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Enhancing Cementitious Materials: A Detailed Review of Bentonite's Role in Optimizing Concrete Performance

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Abstract. Cement manufacturing significantly impacts global CO_2 emissions, contributing around 8% due to its high energy demand and the calcination process in clinker production. To reduce this environmental impact, the industry is exploring sustainable alternatives by integrating supplementary cementitious materials (SCMs), which enhance cement properties and lower its carbon footprint, aligning with sustainable construction goals. One such material is bentonite, a naturally occurring clay with high plasticity and excellent water retention properties. When added to cement mixtures, bentonite improves essential properties like decreasing permeability, enhancing workability, and boosting chemical resistance. Its pozzolanic activity aids in long-term strength development, making it valuable for standard and specialized applications, including geotechnical engineering and waste containment. Bentonite supports environmental sustainability by reducing cement demand thus lowering CO_2 emissions and by increasing durability, which extends the lifespan of structures and cuts down on maintenance costs. This discussion will explore the various environmental and mechanical benefits of bentonite as a sustainable additive in cementitious systems and highlight studies that have demonstrated its effectiveness in promoting more eco-friendly construction practices.

Key words: Cement, CO_2 emissions, Bentonite, environmental sustainability, Pozzolanic activity.

1. Introduction

Cement is one of the most widely used materials in the construction industry, forming the backbone of modern infrastructure. However, cement production is a major contributor to global greenhouse gas emissions, accounting for about 7-8% of global CO_2 emissions(Youn et al., 2019). This significant environmental impact stems from the energy-intensive calcination process and the release of CO_2 from raw materials during clinker production(Wojtacha-Rychter, Kucharski, & Smolinski, 2021). These environmental concerns have driven research towards more sustainable alternatives,including the use of supplementary cementitious materials (SCMs), to reduce the environmental footprint of cement(Miller, 2018)(Hossain, Poon, Dong, & Xuan, 2018).

Among the promising SCMs, pozzolanic additives such as metakaolin, fly ash,bentonite have demonstrated significant potential. These materials not only reduce the reliance on Portland cement but also enhance the durability and resistance of concrete in aggressive environments(Toghroli et al., 2020).

In particular,bentonite, a mineral-rich clay found in nature. has emerged as one of the most promising SCMs. Its fine particle size, high plasticity, and expansive nature contribute significantly to improving the performance of cementitious materials. Bentonite not only enhances workability, but its pozzolanic reactivity also improves the long-term durability and impermeability of concrete, making it ideal for creating more resilient and sustainable structures(Rehman et al., 2019). Moreover, calcined bentonite has been identified for its pozzolanic activity, which contributes to long-term strength development by reacting with calcium hydroxide to form additional cementitious compounds(Trümer, Ludwig, Schellhorn, & Diedel, 2019). When used as a partial replacement for Portland cement, bentonite can significantly improve the overall sustainability of concrete by reducing its carbon footprint while maintaining or even improving its mechanical properties(Noureddine Mesboua, Benyounes, & Benmounah, 2018).Recent studies have also demonstrated the potential of bentonite in optimizing concrete's mechanical performance while mitigating its environmental impact(Ashraf et al., 2022). This review focuses on the role of bentonite as a supplementary material in concrete, examining its effects on key performance parameters such as strength, durability, and sustainability.

2. Materials and Methods

Bentonite, a clay rich in montmorillonite, is widely valued for its high ion-exchange capacity and ability to swell in the presence of water, which makes it an ideal additive in cementitious applications (Barbu et al., 2023). Through treatments like calcinations where it is heated to alter its structural properties bentonite becomes more reactive, enhancing its bonding potential in cement. This treatment improves the clay's mechanical properties, increasing durability and strength in cement-based materials (N. Mesboua et al., 2021).Bentonite's integration into cement results in improved workability, reduced permeability, and enhanced compressive and tensile strengths, which are essential for durable construction projects such as water barriers and structural foundations(Abd Elaty, Azzam, & Eldesoky, 2023).Additionally, the environmental benefits of using bentonite in cement are significant. It reduces the demand for traditional Portland cement, which is energy-intensive to produce, thereby helping to lower carbon emissions associated with construction. Its water-retaining and durability-enhancing properties extend the lifespan of cement-based structures, reducing the need for maintenance and replacement. This durability is particularly valuable in applications like landfill liners and soil stabilization, where extended material lifespan minimizes environmental impact by preventing contamination and reducing structural failures over time (Waqas et al., 2021).

