figure 2: Difference of sum SiO_2, Al_2O_3, and Fe_2O_3 before activation and after activation of bentonite.

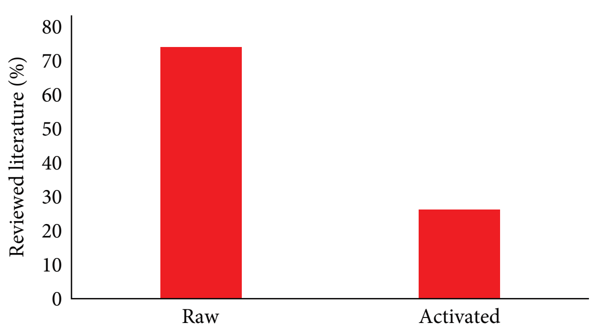

Figure 3: Variation in the number of studies reviewed on raw and activated bentonite used in cementitious materials.

structural imperfections, and structural recrystallization of clay minerals [99]. Naturally, bentonite exists in a consolidated form that is without the required treatment or activation methods. So, it cannot be incorporated directly without activation as a supplementary cementitious material for higher efficiency of cement composite materials [90]. But much of the activation of montmorillonite clay is affected by high heating temperature, which depends on the particle size distribution and specific surface area of the clay [100].

The activation of bentonite promises the enhancement of physiochemical properties for the reduction of concrete acidic attack and mainly to form an extra C–S–H gel through replacing in concrete mixtures [67]. Also, the surface area of ball-milled activated bentonite increases when the pressure rate increases as Sallem et al. [101], and the activation of bentonite significantly can change bentonite color from yellow to reddish. But, above 850°C heating temperature the color of the reddish changed to reddish-black, which mostly indicates as some particles of bentonite start burning. So, prolonged exposure of pozzolanic materials to a temperature above the dehydroxylation enhances recrystallization and, hence, loses its pozzolanic reactivity [79].

Keke et al. [48] found that utilization of raw bentonite reduces the compressive strength of cement composites and 750°C was the best pozzolanic activation temperature of raw bentonite. In contrast, activation of bentonite at 900°C is not conducive to improve the pozzolanic reactivity. Employing bentonite increases strength and pozzolanic reactivity below 750°C and low-temperature bentonite activation enhances water absorption, reduces the water content, and increases the concentration of alkali solution and ion exchange capacities of bentonite. So, as presented in Table 2, many researchers used activation of bentonite between 150 and 1000°C, hence, as shown in Figure 5a,b, most researchers found optimum activation of bentonite between 201 and 800°C for 3 h that can give best performance on strength, durability, and microstructural properties of concrete.

Besides these, incorporation of activated bentonite in concrete is very crucial for the reduction of concrete acidic attack and for the production of C–S–H through increasing the replacement rate of bentonite [67]. Increasing the activation temperature and hydrothermal treatments of bentonite can diminish the chloride migration of concrete [60]. Furthermore, replacing activated bentonite in ordinary Portland cement increases the initial and final setting time and improves compressive strength. However, reduces free calcium hydroxide and lessens the existence of porosity, that is due to its pozzolanic reaction and the filling ability of activated bentonite [105]. Generally, activation of bentonite or any other clay requires less activation temperature than cement clinker. Hence, employing bentonite in concrete is much beneficial for the reduction of CO_2 emission.

4.3. Effect of Different Activation Temperatures on the Reactivity of Bentonite. Most natural pozzolana requires activation temperature to be effectively replaced in cement and to form high reactivity with free calcium hydroxide, especially bentonite naturally occurs as a consolidated form that needs heating. As shown in Figure 6, studied by Fode, Jande, and Kivevele [106], while increasing the activation temperature from 400 to 800°C, the phase changes occurred, that is mainly from crystalline to amorphous. Hence, the study found at the 4 and 5 points, the spectrums are, respectively, 2930.97 and 3620.34 cm^{-1}, which shows the OH^- vibrations that gradually decrease with increasing temperature and totally disappear at 800°C. This is mainly because of dehydration through rising activation temperature; hence, the disappearance of the peaks indicates the crystallization end and occurrence of amorphous bentonite at 800°C which consequently forms a highly reactive bentonite with free lime to form C–S–H gel [107]. However, beyond 900°C, it is the occurrence of recrystallization of activated bentonite [90].

