



Development and Performance Evaluation of TiO₂-activated Carbon-based Air-purifying Paver Blocks for PM_{2.5} and VOC Removal

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ABSTRACT

Air pollution constitutes a major environmental crisis worldwide. Day-to-day, vehicles emit harmful air pollutants, posing various hazards to both living beings and the surrounding environment. The primary air pollutants responsible for health problems in urban areas are PM_{2.5} (particulate matter with an aerodynamic diameter of $\leq 2.5 \mu\text{m}$) and volatile organic compounds (VOCs). Air-purifying paver blocks are used to significantly reduce air pollutants along pedestrian footpaths. The novelty of this research lies in the combined effect of titanium dioxide (TiO₂) and geopolymer-based paver block production and the implementation of an Internet of Things (IoT) system to assess their effectiveness in reducing air pollution. The effectiveness of air-purifying paver blocks incorporated with TiO₂ and geopolymer concrete for the removal of PM_{2.5} and VOCs under field conditions was investigated. The results indicated that the paver blocks removed approximately 70% of PM_{2.5} and 50% of VOCs from the ambient air. In addition, the influence of operational parameters, such as temperature, humidity, and air velocity, on the performance of the paver blocks was examined. Data obtained from the IoT monitoring system revealed that CO and CO₂ levels were lower at the centre of the paver blocks and gradually increased towards their outer edges. Owing to the combined advantages of TiO₂ and geopolymer-based paver blocks, their cost is approximately 5–10% higher than that of conventional fly-ash paver blocks; however, the associated environmental benefits are substantially greater.

Keywords: Air pollution; Air-purifying paver blocks; TiO₂; Removal of PM_{2.5}; Activated carbon; Air velocity.

1. INTRODUCTION

Air pollution is a significant problem in India, affecting both human health and the environment, particularly from vehicle emissions. The use of air-purifying paver blocks provides a long-term strategy for reducing air pollutants. This paper discusses a new methodology for making photocatalytic concrete paver blocks using geopolymer concrete. This method accelerates the strength gain at room temperature and eliminates the need for water and high-temperature drying by partially replacing fly ash with titanium dioxide. TiO₂ acts as a photocatalyst when exposed to sunlight, breaking down nitrogen oxides, NO and NO₂, into nitrate ions (NO₃⁻), thereby reducing air pollutants. Geopolymer concrete further reduces its carbon footprint by eliminating Portland cement and utilizing fly ash and other aluminosiliceous materials as binders. The large, open-pore structure of the air purifier paver blocks allows for faster surface runoff drainage, reducing flooding and improving roadway safety. The mix design procedure and laboratory test results are presented in this paper, demonstrating the viability and efficiency of this green

approach in enhancing urban sustainability and mitigating air pollution.

The photocatalytic reaction in air purifier paver blocks reduces air pollution, which, in turn, lessens the harmful effects of those gases. The addition of nanomaterials, such as TiO₂, to concrete paver blocks enables automatic air purification via photocatalysis. When nano-air-purifying paver blocks are exposed to sunlight or UV radiation, the photocatalysts convert organic and inorganic pollutants into less harmful forms. Many advantages have been reported when photocatalysts are applied to cementitious materials. It can dissolve unwanted organic substances on the surfaces of concrete paver blocks, which are readily removed by rain. This air-purification method is an innovative concept in the field of cementitious materials. It could serve as a new strategy for maintaining cleaner urban environments by reducing air pollution. The photocatalytic reaction may speed up natural oxidation and the breakdown of pollutants. TiO₂ is an ideal photocatalyst owing to its extensive availability, low cost, and excellent chemical

stability. The eco-friendly air-purifying paver brick tends to absorb water and is more permeable.

The photocatalytic reactions are illustrated in Fig. 1. TiO_2 under UV light produces electron-hole pairs, which oxidize water to hydroxyl radicals and reduce oxygen to superoxide ions. These reactive species work in concert to break down VOCs and particulate pollutants on the paver block surface. Meanwhile, atmospheric nitrogen oxides (NO_x) react with superoxide ions and hydroxyl radicals to form nitrate ions (NO_3^-). When these nitrate ions are absorbed into the concrete paver blocks and converted into stable molecules, the concentration of nitrogen oxides in the environment decreases.

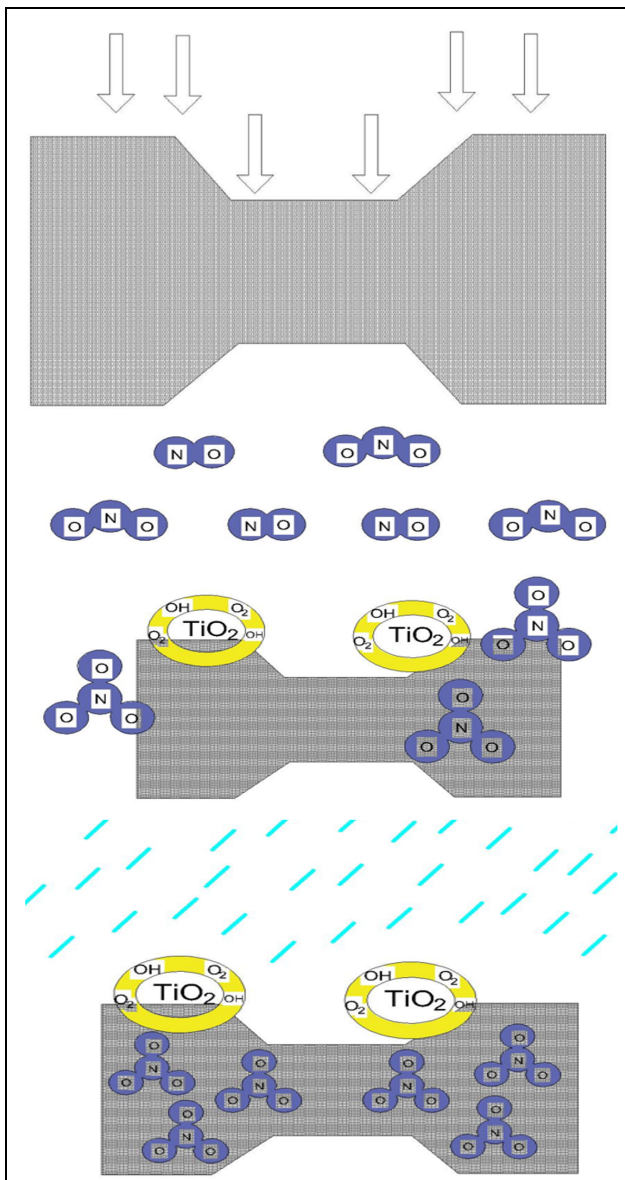


Fig. 1: TiO_2 -based photocatalytic reaction mechanism

Air pollution is a major environmental issue that poses a significant threat to human health, particularly in urban areas. Particulate matter and VOCs are the most

widespread contaminants that degrade air quality (Andrade *et al.* 2009). Traditional methods of air pollution abatement, such as scrubbers and filters, are highly energy- and cost-intensive. Since air-purifying paver blocks eliminate air pollutants from the atmosphere, they have gained significant attention in recent years as a feasible solution. Air-purifying paver blocks are specialized paving stones designed to remove air pollutants (Antoni *et al.* 2017). They are composed of multiple components, including fly ash, activated carbon, and TiO_2 .

