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Enhancing Concrete Performance: Evaluation of Titanium Dioxide Nanomaterial Incorporation

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Abstract

In this study, a series of concrete cubes was produced by incorporating varying percentages of nanomaterials titanium dioxide (TiO_2) as a partial substitute for ordinary Portland cement (OPC). The replacement levels chosen for TiO_2 were 5%, 10%, 15%, and 20% of the OPC content. Initial assessments encompassed fundamental material examinations and evaluations of the freshly mixed concrete. Subsequently, the focus shifted to conducting compressive strength tests on the manufactured concrete cubes. Using nanomaterials cube gives more compressive strength compared to normal concrete cube. Compressive strength increases as TiO_2 content increases. But, after 15% TiO_2 content we increased it to 20% TiO_2 content then we saw that strength starts decreasing. As compared to conventional concrete there is an increase in compressive strength by 10% inTiO_2 concrete cube. To check the durability water absorption test was done which shows TiO_2 concrete cube absorbs 28.4% less water as compared to the conventional concrete.

Keywords

Titanium dioxide, Ordinary Portland cement, Concrete, Nanomaterials, Sustainability, Compressive strength

Introduction

Environmental impacts of cement nature of cement and its production cement serves as a vital binder in the construction of concrete, facilitating the cohesion between coarse and fine aggregates. With an annual global production exceeding one billion tons, cement is poised to witness a substantial surge in demand. Presently, no viable alternative to cement exists. Nevertheless, this study aims to explore the potential utilization of fly ash as a partial replacement for cement. Cement, existing as a fine powder, plays a pivotal role in regulating concrete attributes such as strength and durability. Among various cement types, Portland cement stands as the most widely employed variant worldwide. As articulated by Nawy, the composition of Portland cement and its counterparts involves a fusion of limestone and clay rock, which harbor essential cement production raw materials, including calcium carbonate ($CaCO_3$), iron oxide (Fe_2O_3), aluminum by combining crushed rocks rich in calcium, aluminum oxide (Al_2O_3), and silicon dioxide (SiO_2), a blend is created and subjected to kiln heating to form clinker. The resultant clinker is cooled and finely ground into a powder [1, 2].

The production of Portland cement is energy-intensive, emitting a notable portion of carbon dioxide (CO_2) – a major greenhouse gas. Each ton of cement yields an equivalent ton of CO_2, contributing around 7% of global CO_2 emissions. The process also generates substantial dust. Hence, finding an alternative material is crucial to mitigate these effects [3, 4].

Materials and Method

Materials

Compressive strength test

To assess the compressive strength of concrete samples containing fly ash as a replacement for either cement or fine aggregate, a compressive strength test can be carried out. This examination follows the procedure outlined in the Australian standard 1012.9.

Chemical properties of cement

The predominant constituents of cement, constituting 90% of its volume, comprise four major oxides: calcium oxide (CaO), SiO_2, Al_2O_3, and Fe_2O_3. The primary chemical composition of Portland cement is presented in table 1.

Testing machine

The testing equipment employed must adhere to the specifications outlined in the Australian standards (1012.9). The machine utilized for the testing procedure adhered to these stipulated requirements. A visual representation of the utilized machine is presented in figure 1.

$$\textit{Compressive strength}\ \left(N/mm^2\right) = \frac{\textit{Maximum Applied Force}}{\textit{Cross Sectional Area}}$$

Table 1: Primary chemical composition of OPC.

Chemical content	Amount (%)
Calcium oxide (CaO)	60 - 67
Silicon dioxide (SiO_2)	17 - 25
Aluminium oxide (Al_2O_3)	3 - 8
Iron oxide (Fe_2O_3)	0.5 - 6
Magnesium oxide (MgO)	0.1 - 4
Sodium oxide (Na_2O)	0.2 - 1.3
Potassium oxide (K_2O)	0.2 - 1.3
Sulphur trioxide (SO_3)	1.3

Figure 1: Compressive strength testing machine.