4.4. Effect of Activated Bentonite on the Physical Properties of Concrete

4.4.1. Density. The employment of bentonite in concrete lessens the concrete density and increasing bentonite doses can much lower the density of concrete [78, 94, 108]. Also, increasing the employment of activated bentonite can significantly decrease the density of the concrete mixture. This is

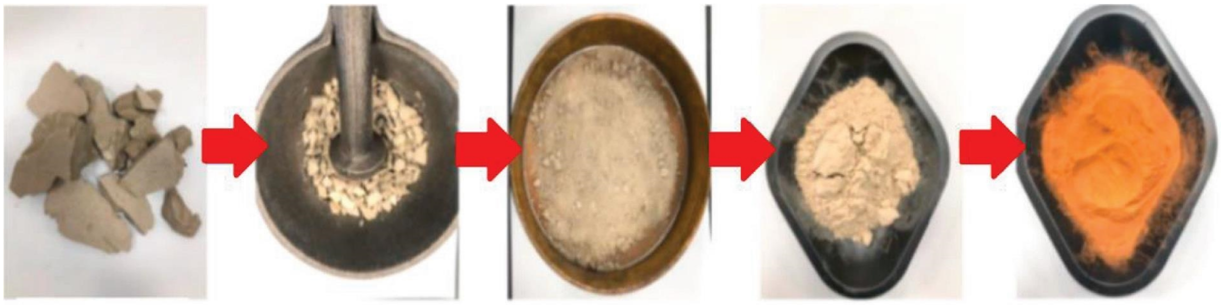

Figure 4: Preparation stage for activation of bentonite by Adjei et al. [53] permission Elsevier.

Table 2: Bentonite activation temperature and duration utilized by different researchers.

Activation temperature (°C)	Duration of activation (h)	References
800	3	[102]
700	2	[101]
800	3	[64]
1000	1.40	[66]
850	6	[67]
800	3	[53]
1100	3	[103]
650/830	1	[104]
200	1	[94]
150/300/450/600/700/900	2	[48]
800	1.5	[79]
600, 800, 1000	2	[78]

due to the specific density of bentonite is much lesser than the cement. The same observation that the cementitious material density can be decreased by employing activated bentonite, which is due to the fine particles of activated bentonite filling voids and some of the cement particle places can be occupied by bentonite, consequently, lessens the density of concrete [64, 108].

Alani et al. [109] studied the effect of high temperature on nanoactivated montmorillonite clay and stated that the use of thermal treatment for nanoactivated montmorillonite clay reduces density, widths of microcracks, amount of calcium hydroxide crystals with improved acidic attack and strength of cement composite materials.

4.4.2. Workability. The degree of fresh mixed concrete that exhibits homogeneity within the process of mixed, put, solidified, and finished condition is known as the workability of concrete and is primarily determined by the slump test for concrete [110]. Workability in concrete is greatly increased when cement weight partially replaced by bentonite [110]. Partial replacement of activated bentonite in concrete significantly improves workability [16, 26, 111–113]. However, the water required to produce the paste of standard consistency increases with the rising of bentonite doses. This maybe due to bentonite reduces the amount of hydration product that can occur during the early hydration process [114–116].

Laidani et al. [52] studied the activated bentonite effect in the fresh and hardened properties of self-compacting concrete. The study used activated bentonite substitution of 0%, 5%, 10%, 15%, 20%, 25%, and 30% by the weight of cement with different superplasticizer doses to reach the required slump. As the results of the study indicate, the employment of activated bentonite in concrete increases the workability and flow time of the concrete mixtures compared to the control mix. This is a good beneficiary of activated bentonite in construction industries to have sufficient transportation and working time for concrete casting.

4.5. Effect of Activated Bentonite on the Mechanical Properties of Concrete

4.5.1. Compressive Strength. The development strength rate for blended concrete depends on the latent hydration reaction of cement and pozzolana. Hence, during the hydration reaction pozzolana actively reacts with free calcium hydroxide, resulting in the enhancement of C–S–H and reduceing the porosity of the concrete mix [89]. Thus, in the construction materials, especially in concrete, replacing bentonite increases the strength and durability [51, 54, 117, 118]. Moreover, incorporating activated bentonite in concrete highly improves compressive strength compared to the control mixture [64, 86]. This is because secondary C–S–H gel can be formed by the reaction of silicate of amorphous bentonite with free calcium hydroxide which improves strength for the final hydrated cement matrix [73, 119, 120]. So, the pozzolanic reactivity of activated clay is dependent on their chemical composition, namely SiO_2, Al_2O_3, and Fe_2O_3 content, fineness, and degree of amorphousness/dehydroxylation [99, 121].