These materials can remove airborne pollutants through various mechanisms, including adsorption and photocatalysis. When these compounds, in the presence of sunlight or UV radiation, come into contact with air contaminants, they transform them into innocuous chemicals (Augustyniak *et al.* 2022). Some of the places where air-purifying paver blocks are used include parking lots, walkways, and urban plazas. They offer numerous advantages over traditional air filtration methods, including lower costs, reduced energy consumption, and fewer maintenance requirements. Moreover, air-purifying paver blocks are available in various colors, shapes, and textures, making them ideal for enhancing the aesthetic appeal of urban environments. Despite the advantages of air-purifying paver blocks, several challenges are associated with their design and application, including concerns about durability, profitability, and environmental impact (Awadalla *et al.* 2011; Hassan *et al.* 2010). Further research is needed on the long-term viability and practical applications of air-purifying paver blocks in real-world settings.

Nevertheless, air-filtering paver blocks appear to be a practical and relatively inexpensive method for improving air quality in cities (Bica and Melo, 2020). Such materials can remove air pollutants through adsorption and photocatalysis. When exposed to sunlight or ultraviolet light, these materials react with air pollutants, converting them into harmless substances (Boonen and Beeldens, 2014).

Further research is required regarding their effectiveness over an extended period in real-life situations. Guidelines for the use of paver blocks can be developed based on research findings that may reveal durability issues or maintenance needs (Chu *et al.* 2021). Air-purifying paver blocks can be used in conjunction with other green infrastructure, such as bioswales and green roofs, to further enhance air quality in cities (Ambient, National, Air Quality, and Monitoring Programme, 2016). This strategy can enhance the benefits of various forms of green infrastructure and increase the resilience and sustainability of urban areas.

This will require the large-scale implementation of air-purifying paver blocks, supported by government policies and initiatives. Governments or urban planners may consider incentives and regulations to promote the use of air-purifying paver blocks in urban architecture, thereby contributing to healthier, more sustainable urban environments (Melo *et al.* 2012). Urban air pollution is a global issue that poses a significant threat to human health. The primary objective of this study is to develop eco-friendly, innovative pavement materials by combining industrial waste with nanoscale TiO₂ particles (Gauvin *et al.* 2018; Gopalan *et al.* 2020). The photocatalytic effect of TiO₂ has been extensively documented in various scientific studies aimed at reducing air pollution. However, little is being done to reduce air pollution by adding TiO₂-infused glass cullets or by using industrial waste to construct double-layer paver blocks. Research was conducted to determine the optimal combination of mixtures for reducing pollution and maximizing the utilization of industrial waste (Hassan *et al.* 2010). The following are the advantages of the proposed system: it is less costly (than large-scale mechanical air filtration methods), eco-friendly, sustainable, and does not require skilled construction labor. It also optimizes indoor air quality, air circulation, and moisture control, and reduces condensation, requiring low energy consumption since it involves no mechanical parts.

Therefore, this experimental research study is aimed at:

- Formulating and evaluating the performance of TiO₂ impregnated activated carbon-based air-purifying paver blocks by evaluating their pollutant removal efficiency concerning PM_{2.5} and VOCs, operational performance under variable environmental conditions, and real-time monitoring using an IoT-based system.
- Assessing the sustainability and practicality of the proposed system. Evaluations are needed on the durability of the paver blocks, the energy performance of the solar-powered drying process, and the techno-economic feasibility of its large-scale implementation in urban areas.

Numerous hazardous air pollutants are released by automobiles every day, endangering both the environment and living things. The need for natural raw materials and population growth has led to a sharp rise in construction costs. Reusing and recycling waste materials discharged from construction sites is essential as a substitute for building materials (Hopewell *et al.* 2009; Hüsken *et al.* 2009). This paver block containing titanium dioxide could reduce air pollution from vehicle emissions (IS:15658-2006, 2006). They are highly stable substances that serve as catalysts to start the photocatalysis process, a photochemical reaction. An investigation into the advantages of glass bead supports for effective gas-phase

photocatalysis was conducted using both a synthetic and a commercial photocatalyst (IS:15658-2006, 2006). 2 mm glass beads with a thin layer of titanium dioxide were prepared to increase TiO₂'s illumination efficiency. Replacement of 10 mm-sized natural coarse aggregates (0%, 15%, 30%, 45%, 60%, and 75%) in I-shaped 80 mm recycled paver blocks with recycled coarse aggregates from construction and demolition debris has been studied (Ke *et al.* 2018; Kim *et al.* 2019; Kumar *et al.* 2020). Paving blocks made with cement to bottom ash ratios of 1:3, 1:4, and 1:5 surpass the required compressive strength of 40 MPa, according to research on bottom ash replacement for fine aggregate in paver block production (Kumar *et al.* 2020; Mikhaylov *et al.* 2009; Padmini *et al.* 2009). Additionally, a study on the characteristics of concrete containing bottom ash as fine aggregate has been conducted. According to test results, photocatalytic activity declines with increasing curing age (Poon and Cheung 2007; Ramirez *et al.* 2010). In recent photocatalytic air-purification applications in Belgium, the effectiveness of single- and double-layer concrete blocks was compared. Due to the high humidity, pollutant degradation cannot be reduced (Reshma *et al.* 2021). It demonstrates how the pavement's porous structure influences the rate of NO_x reduction and how increasing the proportion of nanoparticles could improve its efficiency (Rhee *et al.* 2018; Singh and Siddique, 2015). Coal bottom ash is used in concrete, where gas replaces natural fine particles, affecting characteristics such as bleeding, plastic shrinkage, and setting time (Rosso and Melo, 2020; Verbruggen *et al.* 2011). By lowering atmospheric carbon dioxide, titanium dioxide in paver blocks lowers indoor air pollution. After 90 days of age, the surface layer of the titanium dioxide-containing panel exhibits a decrease in CO₂ levels (Witkowski *et al.* 2019; Sorathiya, 2017). The shape and pore structure of porous construction materials play a crucial role in their performance. By utilizing two distinct porous materials, such as wood wool, cement board, and autoclaved aerated concrete, the photocatalytic oxidation mechanism can effectively lower air pollution (Yu *et al.* 2020). To use photocatalytic nanopowder in the field, purifying pavements have been created using a variety of photocatalyst-loading methodologies (Fan *et al.* 2017; Binag, 2016). Using a hydraulic press, photocatalyst TiO₂ nanopowder is often combined with cement, asphalt, or resin, then cast onto the subgrade or pressed into brick. For instance, a field test study in Denmark investigated the application of photocatalytic paving materials to reduce nitrogen oxide pollution (García *et al.* 2017). Ordinary earth-moist concrete made up 60 mm of the paving block's entire thickness, whereas earth-moist concrete with TiO₂ made up the top 10 mm. Approximately 40 kg/m³ of TiO₂ was added to the top layer of the concrete. The top photocatalytic mortar and the traditional bottom concrete were compacted using a hydraulic press. Since TiO₂ will always remain present

to sustain photocatalytic activity, even in the event of abrasion, this loading approach offers a more durable action (Manivel and Aarthi, 2020). The catalyst's ability to depollute is limited by this method's inability to create a sufficiently large contact area between TiO_2 and pollutants. Additionally, the initial cost will be higher due to the higher TiO_2 content, and it is not suitable for municipal facilities that have already been built (Glenn *et al.* 1999; Raza *et al.* 2023).