Furthermore, studies have shown that incorporating 10-15% bentonite as a cement replacement can achieve a balance between structural integrity and sustainability, making it an eco-friendly choice for green construction(Farhan Mushtaq et al., 2022). By examining several key studies, I will highlight how innovations in materials science are opening pathways for greener, high-performance building materials. The perspectives gained from this research showcase the transformative role of bentonite–cement mixtures in meeting health and sustainability demands in today's construction. Specifically, this document discusses how incorporating bentonite enhances cement's workability, permeability, and durability, establishing bentonite as a promising sustainable additive. Additionally, current advancements in construction practices underscore the potential for a more resilient, eco-conscious future.

2.1. Exploring Raw Bentonite for Partial Cement Replacement in Concrete Applications

In this section, the different studies related to the replacement of cement with raw bentonite in concrete were examined. It points to the fact that the composition of bentonite directly impacts the performance characteristics of various formulations prepared by researchers, influencing factors such as setting time, strength, and durability:

- Shazim Ali Memon (Memon, Arsalan, Khan, & Lo, 2012) was one of the first researchers to pioneer the use of bentonite as a partial cement replacement in concrete, focusing on Pakistani bentonite. His study aimed to evaluate the effects on concrete properties and its potential as a sustainable alternative.The key variable in his study was the proportion of bentonite (ranging from 3% to 21% by cement weight) used as a replacement, while maintaining constant parameters such as total cementitious material, water-to-cementitious ratio, and aggregate contents.The preparation process involved:

- Drying bentonite for 24 hours at 200 °C to reduce moisture content.
- Grinding the dried material using a Los Angeles machine.
- Sieving the ground bentonite through a No. 200 sieve to obtain a fine powder.

Eight concrete mixes were prepared, including a control mix with no bentonite and seven mixes with varying bentonite replacement levels (3%, 6%, 9%, 12%, 15%, 18%, and 21%). The target compressive strength for all mixes was set at 30 MPa, with a consistent water-to-cementitious ratio (W/C) of 0.55.

- B Praveen Kumar (Kumar, Rao, Achyutha, Reddy, & Kumar, 2017) conducted a study in which cement was partially replaced with calcium bentonite at proportions of 5%, 7.5%, 10%, 12.5%, and 15%, as well as with fly ash in the same respective proportions. The objective was to investigate the potential use of calcium bentonite and fly ash in concrete. The materials used in this experimental work include grade 53 Ordinary Portland Cement (OPC) as the cement source. Calcium bentonite, known for its high dry bonding strength, shear and compressive strength, low permeability, and low compressibility, was selected for replacement. Fly ash was sourced from the Vijayawada thermal power plant. Crushed angular stones of 20 mm diameter were used as coarse aggregates, with a density of 2.86. River sand, free from alkalis and impurities, was employed as fine aggregates for concrete production. Ordinary tap water was used as the mixing water, which plays a crucial role in the concrete's hydration process.

- Li Keke and Leng Yong (Keke et al., 2022) undertook a study to optimize the rheological properties of ultra-high performance concrete (UHPC) by using bentonite as a rheology modifier. The results demonstrate that adding bentonite effectively regulates UHPC's rheological behavior, with significant effects observed as bentonite content increases from 0% to 15% by weight. The UHPC mix in their study incorporates Ordinary Portland Cement (PO 52.5), silica fume, limestone powder and bentonite as cementitious materials. River sand, in two specific particle size ranges, serves as the fine aggregate, while a polycarboxylate superplasticizer (PC-10 with 20% solid content) is added to improve workability. Additionally, 13 mm-long steel fibers are included to enhance mechanical performance.

  The unique mineralogical properties of bentonite play a crucial role in its effectiveness as a rheology modifier. Bentonite, primarily composed of montmorillonite, has a layered silicate structure that supports cation exchange, swelling, adsorption, and thixotropy. These properties arise from the substitution of Al^{3+} and Si^{4+} ions with lower-valence cations, balanced by interlayer cations like Na^{+} and Ca^{2+}. This distinctive structure enables bentonite to significantly influence the rheological properties of UHPC, allowing for improved control and optimization in high-performance applications.

Table 1. Summary of Materials, Bentonite Replacement Levels, and Testing Procedures in Studies

Article	Materials Used	Partial cement replacement rate with bentonite [%]	Tests Conducted
Shazim Ali Memon (Memon et al., 2012)	-Ordinary Portland cement -Bentonite -Fine aggregate -Coarse aggregate -Water	3%, 6%, 9%, 12%, 15%, 18% et 21% by weight of cement	-X-ray diffraction -Laser particle size analyzer -Scanning electron microscope -Consistency -Strength activity index -Compressive strength -Water absorption -Density of fresh concrete -Acid attack test
B Praveen Kumar (Kumar et al., 2017)	-Cement grade 53 -Bentonite -Fly ash -Crushed angular stones -The fine aggregate -Water	5%, 7,5%, 10%, 12,5%, 15% by weight of cement	-The fineness -Consistency -Initial setting time -Final setting time -Compressive strength -Split tensile strength
Li Keke and Leng Yong (Keke et al., 2022)	-Ordinary Portland Cement -Silica fume -Limestone powder -Bentonite -River sand -Superplasticizer -Straight steel fibers	2,5%, 05%, 7,5%, 10%, 12,5%, 15% by weight of cement	-The modified Andreasen and Andersen (MAA) model -Static Yield Stress -Dynamic Yield Stress -Plastic Viscosity -Thixotropy -Hysteresis Loop Area