Rehman et al. [90] investigated the incorporation of raw grinded and activated bentonite (heated at 800°C for 3 h) in cementing materials. The study used 0%, 10%, 15%, 20%, 25%, 30%, and 35% each respective to raw and activated bentonite replacement. This investigation found employing activated bentonite in all sampled doses improved compressive strength compared to both the control mixture and raw bentonite addition in concrete. However, adding raw grinded bentonite improves compressive strength only at 10% replacement compared to the control mixture. Hence, observed that raw bentonite can replace less amount relative to the replacement of

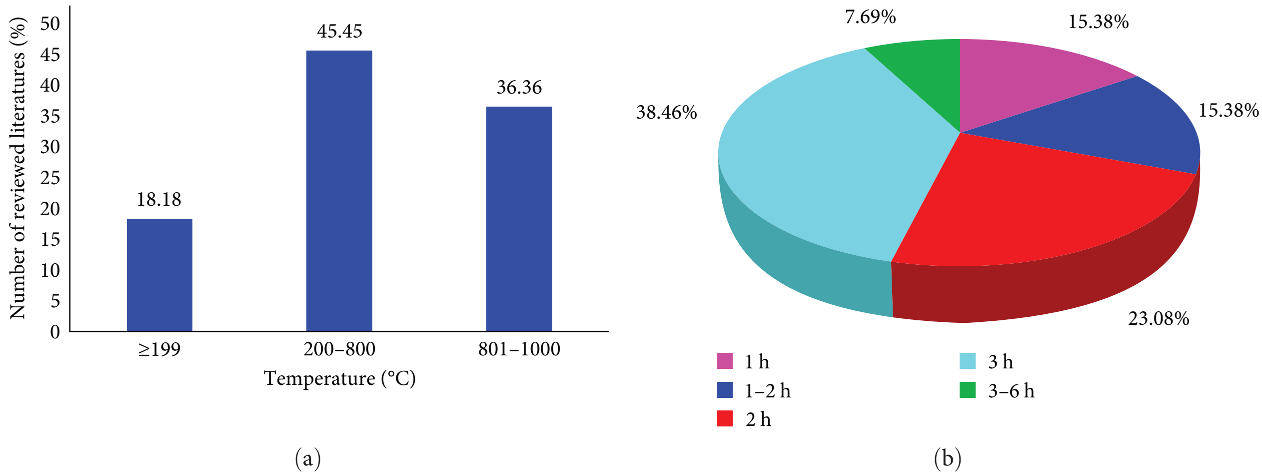

FIGURE 5: Summary from Table 2, bentonite on (a) activation temperatures and (b) activation time in different literatures.

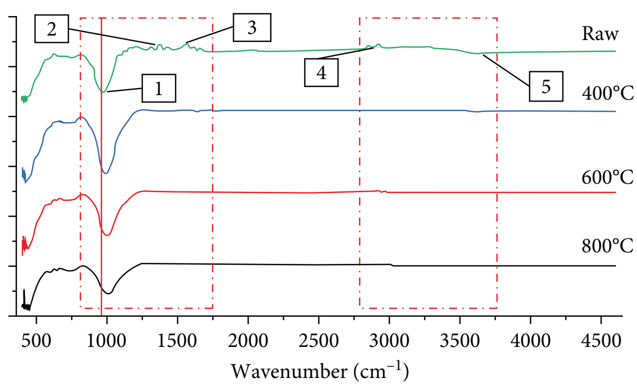

FIGURE 6: The FTIR result on changes occurred by different bentonite activation temperatures by Fode et al. [106] permission Elsevier.

activated bentonite to get improved compressive strength than the control mix. That is mainly due to bentonite being found in a consolidated form means raw bentonite has low pozzolanic reactivity without activation hence, cannot improve much strength without activation. Also, because of raw clay is a crystal that require activation for active pozzolanic reactions that changes to amorphous.

Vijay and Achyutha Kumar Reddy [122] and Reddy and Reddy [123] investigated the optimization of bentonite for the modification of cement mortar at different elevated temperatures. The temperature used for bentonite activation in both studies were 24, 200, 400, 600, and 700, 800°C, respectively. The compressive strength tests undertaken by these studies were for bentonite doses having 0%, 5%, 10%, 15%, 20%, 25%, and 30% to the mass of cement. Hence, the study found that the compressive strength of concrete is highly affected by different activation temperatures, and the effects of activation are mostly observed at 400 and 800°C of bentonite heating, which means at this temperature pozzolancity of bentonite is mostly reactive to consume free calcium hydroxide.