2. MATERIALS AND METHODS

Indoor air quality improvement was investigated through an experimental study of air-purifying blocks. Various air-purifying blocks with different designs, compositions, and technologies were selected for analysis. Given the factors of ventilation, room size, and baseline air quality, studies were conducted in a controlled setting. Accurate measurements of pollutants, including $\text{PM}_{2.5}$, VOCs, and other relevant contaminants, were performed before installing air-purifying blocks. The experimental run was continued for a predetermined time after installing the blocks, as instructed by the manufacturer, to simulate realistic usage conditions. Their effectiveness in removing pollutants was studied. The results were accurately recorded, and a detailed report was written highlighting the outcomes, outlining both their advantages and disadvantages, and recommending further improvements. This procedure ensured that the potential of air-purifying blocks to improve indoor air quality was tested methodically and effectively. To prepare paver blocks, the following ingredients were used: fly ash, ground granulated blast-furnace slag (GGBS), TiO_2 , metakaolin, NaOH, and Na_2SiO_3 .

Figure 2 illustrates the methodology used. It consists of five stages: material collection and physical property analysis, mix design and solution preparation, brick casting, brick drying, and brick testing, followed by the presentation of results.

2.1 Data and Material Collection

The air-purifying blocks were designed using various materials to enhance their functional capabilities. The raw materials and their compositions are presented in Table 1. Fly ash (Class F), which is considered a cheaper alternative to Portland cement, also reduces embodied energy, in addition to its environmental benefits (Sandrine *et al.* 2015). It is suited to numerous uses due to its wide color range, flexibility, and lower water demand than Portland cement. The high reactivity and fineness of metakaoline, a pozzolanic material derived from kaolin clay, improve concrete strength and durability. It enhances compressive and flexural strengths, reduces permeability, and resists chemical attacks by reacting with calcium hydroxide to produce calcium silicate hydrate (C-S-H) gel. GGBFS is obtained by quenching molten iron slag to produce a glassy, granular powder that enhances concrete's

properties. The photocatalytic material (TiO_2) assists in the breakdown of pollutants upon exposure to UV light, providing a sustainable method for air purification. This broad selection was designed to produce air-purifying blocks that support the sustainability goals of the construction sector, offering greater strength and durability while reducing environmental impact (Glenn *et al.* 1999). Geopolymeric solutions are one of the mixing and binding agents that play a crucial role in paver block production. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were mixed and left to react for 24 hours to form a geopolymeric reaction, although they were not directly poured into the blocks. Aggregates are a crucial component of air-purifying blocks, enabling these blocks to remain structurally sound while removing pollutants. The M-sand shall be clean, firm, and free from silt and vegetation. When combined with other paver block components, it creates a properly balanced mix. Table 2 represents the description of the materials used and their specifications for this research.

Chemical composition was assessed by X-ray fluorescence, SEM was employed for particle morphology, and Blaine apparatus was used for estimating the fineness of different materials (fly ash, metakaolin, GGBFS, and TiO_2). The fine aggregates (M-sand) used in the study have been tested for grading by sieve analysis, specific gravity by a pycnometer, and bulk density by a standard cylinder. The alkaline activators used, namely NaOH and Na_2SiO_3 , were tested on a digital pH meter and hydrometer for pH and solution density, respectively. Fresh geopolymer mixes were tested for workability in a flow table and setting in a Vicat apparatus. Compressive strength was determined using a compression testing machine, while water absorption and porosity were measured using the oven-dry and vacuum saturation methods, respectively. Photocatalytic activity was measured using a UV chamber coupled with an air-quality sensor that quantified reductions in VOCs and PM. Similarly, the microstructural characteristics, including gel formation and TiO_2 distribution, were determined using SEM/EDS

2.2 IoT Device for Air Quality Monitoring

The air quality of the paver block was monitored using an IoT-based sensing device, as shown in Figure 3. This was developed to assess the paver block's air-purification capability by measuring a drop in pollutant concentration in the surrounding air. An integrated IoT system comprising various sensors was used to measure crucial environmental and gaseous parameters, including temperature, humidity, and hazardous gas concentrations. The setup consists of an ESP32 microcontroller as the central control unit, integrated with the GY-GPS6MV2 GPS module for real-time location tracking and the ADS1015 ADC for

accurate analog-to-digital data conversion. Several gas sensors, including MQ-131 (O_3 sensor), MQ-135 (CO sensor), MQ-6 (LPG sensor), MQ-136 (NH_3 sensor), and MQ-137 (H_2S sensor), are incorporated to detect specific air pollutants.

Additionally, a DHT11 sensor has been integrated to measure temperature and humidity, while a flame sensor provides fire safety. This IoT-enabled gadget wirelessly interfaces with the mobile app for continuous air quality monitoring. The data collected was saved in CSV format, recorded at predetermined time intervals, and used for further analysis. With this comprehensive system, carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), sulfur compounds (H_2S), temperature, humidity, heat index, air quality index, and all other volatile gases can be tracked.

Additionally, the Ublox NEO-6M GPS receiver provided ± 2.5 m accuracy at a 1–5 Hz update rate, operated on 3.3–5 V, and included a high-sensitivity receiver with exact location data. A GSM module was integrated for real-time data transmission and communication. This guarantees precise, location-based, real-time air quality monitoring, enabling evaluation of the paver block's air-purifying capability in real-world conditions.

2.3 Mix Design and Preparation of Alkaline Solution

Air-purifying paver blocks are manufactured by directly mixing cementitious materials, aggregates, and photocatalytic titanium dioxide in fixed proportions to enhance pollutant removal while maintaining structural

integrity. Mix proportions shall be finalized through trial batches and adjustments based on test performance, exposure conditions, climate, and standard requirements. The added TiO_2 photocatalyst helps degrade air pollutants under light. Table 3 represents the mixed design of the proposed research.

The mix ratio for the paver blocks was 1:2 (fly ash to M-sand). For mix one, 10% of GGBS and 10% of metakaoline were replaced with fly ash, without adding TiO_2 . A mix of 2 parts GGBS and 15% metakaoline is used as a replacement for fly ash to increase the strength of the paver block without adding TiO_2 (anatase). The mix 3, which used 15% GGBS and 15% metakaoline as a replacement for fly ash, was used to increase the strength of the paver block by adding 1% TiO_2 (anatase). For both mixtures, the 12 M alkaline solution used in this process is a mixture of NaOH and Na_2SiO_3 in a 1:5 ratio. In the first batch, 0.528 kg of NaOH was added gradually to 1.1 L of water, ensuring complete dissolution. Similarly, in the second batch, 1.056 kg NaOH was dissolved in 2.2 L of water. Following the same procedure, after the NaOH solutions were cooled to room temperature, 0.22 L and 0.44 L of sodium silicate were added to the prepared alkaline activator solutions, and the mixtures were stirred to ensure uniformity. The prepared activator was left undisturbed for 24 hours to promote a geopolymeric reaction. The alkaline solution is highly caustic and can give severe chemical burns to the skin or eyes, and should be handled with care. Appropriate PPE (personal protective equipment) is recommended when handling the solution, including gloves and eye protection.

