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Performance of Low-cost Concrete Using Bentonite Clay as a Partial Replacement with Cement

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ABSTRACT

Concrete is produced from millions of tons of Cement, which emits a significant amount of carbon dioxide from cement mills and contributes to global warming. Therefore, it is important to seek out less expensive and more environmentally friendly substitutes for OPC. While various substitutes are available, such as recycled glass, marble, silica fume fly ash, or agricultural waste like rice husks or wheat straw, the performance of concrete is significantly affected when bentonite is used as a replacement for Cement. This study aims to evaluate Jhelum bentonite, which is located at 32° 56′ north and 73° 44′ east longitude, as a replacement for Cement in different ratios (0:100, 10:90, 20:80, 30:70, and 40:60) to improve the durability of the system as more bentonite is used to replace conventional Portland cement, the workability, density, and water absorption of the new concrete all decrease. Compressive Strength, Tensile Strength, and flexural strength of blocks and cylinders were tested after being cured for 7 and 28 days. Analysis of these strength tests revealed that the mixes containing bentonite were weaker after 7 days compared to 28 days, and the Strength of blocks was reasonable compared to cylinders.

1. Introduction

Concrete is extensively utilized in construction worldwide due to its great stability and compressive Strength. (Isler, 2012; Sankh et al., 2014; Svintsov et al., 2020). In the building sector, concrete is a widely utilized material owing to its unique qualities, including affordability, great Strength, durability, ease of availability of its component materials, and simplicity in shaping into desired shapes. The main ingredient in concrete that holds aggregates together is ordinary Portland cement (OPC)(Al Bakri et al., 2011). Since concrete building now uses a significant amount of natural resources, it is considered an unsustainable process(Isler, 2012; Taskin et al., 2020). Sustainable development is a kind of analysis whose primary goal is to raise living standards while simultaneously catering to the needs of coming generations. Its goals include, among other things, the provision

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of essentials, the improvement of living conditions, and the promotion of the conservation and management of ecological systems.

Recycling a broad range of waste products from industrial operations is fast growing worldwide in response to growing public concerns about environmental degradation, the depletion of fossil fuels, and sustainable development(Smith et al., 2002). Cement producers have difficulties lowering carbon dioxide emissions, increasing energy costs, and providing raw resources (in particular, guaranteeing a consistent supply of high-quality raw materials)(Benhelal et al., 2013). Overall, harmful pollutants, including carbon dioxide, are emitted in large amounts during the manufacturing of OPC, a crucial component of concrete(Jani & Hogland, 2014).

The Global Cement Association estimates that Pakistan produces 85 million tons of cement yearly, or about 2% of global production. Cement prices have increased by more than 150 percent in the past ten years(Mirza et al., 2009). Building activities have witnessed quick expansion globally due to the rising need for infrastructure brought on by the global rise in population and urbanization over the last two decades. Cement production is thus increasing to meet the growing demand for infrastructure. Due to greenhouse gas (GHG) emissions, cement manufacturing seriously harms the environment. Consequently, there are significant environmental issues with the manufacture of OPC(Lei et al., 2011).

Researchers advise adding supplemental cementitious materials (SCMs) to concrete construction as a partial or complete replacement for OPC to alleviate these worries (Mehta, 2004). To improve concrete's properties while reducing CO2 emissions and the need for natural resources, supplemental cementitious materials (SCMs) may be employed. In comparison to the control mix, carbon emissions may be reduced by around 23% by adding BC (Bentonite Clay) and SF (Silica Fume). In this regard, the merits and proper use of clays as a cement alternative in concrete have been studied for decades(Akbar et al., 2013). In the past, various substances, such as polypropylene, were employed to enhance the general behavior of concrete subjected to high temperatures(Shihada, 2011), fibers, carbon nanotubes(Baloch et al., 2018), and metakaolin(Andrejkovičová et al., 2015). However, these resources are either too expensive or not easily accessible. Therefore, Bentonite is used in this study to substitute Cement in concrete partially. Bentonite is readily available in Pakistan's Jahangira Khyber Pakhtunkhwa (Farhan Mushtaq et al., 2022). Sources claim that one of the bentonite clays from Karak, Pakistan, is dispersed across an area of 18 km^2 (Ahmad & Siddiqi, 1995). The chemical reaction that takes place between bentonite clay and sand results in the production of essential magnesium (MgO) and potassium (K2O) oxides, both of which are known to boost Strength (Kaur et al., 2012). Bentonite clay has also been claimed to be able to partially replace Cement in the creation of concrete with superior mechanical qualities. (Mirza et al., 2009).The previous research shows the significant importance of Bentonite with different proportions.