2.2. Optimizing Concrete Performance with Calcined Bentonite as a Partial Cement Replacement

- In his study, S Ahmad(Ahmad, Barbhuiya, Elahi, & Iqbal, 2011) explored the potential of Pakistani bentonite as a sustainable cement replacement material in mortar and concrete applications. Cement was partially substituted with bentonite at varying levels (0%, 20%, 30%, 40%, and 50% by mass), and the strength and activity indices were evaluated under different conditions: "as-received" at 20°C, and after thermal treatment at 500°C and 900°C. Bentonite samples were processed by grinding them into powder, heating for three hours, and cooling to room temperature before being sieved through a 45 mm mesh. Fine and coarse aggregates were selected to ensure compatibility with typical concrete formulations; the fine aggregate was natural river sand with a fineness modulus of 2.3, while the coarse aggregate was crushed limestone with a maximum particle size of 19 mm and a bulk density of 2.72.

  Mortar cubes of 50 mm were then prepared with a water-to-binder ratio of 0.485, substituting cement with bentonite at the specified levels. Testing encompassed strength and activity indices for both the unheated and heated conditions, as well as assessments of water absorption and sulfate resistance. This investigation contributes to understanding the feasibility and effects of bentonite as a supplementary cementitious material, providing insights into its impact on the mechanical and durability properties of cement-based composites.

- S. Sahith Reddy's (Reddy & Reddy, 2021) study focuses on optimizing the incorporation of calcined bentonite in cement mortar using response surface methodology. This approach evaluates the effect of calcination temperatures (ambient, 700°C, and 800°C) and bentonite levels (0%, 5%, 10%, 15%, 20%, 25%, and 30%) on mortar properties. For the experiments, OPC 53-grade cement was selected, while standard sand compliant with IS650 was used for compressive strength testing. The bentonite, sourced from Tandur in southern India, was calcined in a muffle furnace with a working temperature up to 1200°C. X-ray diffraction (XRD) analysis was performed revealing five mineral crystalline structures. Further microstructural examination was conducted via scanning electron microscopy (SEM).Consistency, initial and final setting times, and workability were assessed according to IS4031 standards, and compressive strength was measured on 189 cement mortar cubes cured for 3, 7, and 28 days using a compression testing machine with a 3000 kN capacity. Strength activity index testing adhered to ASTM C311 standards, while sorptivity was measured per ASTM C1585 – 20. This study provides a systematic approach to understanding how varying bentonite content and calcination conditions influence the mechanical and durability characteristics of cementitious materials.

Table 2. Summary of Bentonite Replacement Levels, Calcination Temperatures, and Testing Methods.

Article	Materials Used	Partial cement replacement rate with bentonite [%]	Calcination temperature and duration	Tests Conducted
S Ahmad (Ahmad et al., 2011)	-Cement OPC -Bentonite -Fine Aggregate -Coarse Aggregate	0%, 20%, 30%, 40% And 50% By Weight Of Cement	500º And 900ºc For 3 H	-SEM -Strength Activity Index -Water Absorption -Sulphate Attack -Workability -Compressive Strength
S. Sahith Reddy(Reddy & Reddy, 2021)	-Cement OPC 53 Grade -Stand Sand -Bentonite	0%, 5%, 10%, 15%, 20%, 25% And 30% By Weight Of Cement	Room Temperature, 700°C And 800°C.	-XRD, SEM -Initial and Final Setting Time -Workability -Compressive Strength -Strength Activity Index
Muhammad Ashraf (Ashraf et al., 2022)	-Cement OPC -Coarse and Fine aggregate. -Selica Fume -Calcined Bentonite	0 %, 7,5 %, 15 % And 22,5 %. By Weight Of Cement	1200 °C For 2 H	-EDX ,TGA, SEM -Sulfate Resistance, -Rapid Chloride Permeability Test (Rcpt) -Compressive Strength