Nanomaterial

In recent decades, the significant mechanical, electrical, and thermal properties of nanomaterials have led to their widespread adoption across various fields. The cement industry has also begun to harness nanomaterials' exceptional attributes, marking a notable shift from traditional additives like calcium chloride and silica. Nanomaterials offer a preferred alternative due to their minimal incorporation in large quantities, yielding substantial outcomes. These outcomes hinge on factors such as nanoparticle synthesis (reaction media, reaction duration), as the reduction in particle size from macroscopic to nanoscale can induce changes in chemical and physical properties, influenced by size and surface effects. Presently, a surge of interest centers on crafting highly effective nanomaterials for enhancing cement-based final products [3, 5].

Nanoparticles, characterized by their ultrafine dimensions and elevated surface area-to-volume ratio, have the potential to expedite cement hydration and foster the development of a more compact microstructure. This, in turn, bolsters the resilience and mechanical attributes of cementitious materials. Consequently, nanoparticles emerge as a promising option for catalyzing cementitious processes in conditions of low temperature. Several research endeavors have concentrated on integrating nanoparticles such as nano-SiO_2, nano-$CaCO_3$, nano-Al_2O_3, nano-TiO_2, nano-Fe_2O_3, and nano-CuO into cementitious materials to enhance their mechanical robustness and long-term durability. Notably, nano-SiO_2 stands as a widely utilized nanoparticle, while nano-TiO_2 holds comparable prominence in this domain [6, 7].

However, scant exploration of SiO_2 and Al_2O_3 nanoparticles' influence on cementitious properties under low temperatures exists, leaving the effect of TiO_2 nanoparticles in such conditions unknown. Investigating nanoparticles under low temperatures aids their application in cold regions [8-10]. This study aims to assess TiO_2 nanoparticle impact on cement properties at 0 °C, 5 °C, 10 °C, and 20 °C, considering pore size, microstructure, and thermal attributes under varying curing temperatures and ages.

Concrete

Concrete is a composite development material made by consolidating concrete, totals (like sand and rock), water, and at times extra added substances. It is quite possibly of the most broadly involved materials in the development business because of its solidarity, strength, and adaptability. Mixing together water, aggregates, and cement is the first step in the concrete-making process. The water starts the chemical reaction known as hydration, which causes the cement to harden and form a solid matrix, while the cement acts as a binder to hold the aggregates together. To improve specific properties of the concrete, such as its workability, strength, and durability, additional additives may be added to the mix. The totals utilized in cement can fluctuate in size and piece. The structure and gaps between the larger aggregates are filled Fine aggregates, such as sand, contribute to concrete composition. Coarse aggregates, typically gravel or crushed stone, enhance concrete bulk and strength. After thorough mixing, the mixture is placed in molds or formwork to set and solidify.

Table 2: Tests on OPC using TiO_2.

S. No.	Tests	Test values of OPC using TiO_2					Range
		0%	5%	10%	15%	20%	
1	Fitness test (%)	8.5	8.3	8.4	8.43	8.44	< 10
2	Specific gravity of cement	2.93	2.93	2.94	2.94	2.94	< 3.19
3	Initial and final setting time of cement (min)	32 and 589	31 and 582	30 and 580	33 and 569	33 and 570	> 30 and < 600
4	Consistency test (%)	32	30	32	31	31	25 to 35

Hydration continues during curing, progressively enhancing concrete's durability and strength. Concrete offers several advantages as a construction material. It boasts exceptional compressive strength, enabling it to withstand heavy loads and tension. Resistant to fire, water, and weathering, it finds diverse applications like buildings, bridges, roads, and dams, offering versatility in shape and size. Different concrete types, like reinforced and pre-stressed, cater to specific project demands. Reinforced concrete employs steel bars for added flexibility and crack resistance, while pre-stressed concrete excels in tension-bearing elements like beams and columns. In essence, concrete is a composite blend of cement, aggregates, water, and additives, renowned in construction for its robustness, endurance, and adaptability.