Priyanka et al. (2018) substituted 5%, 10%, 15%, and 20% bentonite clay for the Cement. Cement with a grade of 53 KCP was utilized. Cement is put through all relevant testing, including checks for fineness, consistency, beginning and final setting times, specific gravity, and compressive Strength. A sieve analysis is done for both fine and coarse aggregate. They used a 1:1.62:2.99 mix design with a 0.47 w/c ratio after 7 and 28 days of curing. Standard tests are done on concrete to assess its split tensile Strength for cylinders, compression strength for cubes, and flexural Strength for beams. According to their findings, substituting 74.5 percent of the bentonite clay in cement yielded suitable outcomes regarding Strength, cost, and the recommended cement replacement ratio.

Similarly, Ahmad et al. (2021) found that wheat straw ash and bentonite clay were used as part of the cement in self-compacting concrete (SSC). Bentonite clay and wheat straw ash were added to the cement at 0%, 5.0%, 10%, 15%, and 20%, respectively. Hardened SCC's compressive and split tensile strengths will likely rise with the addition of bentonite clay and wheat straw ash up to 10% and 15% of the weight of the cement, respectively.

To examine the prospective usage of Bentonite and determine how it may affect different aspects of the Strength of ordinary Portland concrete (OPC). Karthikeyan et al. (2015) From the findings, it can be deduced that, as compared to conventional samples, Bentonite produced low early compression strength and good later compression strength. Even though the proportions of the cementing materials varied, the critical variable percentage of bentonite in the natural and intercalated forms was the same in the bentonite samples: 0, 25, 30, and 35% by weight of Cement for a mix of M25. At 30%, the clay replacement achieved compressive, split tensile, and flexural strengths of 19.55%, 2.72%, and 8.07% over the course of 28 days.

To partly substitute cement, Ashraf et al. (2022) examined the impact of bentonite clay and silica fume on the durability, Strength, and microstructure of concrete. While five different mixtures were developed, each of which substituted varied amounts of BC with Cement at 0%, 7.5%, 15%, and 22.5% (by weight), SF was retained at a replacement level of 10%. Each of these mixes substituted various percentages of BC for Cement at 0%, 7.5%, 15%, and 22.5% (by weight). SF was maintained at a replacement level of 10% while these mixes were formed. The results of these experiments are shown below. The experimental findings demonstrated that the addition of SF increased compressive Strength, reaching a maximum value of 43.09 MPa as curing time increased. For the bentonite-based concrete to reach high Strength, further curing is needed. All of the examined specimens' ultrasonic pulse velocities, which are greater than 3.5 km/s, fall within the range of "excellent" grade concrete.

This research aims to examine concrete's compressive, splitting tensile, and flexural Strength and workability at varied cement-bentonite clay replacement amounts. The results were then compared with control samples that underwent room temperature testing. To determine how Cement's composition affects concrete performance, XRF analysis of both cement and bentonite clay was performed.

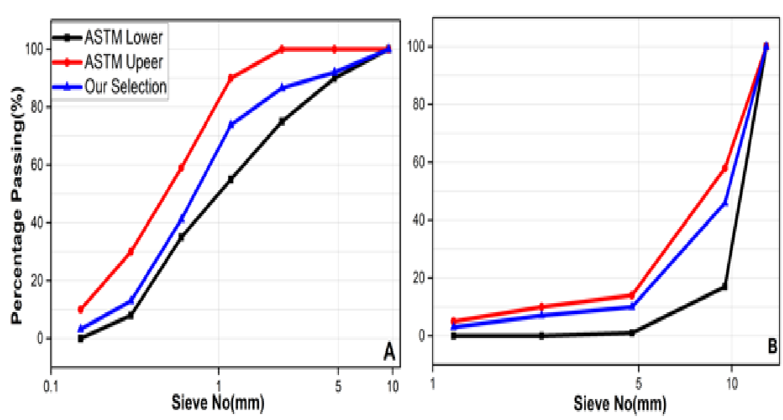
2. Experimental study

2.1 Materials

Cement collected According to ASTM C-150, the Cement is type 1 OPC, while fine and coarse aggregates were sourced from Margalla hills. Smectitic clay makes up most of the layers that make up bentonites, which can range in thickness. These smectite-rich strata were formed when volcanic glass underwent devitrification and modification in an aqueous environment. There have been reports of deposits of bentonite around the country. The bentonite clay used in this study comes from Jehlum, Pakistan. Due to a workability issue, we utilized the Chemrite 303 SP super-plasticizer from Emporium Company in Islamabad.