As Table 3 indicates, most authors reported that the replacement of bentonite in concrete improves compressive strength; however, different doses of bentonite taken by many researchers have different optimum replacements. That is due to different researchers used different site bentonite, different bentonite doses, and different water-to-cement ratios. So, as summarized in Figure 7, in general replacement of either raw or activated bentonite from 5% to 20% can improve compressive strength of cementitious materials; however, as shown in Figure 8a, many researchers employed activated bentonite by 15%–20% found optimum compressive strength and specifically, 15% of activated bentonite replacement in concrete is mostly reported by many researchers to get optimum strength. This indicates that activated bentonite substitutes cement to get the best concrete properties compared to the raw bentonite, hence, can more reduce the consumption of cement, decrease environmental pollution, and make economical cement or concrete productions. Besides this, as shown in Figure 8b, improvement of compressive strength was more visible in a concrete age of 7–28 days. This is due to activation enhances the amount of amorphous bentonite that highly consumes portlandite and consequently can improve mortar/concrete compressive strength.

4.5.2. Splitting Tensile Strength. In the concrete mixture, adding bentonite enhances splitting tensile strength compared to the control mixture [54, 55]. Besides these, employing activated bentonite significantly improves splitting tensile strength than using raw bentonite in concrete [90]. That is mainly due to the heat treatment/activation, which can form active pozzolanic reaction, and enhance strength development compared to employing raw bentonite in concrete.

Khandelwal et al. [107] found bentonite employment that activated at a temperature of 800°C significantly increases the splitting tensile strength compared to raw bentonite. Besides these, as shown in Table 4, splitting tensile strength increased by the employment of 5%–15% either raw or activated bentonite by the mass of cement in concrete. Also, as shown in Figure 9a many researchers found adding 15% of bentonite in concrete is the optimum replacement for improving splitting tensile strength. Besides these, Figure 9b summarized the splitting tensile strength enhancement is more reflected between the concrete ages of 7–28 days;

Table 3: The optimum bentonite dose that improved compressive strength found by various authors.

Bentonite dose range (%)	W/C	Curing time (days)	Optimum compressive strength Doses (%)	Optimum compressive strength Ages (days)	Optimum compressive strength Strength at 28 days (MPa)	Control strength at 28 days (MPa)	References
5, 10, 15, 20, 25	0.40	7, 28, 56	15	7, 28, 56	35.00	—	[102]
0, 5, 10, 15	0.40	3, 7, 28	10	28	56.00	47.00	[124]
0, 5, 10, 15, 20	0.50	28, 56, 90	15	28, 56, 90	48.00	42.00	[118]
0, 10, 15, 20, 25, 30, 35	0.50	7, 28, 180	15	7, 28, 180	35.00	34.00	[90]
0, 5, 10, 15, 20	0.48	7, 28	5	7, 28	26.70	24.90	[117]
0, 5, 10, 15, 20	0.47	7, 28	5	7, 28	25.00	20.00	[54]
0, 10, 20, 30	—	28	20	28	55.65	54.50	[122]
0, 20, 25, 30, 40, 50, 60, 70, 80, 100	0.49	7, 28	20	7, 28	24.96	24.00	[41]
0, 5, 10, 15, 20, 25, 30	0.40	3, 7, 28	15	3, 7, 28	58.00	44.00	[78]
0, 5, 10, 15, 20, 25, 30	—	7, 28	20	7, 28	58.38	54.38	[123]
0, 5, 10, 15, 20	0.53	3, 28, 90	15	90	33 at 90 days	32 at 90 days	[47]
0, 5, 10, 15, 20	0.40	7, 28, 56, 90	15	56, 90	63 at 90 days	61 at 90 days	[64]

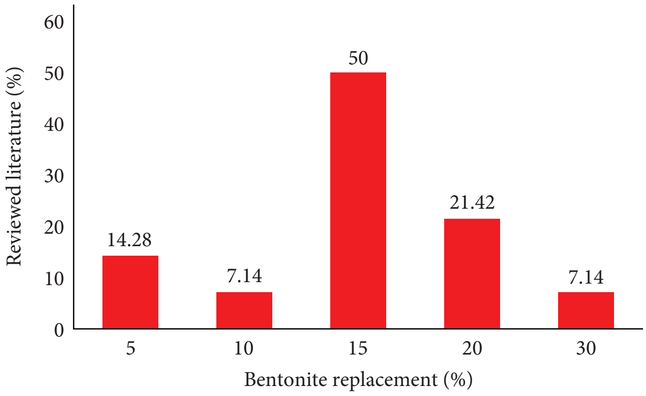

Figure 7: Summary from Table 3 for optimum concrete compressive strength by different bentonite doses (both activated and raw).

however, limited studies on activated bentonite uses for splitting tensile strength.