Concrete cube

A concrete cube, also known as a concrete test cube or a concrete specimen, refers to a standardized sample of concrete that is cast and cured to assess its compressive strength. Concrete cubes are commonly used in quality control and construction projects to evaluate the strength characteristics of concrete. The process of creating concrete cubes involves taking a representative sample of freshly mixed concrete and pouring it into a cubical mold. As per global standards, mold, commonly constructed from steel or plastic, possesses dimensions of 150 mm x 150 mm x 150 mm (or 100 mm x 100 mm x 100 mm). The concrete is compacted within the mold using a vibrating table or a compaction rod to ensure proper consolidation and removal of air voids. After compaction, the concrete cubes are labelled with identification information, such as the project name, date of casting, and a unique reference number. The cubes are then covered with a plastic sheet or placed in a curing tank to protect them from drying out and to allow them to cure properly. The curing process is crucial for the development of concrete's strength. Generally, cubes are cured in a moist environment, such as a curing room or a water tank, at a controlled temperature of around 20 - 25 °C. This curing period typically lasts for 28 days, although shorter durations like 7 or 14 days are also common for preliminary strength assessments. At the end of the curing period, the concrete cubes are removed from the curing environment and brought to the testing laboratory. Using a hydraulic press machine, a compressive strength test is performed by incrementally applying force to a cube until it breaks. The highest load at the point of failure is documented, and the compressive strength is determined by dividing this load by the cube's cross-sectional area.

Methodology

Water absorption test

The water absorption test is a typical system performed to decide how much water a material retains under determined conditions. This test is many times directed on permeable materials like cement, blocks, tiles, and aggregates. The porosity, permeability, and durability of these materials can be deduced from their water absorption properties. The percentage of water that is absorbed by the concrete cube is shown in the water absorption value. Lower water retention values demonstrate better quality cement with lower porousness.

Test on materials

Different tests have been carried out for different materials like cement, fine aggregate, coarse aggregate, and TiO_2. Table 2 demonstrates that the utilization of nanomaterial (TiO_2) as a substitute for OPC at varying percentages aligns with the stipulated criteria of fundamental tests, in accordance with IS standards. This confirms its suitability for incorporation in concrete preparation.

Tests on fine aggregate

Zone III type of fine aggregate has been used for the preparation of concrete cubes. From table 3 it is clear that the fine aggregate has successfully passed the basic tests as per IS standards, confirming its suitability for concrete preparation, thereby ensuring quality and strength. This approval guarantees the concrete's durability and structural performance. Adhering to recommended proportions and procedures is essential for achieving desired properties. For additional guidance on construction or concrete mixing, inquiries are welcome.

Table 3: Tests on fine aggregate.

S. No.	Tests	Test value	Remarks
1	Specific gravity	2.64	Around 2.65
2	Sieve analysis	2.84	Fineness modulus
3	Water absorption	1.25%	0.3 - 2.5%

Tests on coarse aggregate

Concrete cubes have been prepared using coarse aggregate, adhering to the IS standards with a maximum size of 20 mm and a minimum size of 10 mm. This careful selection of aggregate sizes ensures optimal concrete quality and structural integrity, meeting the required specifications for construction purposes.

Table 4 above confirms that the coarse aggregate meets the essential criteria of basic tests according to IS standards. This qualification establishes its suitability for incorporation into concrete preparation, ensuring its appropriateness for use in construction.

Tests on fresh concrete prepared by OPC

Fresh concrete, composed of OPC, fine and coarse

Table 4: Tests on coarse aggregate.

S. No.	Tests	Test value	Remarks
1	Specific gravity	2.62	Around 2.65
2	Impact load test	24.3%	Varies on materials
3	Sieve analysis	3.56	Fineness modulus
4	Water absorption	0.86%	0.3 - 3%

aggregate, underwent testing. Various tests were conducted, involving the substitution of cement with nanomaterials at different percentages. Table 5 demonstrates that the fresh concrete, which utilized nanomaterial (TiO_2) to replace OPC at varying percentages, successfully fulfilled the criteria of fundamental tests outlined in IS standards. This outcome affirms its suitability for incorporation into concrete cube preparation, further supporting its potential for use in construction applications.