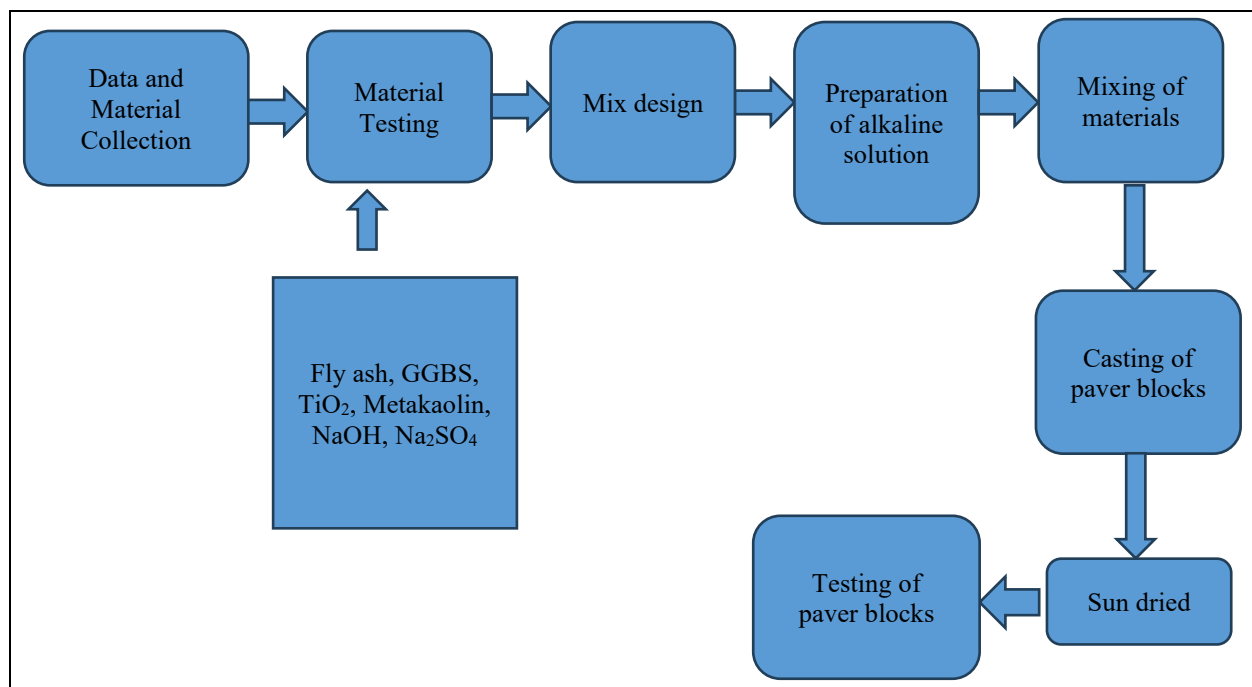
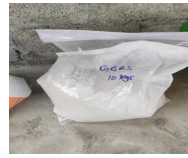


Fig. 2: Methodology flow chart

Table 1. Raw materials and their specifications

S. No.	Materials	Specifications					Pozzolanic Activity	Code (IS/ASTM)
		Fineness	Specific Gravity	Density (kg/m ³)	Chemical composition	Color		
1	Fly ash (Class F)	320 m ² /kg	2.32	2.2	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , CaO, LOI	Grey to dark grey	High to moderate	IS 3812 (Part 1): 2013
2	Metakaoline	23.4 m ² /g	2.6	2.5	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , LOI	Off-white to light cream	Very high	ASTM C618
3	GGBFS	425 m ² /kg	2.9	2.84	SiO ₂ , Al ₂ O ₃ , CaO, LOI	White powder	Moderate to high	IS 12089:2011; ASTM C989
4	TiO ₂	30 nm		4230	Ti – 59.9% O – 40.1%	White powder	Not strength gain via pozzolanic reaction (only photocatalytic)	-
5	NaOH	400 µm	2.13	2130	Na – 57.5% O – 40.0% H – 2.5%	White solid flakes	Binder, activator in geopolymer concrete	-
6	Na ₂ SiO ₃	-	-	1450	Silica -28%, Alkali -10%	Transparent viscous liquid	Binder, activator in geopolymer concrete	-
7	Fine Aggregate	4.75 mm passing	2.6	1500	-	Natural gray	-	IS 383:2016, IS 2386

Table 2. Description of materials used

S. No.	Materials	Description	Image
1.	Fly Ash (Class F)	Fly ash, being a low-embodied-energy byproduct, serves as a low-cost alternative for Portland cement in air-purifying blocks. It is environmentally safe, enhances concrete strength, reduces water consumption, and can be colored in a variety of colors. Due to its versatility and potential for reducing CO ₂ , it becomes a valuable component in sustainable building methods.	
2.	Metakaoline	Metakaoline is the pozzolanic material obtained from calcined kaolin clay, which enhances the strength and durability of air-purifying blocks. Due to its highly reactive nature, it forms a calcium silicate hydrate gel that enhances flexural and compressive strength, reduces permeability, and provides resistance to chemical attack. The byproduct of kaolin promotes reduced carbon emissions and sustainable methods in the building industry.	
3.	GGBFS	GGBFS is a byproduct of the reduction of iron ores to produce iron in blast furnaces. The molten slag is quenched in water, and the resulting glassy, granular residue is GGBS. It is dried and processed into a fine powder for application in construction. It is added as a cementitious ingredient in concrete to enhance strength, sustainability, and durability while minimizing the environmental impact of the construction method.	
4.	NaOH	Although it is not commonly applied as an active agent in air-purifying blocks, NaOH may be used for treatments during material production. Its high corrosiveness must therefore be handled with care. Although not a direct component, it could be used for surface treatment or to adjust pH, thereby indirectly affecting the characteristics of building materials.	
5.	Na ₂ SiO ₃	The general name for the alkaline, viscous liquid of silica composed of sodium oxide is sodium silicate (Na ₂ SiO ₃), generally used as an activator in geopolymer concrete. It enhances the dissolution of aluminosilicate materials and promotes the formation of a potent geopolymer gel, thereby improving early strength and bonding.	
6.	Aggregate	M-sand plays a crucial role in air-purifying blocks by contributing to both structural integrity and overall pollutant-removal effectiveness. The performance of the concrete largely depends on the quality of this inert material, which must be hard, clean, and free from impurities. In sustainable construction, the use of well-graded, carefully selected fine aggregates is essential to ensure durability, long service life, and optimal pollutant neutralization in air-purifying systems.	
7.	TiO ₂	In construction, when TiO ₂ is exposed to UV light, it exhibits photocatalytic properties that degrade pollutants. Toxic nitrogen oxides are converted to soluble nitrate salts via photocatalysis by TiO ₂ , enabling their use in coatings and prefabricated material systems for sustainable air purification. It is used to improve air quality, and, with relatively low maintenance, it can provide a continuous solution.	