4.5.3. Flexural Strength. Flexural strength is the strength of materials that represent the maximum bending stress at the failure point. Employing bentonite in concrete significantly improves flexural strength compared to the control mixture [54, 118]. As shown in Table 5, concrete flexural strength increases by employing 5%–30% bentonite in concrete; however, very limited studies used activated bentonite to analyze changes in flexural strength.

4.6. Effect of Activated Bentonite on Durability of Concrete

4.6.1. Water Absorption and Porosity. Water absorption is used to measure the existence of pores in concrete by water penetration, which is harmful to the concrete because numerous foreign chemicals can easily penetrate the concrete through the pores and can react with concrete ingredients that negatively affect its material properties [47, 102]. Hence, employing activated bentonite in the concrete lessens water absorption compared to the control mixture [56, 67]. That is basically, due to activated bentonite can highly react and fill the cementitious materials void, which can mitigate the entrance of water. Also, bentonite blended cement composite materials exhibited better particle packing and durability, through improving the water absorption resistance of mortar and concrete specimens [49]. This is due to the activation of clay increases the pozzolanic reactivity with free lime in cementitious materials [105, 125].

As Masood et al. [47] reported the water absorption is reduced through employing bentonite and significant reduction of water absorption is recorded at 10% and 15% of bentonite replacement in the natural aggregate concrete. Besides these, Figure 10 shows substitution of raw and activated bentonite in concrete significantly lessens water absorption compared to control concrete. However, employing activated bentonite in concrete more reduces water absorption compared to raw bentonite replacement and control concrete mixture. This water absorption reduction is very beneficial for increasing durability of concrete, which is mainly due to microfilling ability of activated bentonite that can fill pores and reduce water penetration [90].

Besides these, the activated bentonite incorporation in concrete mostly facilitates the pore refinement of the cementitious matrix by improving the microstructure of concrete; hence, it is evident in the reduction of pore size of concrete compared with control concrete mixtures [52, 126, 127]. That is mainly because bentonite has less specific gravity and very fine grains compared to Portland cement [4].

4.6.2. Chloride Ion Migration. Chloride ion migration is a crucial and fast technique for the measurement of chloride ion penetration into the concrete. That is mainly important to show the durability and serviceability of reinforced concrete structures by measuring the penetration of chloride ions, which can come from seawater or deicing salts and is one of the accelerators for the corrosion of steel bars embedded in concrete. Hence, employing activated bentonite in concrete and mortar enhances the resistance of chloride penetration compared with the reference concrete [47, 91, 118, 121]. This means employment of activated clay improves durability, which is basically due to lessening calcium hydroxide matrix, decreasing C_3A compound that forms ettringite and extra hydration, which decreases permeability and enhances the densification of cementitious materials, consequently protecting the migration of aggressive agents.

Especially, incorporating bentonite in concrete from 5% to 15% significantly reduces chloride ion migration. That is due to carbonate ion in bentonite indeed to support calcite precipitation, hence sufficient carbonate content causes a significant lessening of postchloride migration [66]. So using bentonite decreases or maintains the carbonation depth observed in the control mixture [91]. The same observation with Nguyen, Khan, and Castel [128] as activated clay significantly improves the chloride ion resistance compared to control mixtures.

4.6.3. Sulfuric Acid Resistance. Wastewater sewers of various industries and storage tanks mainly use concrete; however, degradation of concrete begins as soon as water containing sulfuric acid penetrates the concrete [47]. A similar finding with Habib, Saad, and Abbas [102] found the structure of concrete can deteriorate in the acidic environment when acid mix water penetrates to a concrete matrix, which is due to sulfuric acid reacting with portlandite and aluminate hydrate to form sulfoaluminate products. Hence, sulfoaluminate causes swelling of concrete that can simply deteriorate concrete. So, partially substituting cement by montmorillonite clay (like bentonite) in concrete enhances acidic resistance and decrease dry shrinkage of concrete by improving concrete ductility compared to the reference concrete [118, 129–133]. This is due to the active pozzolanic reaction of activated bentonite form a secondary C–S–H gel that potentially participates in the densification of the hardened cement paste [134] and is also used to reduce the expansion and acidic attack degradation of cement-based materials that may come due to free lime [127, 135–137]. This is because

