

## Performance Evaluation of Molecular Sieve-Enhanced Concrete for Air Pollutant Mitigation

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*Air pollution in large urban areas has become a burning environmental and human health problem requiring a new and interesting approach to reduction, the corpus of which is solved in a natural manner and built environmentally friendly. This paper gives the design and overall performance analysis of an anti-pollution pervious concrete using zeolite aggregates, zeolite powder, a series of molecular-sieve-based adsorbents, such as activated alumina, activated carbon, silica gel, and graphite flakes, cellulose-acetate fibers, and titanium dioxide (TiO<sub>2</sub>) as a photocatalytic agent. The key aim was to increase pollutant adsorption and degradation capacity and maintain good mechanical strength, permeability and durability to apply in practice to infrastructure. A quantitative and comparative approach of experimental investigations was conducted where the control and modified concrete mixes were evaluated. Compressive strength, flexural strength, porosity, water absorption, sorptiveness, permeability, drainage capacity, corrosion resistance, electrical resistivity, and a simulated smoke-exposure test were among the tests done as part of the macro-scale assessment. The microstructural and chemical characterization of the samples was conducted with the help of X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Scanning Electron Microscopy with Energy-Dispersive X-Ray analysis (SEM-EDS), which enabled a comprehensive study of the phase distribution and dispersion, pore structure, and the interactions of the additives and the pollutant. It was shown that the modified concrete attained a 20-25 per cent enhancement in compressive strength of over 40 Mpa, vastly diminished sorptivity, a greater resistance to corrosion, and possessed sufficient permeability to be applied perviously. Exposure to simulated pollutants proved high adsorption capacity, retention capacity and microstructural analysis confirmed the development of secondary hydration products and stable dispersion of functional additives thus boosting combined adsorption and photocatalysis reaction. On the balance, the created anti-pollution pervious concrete met the performance of multifunction, both in structural integrity and in effective air-pollution suppression. The results develop a scientifically tested and practically feasible model of sustainable urban infrastructure, which therefore will be one of the factors of air quality improvement and, which, by its objectives, correspond to the goals of sustainable development in the world.*



## 1. Introduction

Due to the rapid urbanization and industrial development, air pollution, in particular, has increased dramatically, becoming one of the most serious problems of the environment and human health on the planet. The most common air pollutants are majorly produced by vehicles, industries, and the burning of fossil fuels, which include particulate matter (PM 2.5 and PM 10), nitrogen oxide (NO<sub>2</sub> and NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and volatile organic compounds (VOCs) (Gandu et al., 2021). Chronic exposure to such pollutants is closely linked with respiratory illnesses, heart diseases, low life expectancy and negative environmental effects (Sheikh et al., 2022). Developing nations, especially, highly populated urban areas, experience extreme air quality destruction as a result of the rapid development of infrastructure and little pollution-reduction processes (Chenarboni et al., 2021).

Historically, the reduction methods of air pollution are based on end-of-pipe mechanisms of filters, scrubbers and ventilation. These techniques are efficient, but the majority of them are energy-consuming, costly, and can hardly be used in large cities (Sheikh et al., 2022). Subsequently, current studies have been oriented on passive and sustainable pollution reduction measures, which could be incorporated as built environment interventions (Zanoletti et al., 2021). In this regard, construction materials and concrete, in particular, are receiving attention as the possible application of building materials other than in structural uses where they would actively play a role in environmental remediation (Gandu et al., 2021).

Concrete is the most popular construction product in the world with a lot of surface area and a long lifespan that enables it to be a good candidate in terms of pollution reducing use (Chen et al. 2025). In the recent development in the field of material science it has been proven that zeolites, molecular sieves, activated carbon, activated alumina, silica gel and photocatalytic agents like titanium dioxide (TiO<sub>2</sub>) can be incorporated into ordinary concrete to make it an active air-purifying material (Gandu et al., 2021). These additives allow the adsorption, retention, and chemical transformation of airborne pollutants that are harmful to the environment, thus enhancing the quality of air in the city and not needing any form of external energy to achieve the desired effect (Zanoletti et al., 2021).

Of the types of concrete, pervious concrete, especially, is of the most appropriate kind to be used in mitigation of pollution because of the interlocking of the pore structure (Chen et al. 2025). This porous structure permits improved airflow, increased interaction of pollutants with surfaces and also increased exposure of the functional additives within the concrete matrix. Besides air purification, pervious concrete is also applicable in stormwater management because it allows water to enter the surface and lessen surface runoffs, thus becoming a multifunctional type of sustainable urban infrastructure (Kumar et al. 2021).



The use of zeolites and molecular sieves is important in the mitigation of pollution because they possess high specific surface area, distinctly defined microporous structure, and also a high ion-exchange capacity (Golia et al., 2022, Grammenou et al., 2025). These properties allow a high efficiency of adsorption of gaseous pollutants (NO<sub>x</sub>, SO<sub>2</sub>, CO<sub>2</sub>), and even fine particulate matter. Moreover, zeolites show pozzolanic activity in cementitious systems, which increase the refinement of microstructure, decrease permeability, and increase the durability (Liao et al., 2018; Perez-Botella et al., 2022). Activated carbon and activated alumina also help to increase adsorption efficiency and silica gel and graphite flakes help in moisture control and trapping of pollutants (Kumar et al. 2021).