2.2 Methodology of research

Sand, gravel, and crushed rocks were utilized to standardize the construction material typically employed as a filler ingredient in concrete. Standardization tests on coarse aggregate were carried out to assure the quality of the material that should be used in concrete casting. All tests were performed according to ASTM standards. The Sieve Analysis curve of coarse and fine aggregates more precisely lies within ASTM limits, as shown in Table 1. Concrete was cast using blocks and cylinders acting as controls and uncontrolled samples for 7 and 28-day curing intervals, respectively. The curing was done in line with ASTM standard C192(ASTM, C192/C192M., 2007)). To evaluate the performance of the samples, slump tests, compressive strength tests, flexural tests, and split tensile tests were carried out. Densities of the controls and Bentonite-substituted samples were also calculated.



(A) Fine aggregates (B) Coarse aggregates

Fig. 1 Sieve analysis

3. Results and discussion

3.1 Test performed on fine and coarse aggregates

The aggregates' physical properties considerably impact how they behave in concrete after it has been mixed.

Concrete with more vital aggregates is capable of withstanding larger forces. The findings of the physical and mechanical property tests on the coarse and fine aggregates used in this research study are shown in Table 1. Fine and coarse aggregates have specific gravities of 2.61 and 2.81, respectively. These numbers are within the range of aggregates with typical weights for particular gravities. Aggregates that are crushed from their natural source may pass through rocks because they have pores.

The volume of aggregates and the continuity of the pore determine the quantity and pace of penetration. This is crucial because the amount of water allowed in the concrete mix, which governs the workability and Strength of concrete, is affected by aggregate porosity and water absorption(ASTM, C192/C192M., 2007; Okpala, 1990; Arumugam & Ramamurthy, 1996). Depending on their structure and texture, aggregates may absorb more or less water. While flaky and elongated particles have greater surface area and thus absorb more water, well-rounded aggregates require less water to be workable since they have less surface area (British Standards, 1992; Mohammadinia et al., 2019).

Table 1 – Physical properties of aggregates.

Tests	Specification	Result	Limits
Flakiness Index	ASTM D 4791(Jamkar & Rao, 2004)	12.90%	≤15%
Elongation Index	ASTM D 4791(Siddiqi et al., 2013)	3.58%	≤15%
Aggregate Absorption	ASTM C127(Fine)(Padmini et al., 2002)	2.1%	≤3%
	ASTM C127(Coarse)(Padmini et al., 2002)	0.5%	≤3%
Impact Value	BS 812(Adom-Asamoah & Afrifa, 2010)	19.00%	≤30%
Specific Gravity	ASTM C128(fine)(Black, 1986)	2.61%	-
	ASTM C127(Coarse)(Black, 1986)	2.81%	-
LOS Angles Abrasion	ASTM C131(Umar et al., 2020)	22.00%	≤45%

3.2 Cement testing

For the project, regular Portland cement that complied with BS12:1989 was utilized. The physical characteristics of Cement have been determined using criteria including fineness, consistency, specific gravity, and initial and final setting times. At the same time, X-ray fluorescence (XRF) tests were conducted at the Fecto Cement Factory Sanjani in Islamabad to ascertain the composition of Cement. Table 2 displays the chemical and physical characteristics of Cement.

Table 2 – Physical and chemical properties of cement.