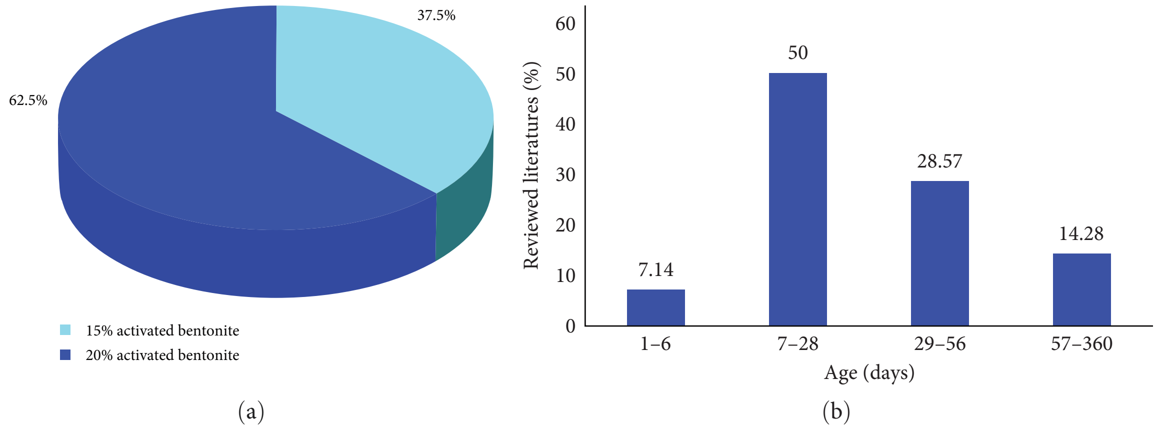

Figure 8: Summary from Table 3: (a) influence of activated bentonite doses and (b) influence of age to achieve optimum concrete compressive strength.

activated clay actively react to consume portlandite forms calcium–silicate–hydrate compound that is used for excellent sulfate resistance [127, 138].

In general, it is observed employing activated bentonite significantly improves water absorption, sulfuric acid attack, and chloride ion migration compared to the control concrete mixture and the addition of raw bentonite in concrete. Hence, can highly enhance the long-term durability of concrete by employing activated bentonite in cementing materials [105].

4.7. Effect of Activated Bentonite on Microstructural Properties of Concrete. The consumption of free calcium hydroxide by pozzolanic reaction to form extra C–S–H gel can be implemented through the employment of pozzolanic materials in concrete [72]. The occurrence of extra C–S–H gel is beneficial to improve the microstructural properties of concrete that can produce a visible densification surrounding natural pozzolana and cementing materials which highly reduce permeability and porosity of concrete matrix, so, can increase concrete durability [48, 49, 139, 140].

Also, the microstructural analysis for the employment of bentonite is important to form a dense concrete composite structure through the hydration of cementitious materials that promotes the gradual release of free water absorbed by bentonite during the curing process and provides a dense microstructure with improved rheological properties of concrete [48]. Also, employing activated bentonite clay modifies the microstructure of cementitious material by lessening $Ca(OH)_2$, increasing C–S–H and C–A–S–H contents, which are mainly used for the refinement of pores in the concrete matrix and densification of cementing materials [4, 132, 141], these are due to using activated clay significantly reduces the formation of $Ca(OH)_2$ during Portland cement hydration and produce large amount of cementitious compounds [142]. Also, Tironi et al. [61] reported on the variation of microstructure by hydration products associated with the pozzolanic reaction mostly dependent on argillaceous minerals that exist in the clay.

Furthermore, the addition of bentonite in the concrete mixture is used to make a denser microstructure compared to the control concrete mixture [143]. Also, as illustrated in Figure 11, activated bentonite highly can make a dense and more agglomerated concrete structure compared to raw bentonite. This is due to the higher pozzolanic reaction in the activated bentonite and the dissolution of montmorillonite that can produce the secondary cementitious minerals C–S–H gel [144]. Also, it is due to the combination of activated clay filler effect, higher surface area than cement, improvement of hydration reaction, and the production of a highly reactive aluminate-rich phase that favors densification of microstructure.

This is because activated bentonite leads to a rise in the volume of the hydrated phase due to it is highly amorphous phase, which results in higher density or agglomeration of the microstructure [107, 145, 146]. Also, activated clay has higher pozzolanic reactivity that owes to the existence of amorphous phases during the activation process [147].