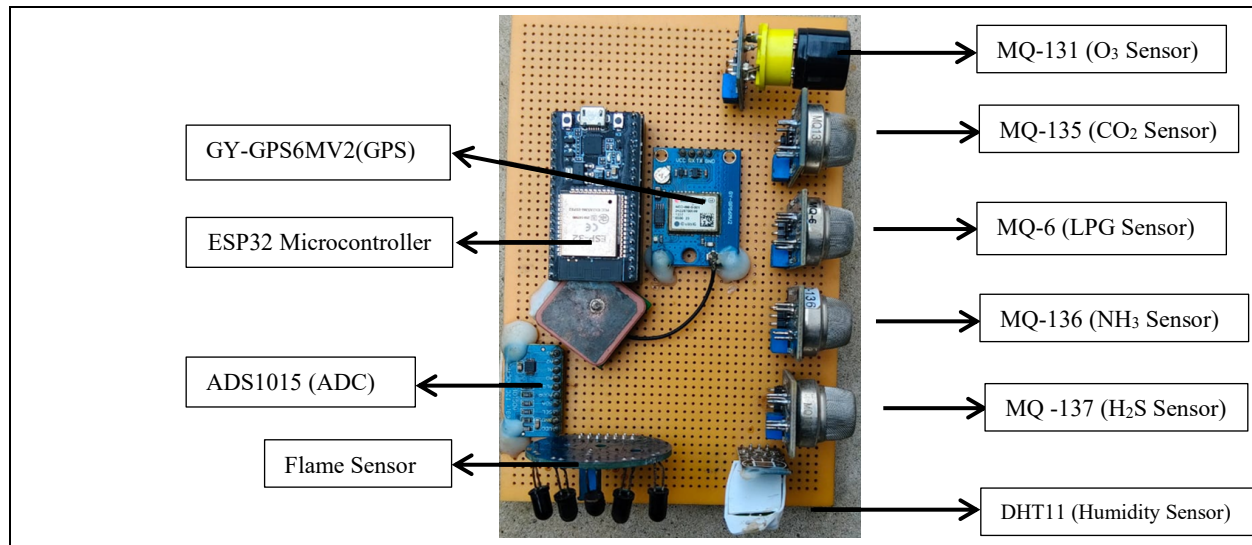


Fig. 3: IoT devices for air quality monitoring

Table 3. Mix design

Mix ID	No. of Blocks	Fly ash (kg)	GGBFS (kg)	Metakaoline (g)	Fine aggregate (kg)	TiO ₂ (anatase) (g, 1 wt.% of binder)	NaOH (kg)	Na ₂ SiO ₃ (L)	Water (L)
Mix 1	4	3.84	0.48	0.48	9.6	-	0.528	0.22	1.1
Mix 2	4	3.76	0.72	0.72	9.6	-	0.528	0.22	1.1
Mix 3	8	7.52	1.44	1.44	19.2	96	1.056	0.44	2.2

2.4 Casting of Paver Blocks

First, the raw materials were batched according to the mix design. Fly ash, M-sand, GGBFS, and metakaolin were dry-mixed together to ensure uniform dispersion. The alkaline activator solution was then slowly added to mix 1, followed by mix 2, and TiO₂ (anatase) was added to mix three as the air-purifying additive. The entire mass was further mixed to achieve a uniform, homogeneous geopolymer paste. The fresh mixes were placed in 9 × 4 × 3-inch nylon molds and compacted sufficiently to remove air pockets. The setting was allowed to take place under controlled conditions. From Figures 4 and 5, it is seen that fly ash-based geopolymer mixes require a higher amount of alkaline activator to achieve good workability and casting consistency.

3. RESULTS AND DISCUSSION

According to IS:15658-2006, the wearing layer's thickness must be at least 6 mm. The measured thickness of the wearing layer, 7.8 mm, is within the allowable tolerance limit. This layer consists of titanium dioxide and recycled glass particles and serves as the surface layer, improving the paver block's photocatalytic properties. The overall thickness of the paver block used in this study falls within acceptable tolerance limits, although it is slightly above the nominal measurement.

3.1 Compressive Strength of Paver Blocks

The purpose of the compressive strength test was to assess the performance, strength, and quality of the paver blocks. Tests were performed after 7, 14, and 28 days of drying to determine how the specimens' strength evolved. According to IS 516:2014, each specimen was placed in a 200-ton compression testing machine, and stress was applied progressively at a constant rate of 140 kg/cm² per minute until the specimen failed. The standard formula for compressive strength was used to determine the paver block's compressive strength after the maximum load at failure was noted. Figure 6 displays the results.

Figure 6 shows the compressive strength development of all geopolymer paver block mixes containing fly ash, with variable GGBFS and metakaolin contents, with and without TiO₂, after 7, 14, and 28 days of testing. For each mixture, compressive strength increased with curing age. For all ages, the strength was slightly higher for the 15% GGBFS and metakaolin mix than for the 10% replacement mix. Notably, the mix containing 15% GGBFS and metakaolin with TiO₂ showed the highest compressive strength of 44 N/mm² at 28 days, indicating that TiO₂ enhances geopolymerization and improves mechanical performance (Rosso and Melo, 2020). The test results confirm that increasing the GGBFS and metakaolin content, along with the addition of TiO₂, leads to a

remarkable improvement in the compressive strength of geopolymer concrete.