Results and Discussion

Compressive strength test

From figure 2, we can see that compressive strength of conventional concrete is 25.60 N/mm^2, as we added nanomaterial there is increase in strength. We added nanomaterials in different percentages 5%, 10%, 15%, and 20%. But strength starts decreasing after 20% nanomaterial is added. So, we can conclude that we can add nanomaterial till 15% if we increase more than that then strength will keep decreasing. There is a 10% increase in strength in TiO_2 concrete cube than conventional concrete cube (Table 6).

Water absorption test

In comparison to conventional blended concrete mixes, the mix reinforced with TiO_2 at different ratios showed lower water absorption values. When we compare water absorption test with conventional concrete cube and TiO_2 concrete cube, the result was TiO_2 concrete cube absorbs less water i.e., 28.4% less than conventional concrete cube (Figure 3). When these values were compared to the conventional concrete after 56 days of curing, the quaternary blended concrete reinforced with the nanomaterial performed as an optimal mix since the mix demonstrated the lower water absorption rate compared to conventional one. Therefore, it was evident that the combined effect of the or improved pozzolanic activity by producing a calcium silicate hydrate gel, which helped to refine the pore structure and build a denser composite. When compared to ordinary mix, the cement composite's durability performance has improved due to the production of the thick microstructure, which has reduced cement composite permeability.

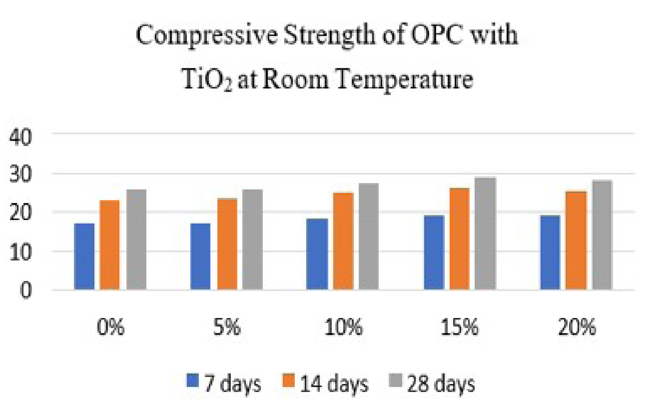

Figure 2: Compressive strength of OPC with TiO_2 at room temperature.

Table 6: Compressive strength test result.

S. No.	Material	Days	% replacing for cement				
			0%	5%	10%	15%	20%
1	TiO_2	7	16.99	17.19	18.23	19.07	18.89
2		14	23.14	23.14	24.85	26.02	25.32
3		28	25.60	25.90	27.50	28.80	28.18

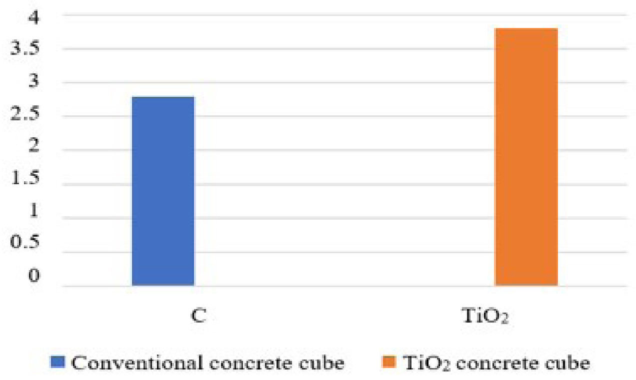

Figure 3: Water absorption test.

Conclusion

From the test, it is clearly shown that the water absorption has been reduced by about 28.4% using TiO_2 when compared to conventional concrete.

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Conflict of Interest

None.

Table 5: Compaction factor and slump tests on OPC using TiO_2.

S. No.	Tests	Test values of OPC using TiO_2					Range
		0%	5%	10%	15%	20%	
1	Compaction factor test	0.85	0.82	0.87	0.89	0.88	0.7 to 0.95
2	Slump test (mm)	78	75	73	74	77	25 to 125

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