4.8. Assessment of Environmental and Economic Beneficiary. Ordinary Portland cement production mostly requires heating of raw materials at a temperature of 1450°C [148]. However, as most of the reviewed literature indicates, bentonite employment is highly reactive at 800°C activation temperature for high-performance improvement of cement composite materials. Therefore, replacing activated bentonite in cement composite materials, especially in concrete is crucial by reducing around 45% energy consumption and environmental pollution compared to the total use of OPC in cementing materials.

Also, raw material of cement mills, especially, limestone requires much energy, besides the cost of OPC is higher which is reported that 1 kg of bentonite unit price is 85.7% lesser than the same OPC content [80]. So, as most authors found 15%–20% incorporation of activated bentonite significantly enhances strength and durability; moreover, this indicates replacement of activated bentonite can reduce 12%–17% concrete production cost. Generally, employment of activated bentonite in concrete is highly crucial to lessen the CO_2 emissions, energy consumption, and cost-effective concrete production in addition to improving concrete properties.

Table 4: The optimum bentonite dose for high splitting tensile strength by various authors.

Activated bentonite dose range (%)	W/C	Curing time (days)	Optimum splitting tensile strength			Control strength (MPa)	References
			Doses (%)	Ages (days)	Strength (MPa) at 28 days		
0, 5, 10, 15, 20	0.48	7, 28	5	7, 28	26.69	3.47	[117]
0, 5, 10, 15, 20	0.47	7, 28	5	7, 28	25.00	20.00	[54]
0, 10, 15, 20, 25, 30, 35	0.5	7, 28, 180	15	7, 28, 180	2.39	2.35	[90]
0, 5, 10, 15, 20	—	28, 56, 90	15	28, 56, 90	12.00	9.00	[118]
0, 10, 15, 20, 30	—	28	15	28	2.17	2.14	[55]
5, 10, 15, 20, 25	0.40	7, 28, 56	15	7, 28, 56	2.50	—	[102]

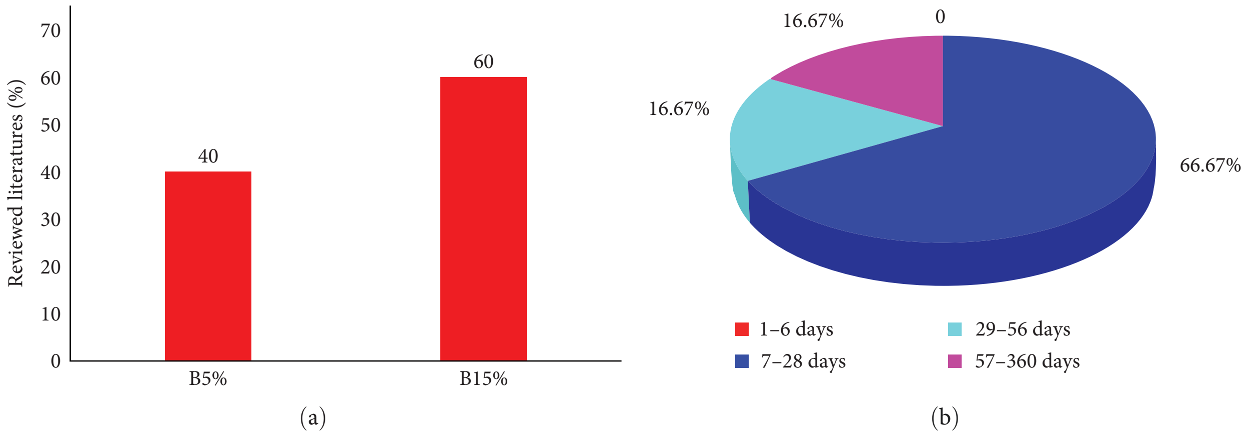

Figure 9: Summary from Table 4 for improved concrete splitting tensile strength (a) influence of bentonite doses for both raw and activated (b) influence of age.

Table 5: The flexural strength improvement by optimum bentonite dose found by various authors.

Activated bentonite dose range (%)	W/C	Curing time (days)	Optimum flexural strength			Control strength (MPa)	References
			Doses (%)	Ages (days)	Strength (MPa)		
0, 5, 10, 15, 20	0.48	7, 28	5	7, 28	25.12	20.12	[117]
0, 5, 10, 15, 20	0.47	7, 28	5	7, 28	3.80	3.50	[54]
0, 5, 10, 15, 20	0.50	28, 56, 90	15	28, 56, 90	19	11	[118]
0, 5, 10, 20	0.485	28, 56	5	56	9.1	8.1	[106]