Fig. 4: Wet casted blocks without TiO₂



Fig. 5: Wet casted blocks with TiO₂

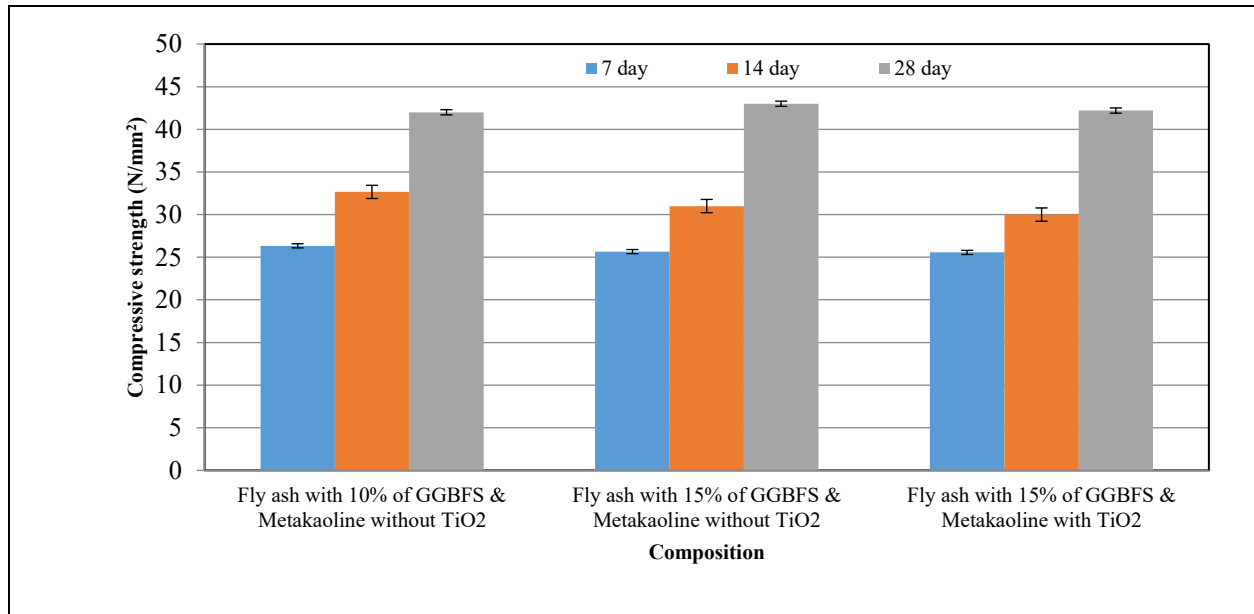


Fig. 6: Compressive strength of paver blocks

3.2 Water Absorption Test on Paver Blocks

The water absorption test was conducted on the paver blocks after 28 days of drying, as recommended by IS 15656:2006. The samples were submerged in water for 24 hours to measure their wet weights, then dried in an oven for another 24 hours to obtain their dry weights. From these measurements, water absorption in percentage was computed by using the standard formula (IS:15658-2006). The results indicated the permeability of different mixes. A water absorption of 1.582% was recorded for the mix containing 10% GGBFS and metakaolin without TiO₂, indicating moderate permeability. When the replacement level was increased to 15% without TiO₂, water absorption was substantially reduced to 1.085%, indicating a denser, less porous matrix.

On the other hand, when TiO₂ was incorporated at a 15% replacement level, water absorption increased to 1.767%. This suggests that, though TiO₂ improves mechanical properties, it may undergo microstructural changes that increase pore connectivity. Overall, the lowest water absorption was observed for the 15% replacement mix without TiO₂, as presented in Table 4.

Methylene blue solution, an organic dye, was diluted in distilled water in a 1:20 ratio. The TiO₂ active surface layer was then exposed to sunlight after 1–2 mL of the produced solution was put onto it.

The three paver blocks, with and without recycled glass (RG), are then covered with the

methylene blue solution for the time required for its color to change. Regular blocks were used as controls to assess the photocatalytic activity of the paver block containing titanium dioxide.

Table 4. Water absorption results

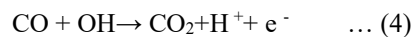
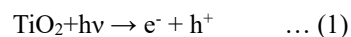
S. No.	% of Replacement	Water Absorption (%)
1	Fly ash with 10% of GGBFS and metakaoline without TiO ₂	1.582
2	Fly ash with 15% of GGBFS and metakaoline without TiO ₂	1.085
3	Fly ash with 15% of GGBFS and metakaoline with TiO ₂	1.767

3.3 Photocatalytic Activity Test

The photocatalytic action showed that paver blocks with a recycled glass face layer had more photocatalytic activity than other combinations. The mix with 0% bottom ash (BA) and 100% recycled concrete aggregate (RCA) had the best degradation efficiency, with a recorded length of 87 minutes. Reduced surface reactivity was shown by a modest increase in time following a 50% partial substitution of BA. While mixtures without RG or a face layer showed higher reaction times, regular and commercial pavers showed no activity (NIL). By enhancing UV reflectivity and active surface locations, RG improved photocatalytic activity.

The generated hydroxyl radicals and superoxide ions are potent oxidizing agents that react with the adsorbed carbon monoxide, breaking it down into carbon dioxide.

Reaction mechanism of TiO₂



3.4 Dye Degradation Test

Table 5 shows that paver blocks treated with titanium dioxide exhibit an 86.5% degradation efficiency. The UV-Vis spectrophotometer indicates that the degradation efficiency rises as the rate of methylene blue absorbance decreases. The rate of methylene blue dilution determines the rate of absorbance change. Figure 7 shows how well modified titanium oxide degrades paver block material.

Table 5. Degradation efficiency of TiO₂ in paver block

S. No.	Wavelength (nm)	Time (min)	Absorbance (A ₀)	Efficiency (%)
1		7	1.102	1.3
2		60	0.898	20
3	660	120	0.614	45.3
4		180	0.452	59.8
5		240	0.152	86.5

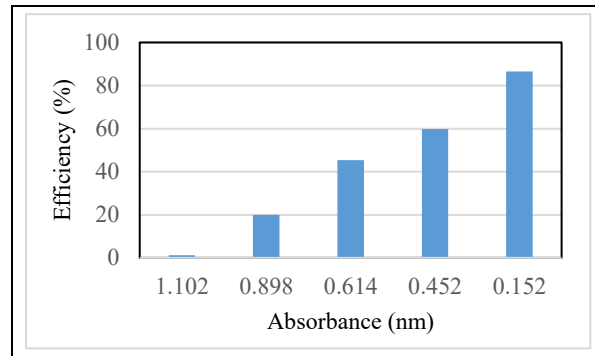


Fig. 7: Degradation efficiency of the modification in concrete

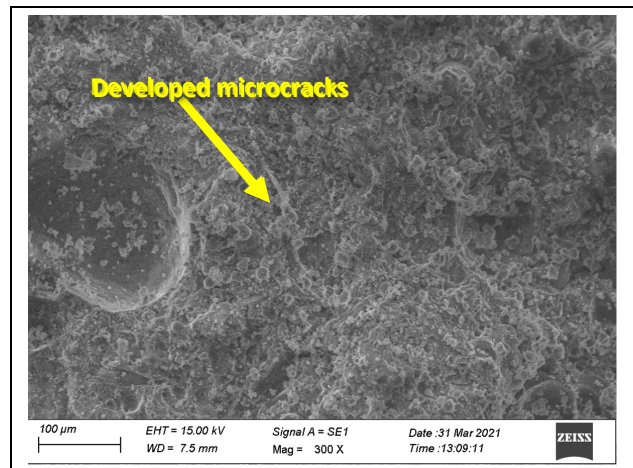


Fig. 8: SEM image at 100 μm with WD = 7.5 mm

3.5 SEM Analysis

A 1 cm-thick paver block sample was examined using SEM, and high-resolution images at different magnifications were obtained.