Physical Properties		Chemical Properties	
Fitness	91%	Silica, SiO_2	52.72%
Consistency	40%	Lime, Ca0	31.38%
Specific Gravity	3.2	Fe2o3 and Al2O_3	6.79%
Initial setting time	32min	Magnesia (Mgo)	2.02%
Final Setting Time	340min	Sulpher Trioxide (SO_3)	3.14%
Soundness	1.55mm	Loss on Ignition	2.70%
-	-	Insoluble residue	1.25%

3.3 Test on bentonite

Sieve analysis was performed initially to characterize the collected bentonite, followed by tests for Gs, Atterbergs limits, Swell potential, Compaction, and Direct shear Test, and particle size analysis. After the profile of the bentonite was established, Cement was used in its place. The initial physical tests conducted on bentonite are displayed in Table 3

Table 4 illustrates the chemical characteristics of bentonite as measured by XRF. X-ray fluorescence spectroscopy (s) can be used to analyze the elemental composition of bentonite clay, including critical elements like aluminum, silicon, and calcium. Notably, XRF results alone may not provide a comprehensive understanding of the effects of bentonite clay on the Strength of concrete. Because of its pozzolanic properties, which may make concrete more durable and robust, bentonite clay is frequently employed as a mineral additive in concrete. Concrete can be boosted regarding workability, water permeability, and compressive Strength by adding bentonite clay.

Table 3 – Physical properties of bentonite clay.

Properties of Bentonite	Values	Standards
Sieve Analysis	92.80%	ASTM D_7928 (Hussain, 2017)
The specific gravity of soil	2.74	ASTM_D854 (ASTM, D854., 2010))
Liquid limit	54.36%	ASTM_D4318 (ASTM, D4318., 2010))
Plastic Limit	23%	ASTM_D4318 (ASTM, D4318., 2010)
Plasticity Index	31.36%	ASTM_D4318 (ASTM, D4318., 2010)
Sand	9.20%	ASTM_D6913 (ASTM, D6913 /D6913M., 2017)
Silt	12.80%	ASTM_D6913 (ASTM, D6913 /D6913M., 2017)
Clay	78%	ASTM_D6913 (ASTM, D6913 /D6913M., 2017)
Modified Free swell Index	48%	ASTM D5890-19 (Niu et al., 2022)
Swell Potential	High	ASTM_D4546 (Signes et al., 2016)
USCS Classification	CH	ASTM_D2487 (ASTM, D698 ., 2012)
Maximum Dry Density	1.65 g/cc	ASTM_D698 (ASTM, D698., 2012)
Optimum Moisture Content	31.43%	ASTM_D698 (ASTsM, D698., 2012)
Cohesion	22 kPa	ASTM_D6528 (Alshameri et al., 2017)
Angle of Internal Friction	18.74°	ASTM_D6528 (Alshameri et al., 2017)
Particle Size	4.41	-
Blains Fines	4800 cm^2/g	-

Various elements may modify concrete Strength, such as the quality and amount of the ingredients used, the ratio of water to cement, and the curing conditions. Consequently, the effect of the XRF findings of bentonite clay on the Strength of concrete may depend on these parameters in addition to the clay's unique characteristics, which indicate that bentonite is predominantly composed of silicon dioxide ($SiO2$). In contrast, cement contains roughly equal amounts of Silica. According to (Mazloom et al., 2004), the workability of concrete decreases as silica content increases in the mix. In addition, Silica significantly increases the compressive Strength, tensile Strength, and flexural Strength of concrete (Bhikshma et al., 2009).

Table 4 – Chemical properties of bentonite clay (XRF).

Compounds	Percentages
SiO_2	51.12%
Al_2O_3	22.45%
FE_2O_3	7.13%
MgO	6.80%
CaO	1.45%
K_2O	2.17%
Na_2O	0.53%
TiO_2	1.32%
P_2O_5	0.40%
LOI	6.63%

4. Tests on concrete

4.1 Effect of bentonite on workability

Following ASTM C125-15, the slump test was conducted on concrete with varying amounts of bentonite substituted for cement in each mix design. The experiment aimed to determine if it would be possible to set the concrete in a mold and how much the rodding temperature would increase subsequently. The findings from Figure 2 show that as the bentonite content of the mixture increased, slump values reduced, indicating that workability was reduced. The moderate particle size and comparatively large surface area of bentonite particles have diminished the droop value. Consequently, bentonite-made concrete is less practicable than the control mix with the same water-binder ratio. In addition, Silica significantly increases the compressive Strength, tensile Strength, and flexural Strength of concrete (Farhan Mushtaq et al., 2022).