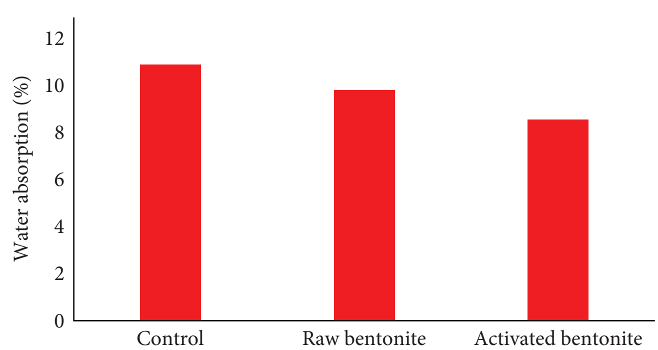

Figure 10: Employment of raw and activated bentonite by 15% on the water absorption of concrete by Rehman et al. [90].

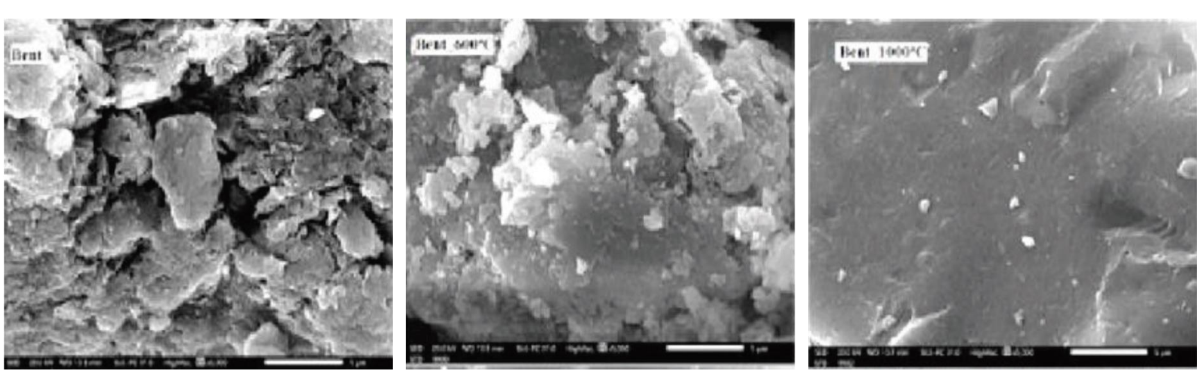

Figure 11: Microstructure of raw and activated bentonite by El Refaey [60].

5. Conclusions

The present study detail reviewed the effect of employing activated bentonite on concrete physical, mechanical, durability, and microstructural properties. Based on various reviewed literature, the following conclusions have been reached:

1. Activation of bentonite significantly improves the pozzolanic reactivity of bentonite and changes crystalline bentonite structure to amorphous.
2. Most researchers used bentonite activation temperature between 201 and 800°C for 3 h activation time to get the best performance in the concrete properties.
3. Also, most of the studies found the employment of activated bentonite in concrete reduces density, porosity, chloride ion migration, and improves the compressive strength, splitting tensile strength, and acidic resistance of concrete.
4. Besides these, many researchers reported replacing activated bentonite by 15%–20% in concrete enhances the concrete mechanical properties, specifically, most literature found using 15% of activated bentonite in concrete gives the optimum compressive and splitting tensile strength that found in the concrete age of 7–28 days.
5. Furthermore, activated bentonite improves the microstructure of concrete by making a denser structure compared to raw bentonite blended concrete.

Generally, for a better beneficiary of bentonite replacement in concrete, the authors encourage the replacement of activated bentonite in concrete mixtures, which also support green environment due to its effective improvement of concrete properties beside reducing ordinary Portland cement production that highly causes environmental pollution.

6. Future Perspective

In the review of most studies, the chemical composition of raw and activated bentonite was tested. However, the content of chloride ions, which exist in bentonite is not comprehensively studied in much literature. However, it can cause steel corrosion in the reinforced concrete structure. Hence, there is a need to consider how the employment of activated bentonite positively or negatively affects the life of reinforced concrete bars related to its chloride ion contents.

Another consideration is that bentonite is abundant material in most countries worldwide; however, there are limited studies on the ways to employ activated bentonite in cementitious materials compared to other pozzolanic materials like kaolin, fly ash, and SiO_2 fume. Especially, there is a limited studies on the effect of the activation rate of bentonite on the physical, mechanical, and durability of concrete.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

No funding was received for this research.

Acknowledgments

The authors are thankful to the partnership for Applied Sciences, Engineering, and Technology (PASET)–Regional Scholarship and Innovation Fund (RSIF) for the support of the current study.

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