In Figure 8, the surface morphology at 300X magnification and an electron beam tension of 15 kV at 100 μm depicts the paver block's body layer, which represents the uniform distribution of fly ash and M-sand. There was no indication of a contact zone because the items were closely packed together. The lack of a contact zone implies the presence of nanoparticles with a densely packed, firmly linked structure. The contact zone is visible through the fracture, and the white traces

show the presence of titanium dioxide. The paver block's porosity is visible through the microholes in this picture. The photochemical reaction is enhanced by the porous structure, among other things (Mikhaylov *et al.* 2009). Nano-TiO₂ improves the microstructure of paver blocks by enhancing hydration and filling pores, thereby extending their longevity. C-S-H forms contribute to a denser matrix, increase strength, and reduce drying shrinkage. This hydrophilic nature contributes to moisture retention. It can be seen that the bottom ash is mainly composed of high levels of silica and alumina, which enhance its strength. It has been shown that finer particles, such as cenospheres, adhere to coarser particles. These cenospheres are present in the bottom ash heap as aggregate for the production of lightweight concrete. Hydrophobic behaviour and low density of unburned carbon make them float on the surface of low water and are easy to wash out (Bruno *et al.* 2014). The type of microstructure has a significant impact on the physical properties of the paver block, such as its compressive strength, elastic modulus, permeability, and shrinkage. Because of particle aggregation and limited reactivity, the silica fume in this investigation appeared either overly dense or poorly distributed within the cement matrix.



Fig. 9: Location for laying paver block footpath

3.6 Air Quality Monitoring Using an IoT Device

The paver blocks were deployed at the Chennai Institute of Technology, located in the southwest of Chennai, India, along the Kundrathur–Sriperumbudur route (latitude 12.97158° N, longitude 80.04342° E). This location was chosen because it has a relatively high traffic density and pollution level, is close to a road intersection, and is about five meters from the roadside. At the chosen location, the paver blocks and the IoT-based air quality monitoring system were installed, as shown in Figure 10. The efficacy of TiO₂-based paver blocks in reducing airborne pollutants was evaluated using data collected from an IoT device. The TiO₂-coated paver blocks were installed over an area of 16 m², and the IoT monitoring device was

positioned at the center of this layout. Additional measurements were taken at 0.5 m, 1 m, 1.5 m, and 2 m on either side of the central point to evaluate air quality variations at different positions. The monitoring process has been taken for a total of 5 days, with two peak hours monitored per day, and the data is stored in IoT. Figure 9 illustrates the implementation site, while Figure 10 represents the air quality monitoring arrangement over the laid paver blocks.

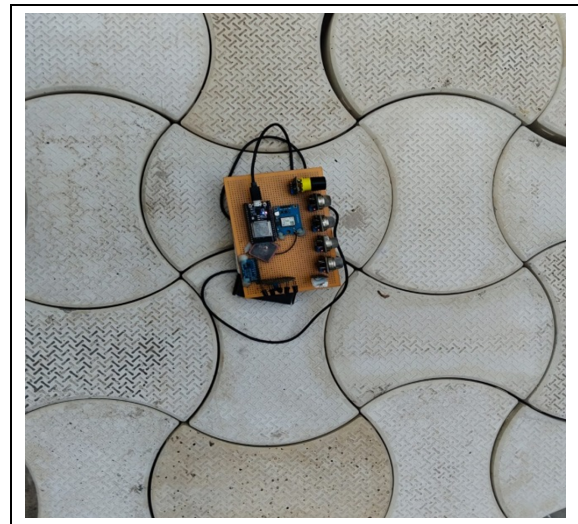


Fig. 10: Air quality monitoring arrangement above laid paver blocks

One of the main factors considered in this study is carbon monoxide, which has detrimental effects on the environment and living organisms. This study examines the air quality surrounding the paver block system. CO falls within the reasonable range if it is 0-1 ppm, as per the air quality index of India (CPCB, 2014). Figure 11(a) shows that the CO levels in the center range from 0 to 1 ppm, whereas the CO levels 2 m away from the paver block range from 2 to 3 ppm. This demonstrates that CO levels clearly decreased when the device was positioned in the middle of the setup. Although carbon dioxide is a gaseous pollutant and less hazardous than carbon monoxide, it nevertheless contributes to excess greenhouse gases with negative consequences for the ecosystem. CO₂ levels range from 300–500 ppm in the center to 800–900 ppm, 2 m away from the paver block, as shown in Figure 11(b).

The same hydrocarbons and nitrogen oxides are produced by ethanol in the gas phase. When it burns, it releases greenhouse gases and carbon dioxide. Ethanol reduction thus lowers CO and CO₂ levels. The levels of ethanol near the center of the paver block are clearly lower than those at 2 m from the paver block arrangement, as shown in Figure 12 (a). The ammonium levels at the center were lower than those 2 m away from the paver block, as seen in Figure 12 (b).

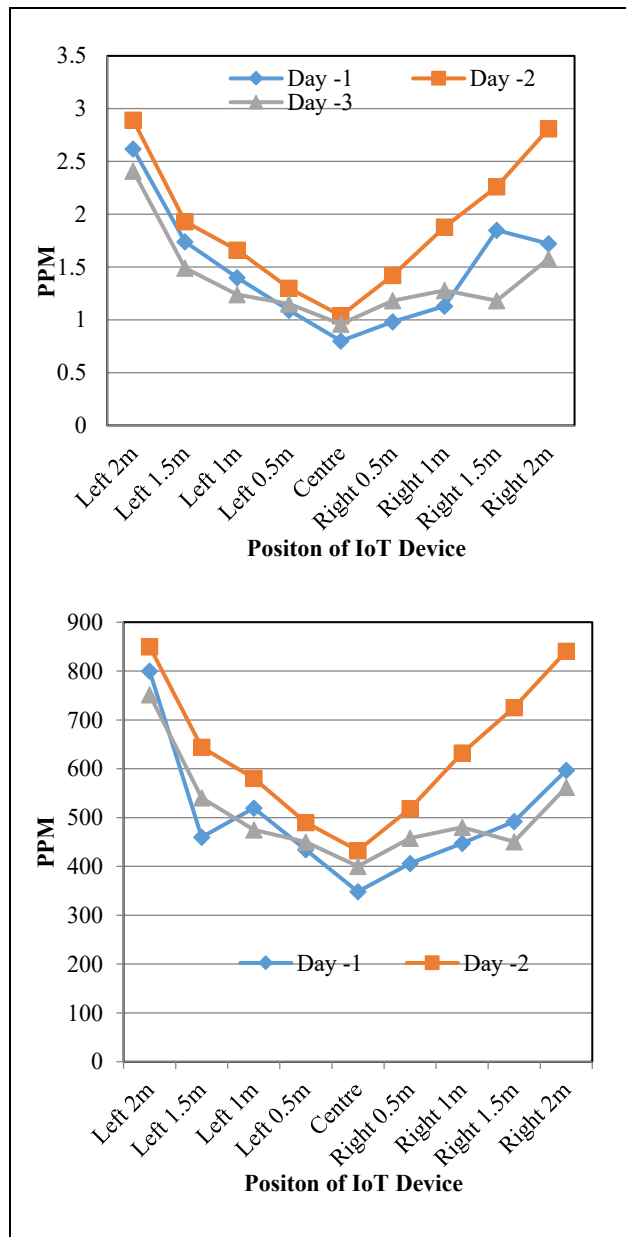


Fig. 11: Monitoring of oxides of carbon (a) Monitored carbon monoxide concentration (ppm) and (b) Monitored carbon dioxide concentration (ppm)

Referring to Figure 13(a), the toluene content steadily decreases toward the center, thereby reducing atmospheric pollution. Numerous health problems, including headaches, nausea, vomiting, and dizziness, are brought on by acetone. Reducing the amount of acetone in the air can lessen such issues. The paver block containing TiO₂ reduces these hazardous air pollutants, as shown in Figure 13(b).