- The research by Muhammad Ashraf (Ashraf et al., 2022) examines the potential of bentonite clay and its synergistic interaction with silica fume as partial replacements for cement, focusing on their effects on the strength, durability, and microstructure of concrete. Five concrete mixes were developed with bentonite levels at 0%, 7.5%, 15%, and 22.5% by weight, while maintaining a constant 10% replacement with silica fume. The materials used included Ordinary Portland Cement (Type I), locally available crushed stones as coarse aggregate (maximum size of 20 mm), and natural river sand as fine aggregate. Silica fume served as the supplementary cementitious material, while calcined bentonite clay (BC) was sourced from a riverbed and treated at 1200°C for two hours to enhance its reactivity.For the mix designs, a control mix (CTR) contained no cement replacement, while a second control mix (SCTR) included only 10% silica fume. The bentonite-silica fume combinations 7.5BSC, 15BSC, and 22.5BSC featured increasing levels of bentonite. To assess sulfate resistance, cylindrical specimens were cured for 28 days, dried at 100°C for 24 hours, and then weighed. These samples underwent 15 cycles of immersion in a 5% magnesium sulfate ($MgSO_4$) solution followed by drying. Weight loss between initial and final cycles indicated the material's resistance to sulfate attack, providing insights into the durability improvements achieved with bentonite and silica fume in cementitious materials.

3. Conclusions

Using raw bentonite as a partial cement replacement improves key properties of mortars and concrete, such as durability, workability, and compressive strength. Studies show that the pozzolanic activity of raw bentonite enhances mechanical and physical properties, making it an eco-friendly alternative for construction materials.

- Studies consistently highlight the sustainable benefits of using raw bentonite and other industrial byproducts as partial cement replacements in concrete. For example, Shazim Ali Memon's(Memon et al., 2012) research demonstrates that incorporating bentonite improves the environmental profile of concrete while maintaining high performance. His findings showed that although bentonite reduces workability, density, and water absorption, it enhances the compressive strength at 28 and 56 days, outperforming conventional mixes and increasing resistance to acid attack. This confirms that bentonite use in concrete is both economical and effective in meeting strength requirements, supporting more sustainable construction practices. Similarly, B. Praveen Kumar's(Kumar et al., 2017) study supports the use of Industrial Byproduct Fly Ash Cement (IBFC) as a cement replacement, showing that a 15% substitution rate optimizes both compressive and tensile strength across various ages, from 3 to 28 days. This not only underscores IBFC's potential in enhancing concrete durability but also establishes it as a viable option for improving performance. Further, Li Keke and Leng Yong's (Keke et al., 2022)study confirms that bentonite additions significantly improve the rheological properties of Ultra-High Performance Concrete (UHPC). For instance, increasing bentonite content up to 10% optimizes fiber distribution and reduces matrix defects, enhancing flexural strength by 60% and yielding a stronger, denser UHPC composite through moderated hydration. Together, these studies illustrate the benefits of using alternative materials to improve concrete's strength, durability, and sustainability.
- Calcined bentonite often outperforms its raw form due to heat treatment, which boosts its reactivity and leads to greater strength and durability in construction materials. Studies highlight calcined bentonite as a sustainable option that enhances performance in the construction industry.
- The studies conducted by Muhammad Ashraf ,S. Ahmad and Sahith Reddy (Ahmad et al., 2011; Ashraf et al., 2022; Reddy & Reddy, 2021) confirm the benefits of using calcinate

bentonite and other supplementary materials in concrete, enhancing both its performance and environmental impact. For example, S. Ahmad's(Ahmad et al., 2011) research reveals that while bentonite's activity index met specifications, water absorption decreased in mortars with up to 30% bentonite before increasing again at higher bentonite levels. Additionally, in sulfate-rich environments (5% Na_2SO_4 and 2% $MgSO_4$), mortars containing 30% bentonite achieved the highest compressive strength, underscoring bentonite's resilience in sulfate exposure. Similarly, Sahith Reddy's(Reddy & Reddy, 2021) findings indicate that increasing the proportion of calcined bentonite reduced workability, with a 20% substitution of bentonite calcined at 800°C achieving the highest compressive strength due to effective pore filling from smaller bentonite particles. This substitution also improved strength activity, showcasing bentonite's pozzolanic properties. Muhammad Ashraf's(Ashraf et al., 2022) study further supports bentonite's potential, noting that mixes with silica fume (SF) displayed high early-age compressive strength. However, bentonite-based concrete requires extended curing to reach optimal strength. His findings suggest that a blend of bentonite and silica fume results in a denser microstructure, with improved resistance to chloride penetration. Environmental analysis reveals that incorporating 22.5% bentonite can reduce carbon emissions by 23% compared to conventional concrete, emphasizing its value in sustainable construction practices. Together, these results reinforce the potential of bentonite and related materials to enhance concrete durability, strength, and environmental sustainability.

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