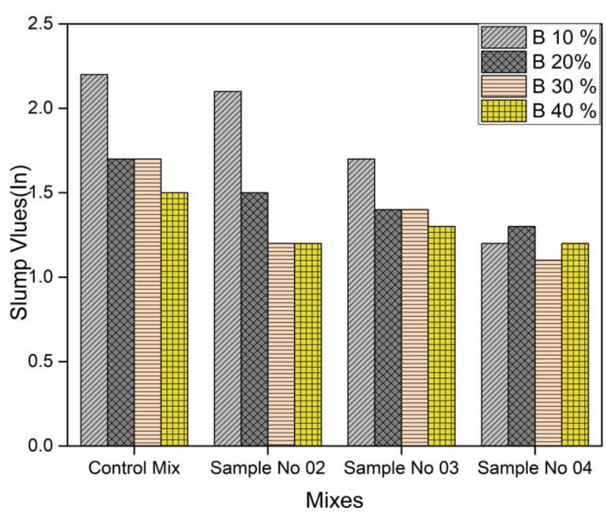


Fig. 2 Workability of control and Bentonite mixes

4.2 Temperature measurement of fresh concrete and mix materials

Measuring the temperature is essential before casting, pouring, or setting concrete. The hydration process will cause the freshly mixed concrete to assess if the temperature is above 20 degrees. We have no control over this process once it has started. Thus, our sample will be set. All of the materials we employed in the mixture, including the Cement, sand, crushed stone, and water-bentonite mix temperatures, were measured over 10 minutes. it is also essential to monitor the concrete temperature during the curing process. This can help ensure that the concrete achieves the required Strength and durability.

Table 5 – Temperature measurement of materials.

Materials	Temperature
Coarse Aggregate Temperature:	17.1 C
Fine Aggregate Temperature:	18.2C
Water Temperature	16.7C
Bentonite Temperature	20.5C
Mix Temp. at every 15-minute interval	22 C 24 C
Concrete Mix Temperature:	21 C

4.3 Effect of bentonite on fresh density of concrete

Figure 3 provides a graphical representation of the fresh density of various mixtures. It is clear that the control mix (CM) has the most considerable thickness, or that is 2470 kg/m3 when it is fresh. When Bentonite was employed in place of Cement, the density decreased; the higher the amount of bentonite, the lower the density. This is valid since specific gravity is what determines density. Because cement has a higher specific gravity than bentonite, the CM mix has the maximum density.

4.4 Effect of bentonite on water absorption

The findings from the water absorption test are visually shown in Figure 3. According to test results, water absorption decreased when more Bentonite was used instead of OPC. Because bentonite has smaller particles than Cement, it may minimize porosity and pack the binder phase, which is what caused the drop. As a result, this increases the mixes' Strength (Shannag, 2000).

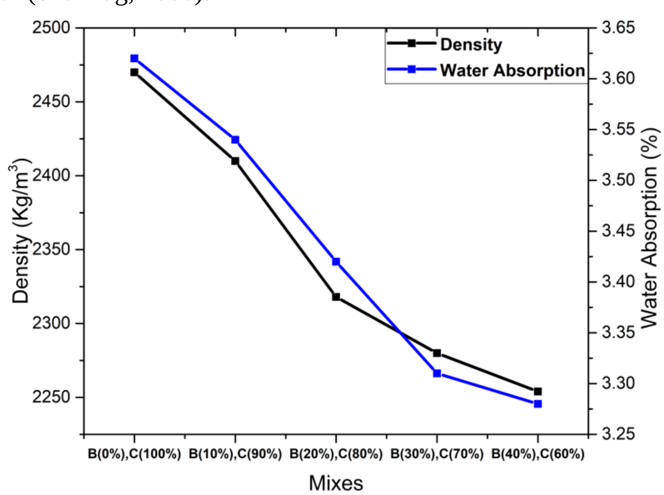


Fig. 3 Density and water absorption of concrete blended with BC

4.5 Effect of bentonite on compressive strength

ASTM 39 was followed in conducting the test (Alwesabi et al., 2022) to determine the concrete's compressive Strength. Tables 6(for blocks) and 7 (for cylinders) show the compressive strengths of Bentonite concrete and OPC concrete at the ages of 7 and 28 days, respectively. Due to Silica's high pozzolanic nature and capacity to fill voids, concrete's Strength has significantly increased. Bentonite-containing concrete had a lower 7-day compressive strength than the 100% OPC-containing control mix (CM). As the replacement level in regular Portland cement was raised, the Strength gradually fell.