Carbon dioxide, carbon monoxide, acetone, toluene, ammonium, and ethanol are among the factors that are examined. The data collected from the research area are

presented on several graphs. The concentration of contaminants in this investigation is influenced by temperature and humidity. Pollutant concentrations rise when humidity rises and vice versa. The figures show that all the previously listed gases in the atmosphere decreased when the IoT device was placed in the middle of the paver block arrangement. The CO and CO₂ values were first categorized as moderately contaminated by the air quality index. The concentrations of the pollutants mentioned were high at a distance of 2 m from the paver block. As the device was moved from 2 m away to the center of the arrangement, its location gradually decreased. This implies that air pollution concentration is considerably reduced when TiO₂-containing paver blocks are installed.

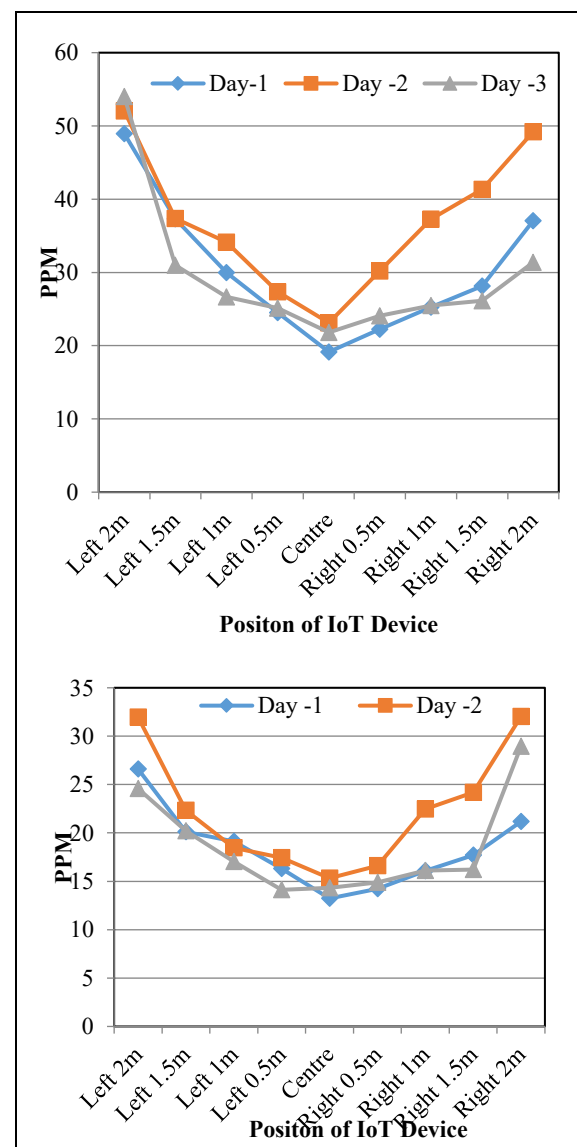


Fig. 12: Monitoring of ethanol and ammonium (a) Monitored ethanol concentration (ppm) and (b) Monitored ammonium concentration (ppm)

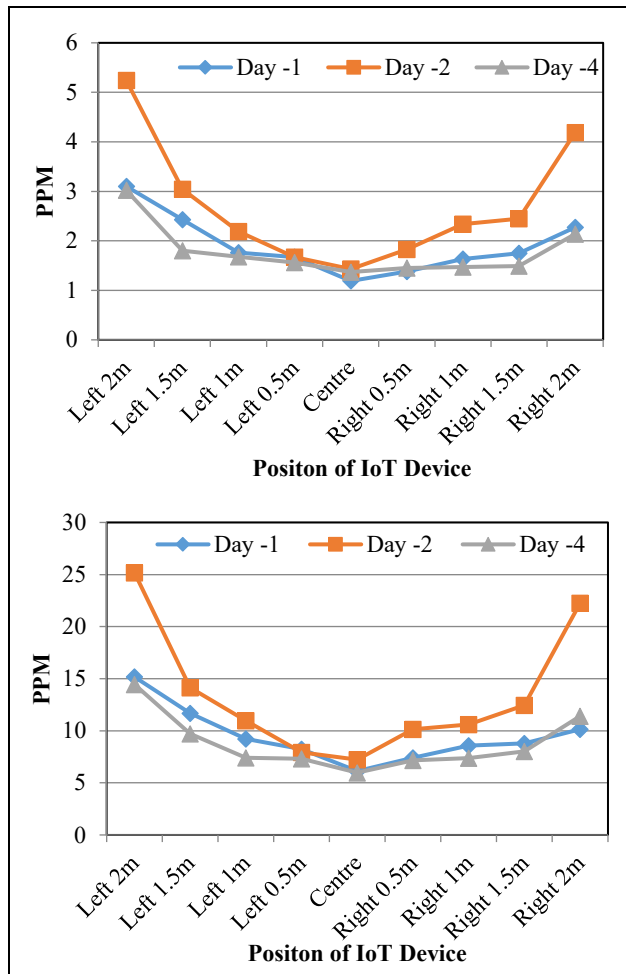


Fig. 13: Monitoring of toluene and acetone (a) Monitored toluene concentration (ppm) and (b) Monitored acetone concentration (ppm)

4. CONCLUSION

This research has successfully developed and assessed the mechanical performance of TiO₂-activated carbon-based air-purifying geopolymer paver blocks, and their real-time photocatalytic efficiency in removing pollutants. The geopolymer mix containing fly ash, GGBFS, metakaolin, and 1% TiO₂ exhibited a compressive strength of more than 40 N/mm² at 28 days, reaching a maximum of 44 N/mm². Water absorption remained within the permissible limits, indicating a dense and durable matrix. Photocatalytic tests confirmed that up to 86.5% of the dye was efficiently degraded. IoT-based on-site monitoring revealed noticeable reductions in PM_{2.5} concentrations, and in VOCs such as CO, CO₂, ethanol, acetone, ammonium, and toluene in the immediate surroundings of the installed paver blocks. The overall results confirm that TiO₂-infused geopolymer paver blocks are a promising, sustainable, and cost-effective solution for mitigating air pollution while utilizing industrial byproducts.

The resultant TiO₂-activated carbon geopolymer paver blocks have a high mechanical strength of 40 N/mm²

and efficient air-purifying performance, achieving up to 70% PM_{2.5} removal and 50% VOCs under controlled conditions. IoT-based monitoring confirms a reduction in pollutants within the photocatalytic pavement area, using waste-based fly ash, GGBFS, and bottom ash to support industrial waste valorization. This low-energy, cement-free solution is considered suitable for sustainable urban applications.

This work has some limitations regarding short-term field monitoring, small-area pollutant measurement, climate-dependent photocatalytic performance, and the moderate increase of water absorption caused by TiO₂. The use of recycled materials, surface coatings, the development of smart IoT-enabled photocatalytic pavements, and detailed techno-economic and life-cycle assessments will facilitate large-scale, sustainable deployment.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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