In contrast, the compressive strength of bentonite-containing concrete declined as the substitution level rose after 28 days, but at a much slower rate than it did for the 7-day-cured sample. As a result, these values can be regarded as enough for affordable construction. Second, the decrease in strengths is primarily due to two factors. The mix design was kept (1:1.5:3) because it contains more Cement than other mixes, such as 1:2:4, 1:4:8, etc.

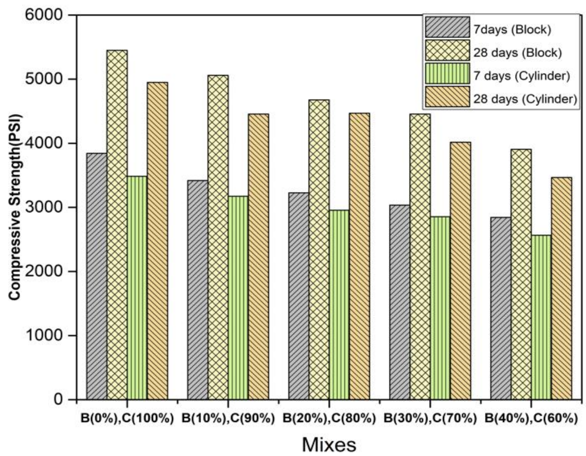


Fig. 4 Comparison of compressive strengths of CM and BM

4.6 Effect of bentonite on tensile strength

The test was carried out under ASTM C496 (ASTM, C496/C496M., 2017)) to obtain the required tensile strength of concrete. The highest tensile Strength of concrete was 489.2 PSI, which is greater than the tensile Strength for 7 days but lower than for 28 days. In comparison to 100% OPC-containing concrete, which served as the control mix, bentonite-containing concrete exhibited a decreased 7-day tensile strength.

The Strength significantly decreased when the replacement amount in regular Portland cement was increased.

On the other hand, as the substitution level grew, the tensile Strength of bentonite-containing concrete dropped after 28 days, but at a far lower rate than it did for a sample that had been cured for only 7 days. Consequently, these values may be deemed enough for low-cost construction.

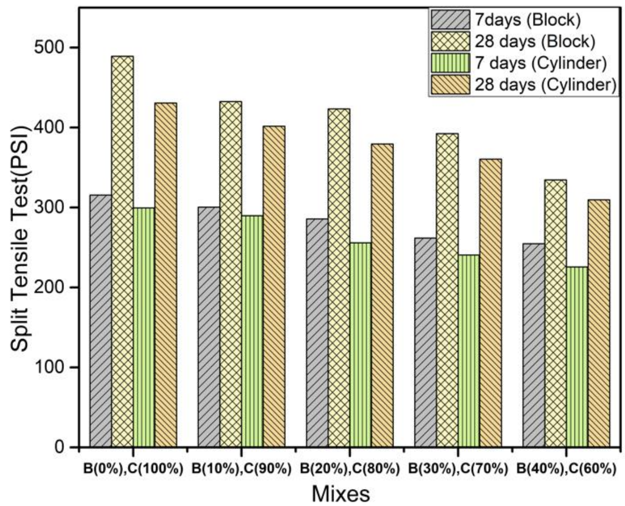


Fig. 5 Comparison of tensile strengths of CM and BM

4.7 Effect of bentonite on flexural strength

One way to assess the tensile Strength of concrete is by its flexural Strength. A concrete beam's ability to withstand failure due to bending is measured by this property. A concrete beam with a span length of 700 mm that is 150 x 150 mm is loaded to determine the value. Beam flexure strengths were also decreased when bentonite was utilized instead of regular Cement in the concrete beams. The cause is due to bentonite's having a comparable pozzolanic bonding to Cement. Concrete had a 28-day flexural strength that was greater than 7 days. So, the Cement Flexural Test results for Bentonite Concrete may be examined in Figure 5. We may give a safer and structurally more affordable building or structural component by offering bentonite flexural members (to fulfill the design criteria).

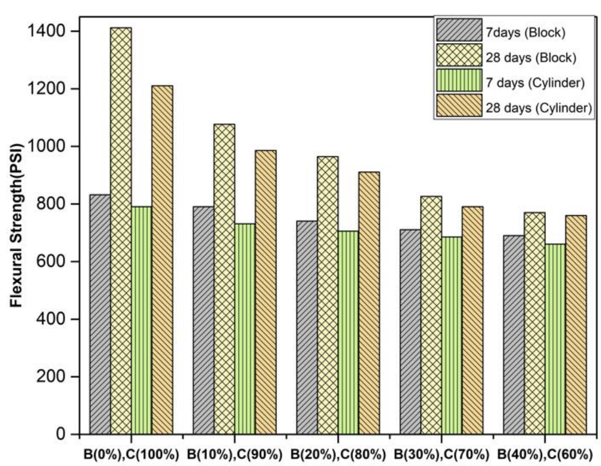


Fig. 6 Comparison of flexural strengths of CM and BM

4.8 Strength reduction due to geometry

In this regard, the block and cylinder strengths decrease for control mixes, and bentonite sample replacement for Cement is also assessed. Additionally, it should be emphasized that the geometry, or more specifically, the cross-section geometry, of the specimen used for observation affects the stability and Strength of concrete. Blocks resist loads applied along their common axis because their hard edges are typically at a standard angle of 90 degrees (from all sides). Contrarily, when subjected to airborne weight, the cylinder's circular cross-section renders it less stable than cuboids or blocks. Consequently, for 7 days and 28 days, respectively, concrete's compressive Strength, split tensile Strength, and flexural Strength decreased for cylinders in contrast to blocks with high strength values, as shown in Tables 6 and 7. The cross-sectional design of the blocks increases their ability to withstand or support vertical loading.

Table 6 – Compressive strength test, flexural and tensile strength test of concrete for control mixes and bentonite mixes for blocks at 7 days and 28 days.

Bentonite (%)	**0**	**10**	**20**	**30**	**40**
Cement (%)	**100**	**90**	**80**	**70**	**60**
Compressive Strength at 7 days	3484.45	3173.32	2956.34	2853.85	2565.23
Compressive Strength at 28 days	4950.21	4455.78	4469.32	4016.52	3465.81
Flexural Strength at 7 days	790.43	731	705.78	685.56	660.45
Flexural Strength at 28 days	1210.65	985.76	910.65	790.65	759.87
Tensile Strength at 7 days	299.65	289.76	255.87	240.65	225.76
Tensile Strength at 28 days	430.76	401.75	379.49	360.54	309.65

Table 7 – Compressive strength test, flexural and tensile strength test of concrete for control mixes and bentonite mixes for blocks at 7 days and 28 days.

Bentonite (%)	**0**	**10**	**20**	**30**	**40**
Cement (%)	**100**	**90**	**80**	**70**	**60**
Compressive Strength at 7 days	3842.71	3419.38	3227.28	3035.18	2843.08
Compressive Strength at 28	5450.24	5060.68	4675.67	4455.49	3905.8
Flexural Strength at 7 days	832	790.45	740.64	710.78	690.34
Flexural Strength at 28 days	1412	1076.83	964.43	826.45	769.94
Tensile Strength at 7 days	315.67	300.56	285.67	261.84	254.76
Tensile Strength at 28 days	489.2	432.5	423.4	392.5	334.6

Fig. 7 Blocks and Cylinder specimens for Compressive, Tensile, and Flexural strength test

4.9 Sustainable factor

Bentonite is generally considered more sustainable than Cement because it is a naturally occurring clay material abundant in many world regions. It is typically obtained through surface mining, which has a lower environmental impact than the energy-intensive process used to produce Cement. Cement production results in CO2 emission. In addition, the production of Cement requires significant amounts of energy and raw materials, including limestone, clay, and sand.

Bentonite, on the other hand, is typically mined from surface deposits and requires minimal processing. It is also biodegradable and can be recycled, making it a more sustainable option for many applications. However, it is worth noting that the Sustainability of any material depends on a range of factors, including its source, production process, transportation, and disposal. It is also essential to consider the specific application and the environmental impact of the entire supply chain, including the extraction, processing, and transportation of raw materials and the disposal of waste products. Ultimately, the choice between Cement and bentonite will depend on the specific

5. Conclusions

The addition of bentonite clay to concrete mixes can improve the material's durability and mechanical qualities while lowering manufacturing costs.

The compressive strength, splitting tensile strength, and flexural strength decline less over 28 days than they do over 7 days when cement is partially replaced with bentonite. Blocks outperform cylinders in terms of strength. The inclusion of bentonite also increases the density of the mix and reduces workability and water absorption, indicating decreased porosity, which in turn enhances strength. Despite a minor reduction in strength, substituting bentonite offers a low-cost and sustainable construction.

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