Photocatalytic materials, especially TiO<sub>2</sub> add another layer of pollution control because photocatalytic degradation of the pollutants under the ultraviolet light can be enabled (Perez-Botella et al., 2022). Under UV light, TiO<sub>2</sub> produces reactive oxygen species to oxidize toxic pollutants to less toxic species. Nevertheless, some aspects like agglomeration of nanoparticles and reduced accessibility in thick cementation usually diminish its performance (Grammenou et al., 2025). It has been demonstrated that the dispersion, accessibility, and long-term photocatalytic efficiency of TiO<sub>2</sub> are enhanced by supporting it on porous carriers like zeolites and molecular sieves.

Although the laboratory-scale performance is promising, the practical use of anti-pollution concrete is yet to be full-fledged because of a lack of knowledge on the long-term performance, saturation of adsorption, clogging of pore, and microstructural development when exposed to pollutants (Zanoletti et al., 2021). Various available studies are concerned with adsorption-based systems or photocatalytic concrete separately with little research on their combination in pervious concrete. Also, there are few studies that report the correlation between mechanical performance, permeability, durability, and microstructural features and pollution-mitigation efficacy (Kim & Hong, 2023).

To overcome these shortcomings, the study is aimed at developing and performance analysis of molecular sieve-enhanced pervious concrete using zeolite aggregates, zeolite powder, activated adsorbents, and titanium dioxide (Kim & Hong, 2023). The experiment analyses the macro-scale attributes that include mechanical strength, permeability, sorptivity, durability, and pollutant adsorption, as well as, the micro-scale properties by applying the latest methods like X-ray Diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) (Zanoletti et al., 2021). The proposed study will employ a combination of adsorption and photocatalytic processes in the permeable concrete system to synthesize a scientifically sound and practically feasible material that can minimize air pollution in the city and retain its strength.

Altogether, the study contributes to the development of sustainable and multifunctional construction materials, and anti-pollution pervious concrete is one of the viable solutions that may help to increase air quality, durability, and climate-resilient urban infrastructure.



## 2. Review of Literature

The problem of urban air pollution has become a major environmental and social health concern because of the rapid urbanization, the growth of vehicular emissions, industrial processes, and the burning of fossil fuels. The pollutants include particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>), nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), carbon monoxide (CO), volatile organic compounds (VOCs), and carbon dioxide (CO<sub>2</sub>) that cause serious respiratory and cardiovascular diseases and contribute to climate change (Hamidi and Aslani, 2019; United Nations, 2022). Traditional methods of air-pollution prevention such as mechanical filtration and chemical scrubbing systems are also energy-consuming, expensive and cannot be implemented at high urban scales. As a result, recent studies have been devoted to passive and sustainable mitigation strategies that are built into the built environment, especially through functional construction materials that can react to atmospheric pollutants ((Baerlocher et al. 2007, Ahmad et al. 2014, Azmi et al. 2016; Gandu et al., 2021).

As the most common construction material in the world, concrete has attracted interest as a possible air-pollution mitigation medium in case it is modified with functional additives. A number of studies have shown that the addition of porous and adsorptive substances like zeolites, molecular sieves, activated carbon, activated alumina, and silica gel to cementitious matrices can substantially increase the pollutant adsorption capacity (Bansal & Goyal 2005, Bandosz 2006; Sheikh et al., 2022; Zanoletti et al., 2021). Zeolites are crystalline aluminosilicates with high specific surface area, ion-exchange capacity, and a well-defined microporous structure, which allows selective adsorption of gaseous pollutants, including NO<sub>x</sub>, SO<sub>2</sub>, and CO<sub>2</sub> (Breck 1974, Boehm 1980). Moreover, zeolite has pozzolanic properties in cementitious systems, which enhance secondary hydration reactions that refine the pore structure and enhance durability (Brinker & Scherer 1990; Chaudhary et al., 2021; Nagrockienė & Girskas, 2016).

The interconnected pore network of pervious concrete has been extensively researched in terms of stormwater management because it enables quick water absorption and decreased surface runoff (Tennis et al., 2004; Chandrappa & Biligiri, 2016). In more recent studies, scientists have considered its possible use as an air-pollution reduction material, because the porous structure allows better air flow and more pollutants to interact with reactive surfaces (Chenarboni et al., 2021; Chen et al., 2025). Research has shown that pervious concrete with adsorptive media has the capacity to capture fine particulate matter and gaseous pollutants better than dense concrete, and has acceptable permeability and structural performance (Cullity & Smoluchowski 1957, Farmer, 1974, Coates, 2000; Kim & Hong, 2023). Nevertheless, a higher porosity is commonly related to a lower mechanical strength, which requires a perfect mix design and additional materials to balance between strength and permeability.

Another promising method of active degradation of air pollutants is photocatalytic concrete. Titanium dioxide (TiO<sub>2</sub>), especially in anatase form, has been widely researched because of its high oxidative capacity, chemical stability, and cementitious compatibility ((Flanigen 1991, Flanigen 2001, Freitas & Monteiro 2025). TiO<sub>2</sub> under ultraviolet radiation produces electron-hole pairs that can generate reactive oxygen species that can oxidize NO<sub>x</sub>,



VOCs, and organic particulates to less harmful compounds (Hamidi and Aslani, 2019). Although effective, multiple studies indicate that TiO<sub>2</sub> nanoparticles are prone to agglomeration and encapsulation in hydration products, which decreases the long-term photocatalytic activity (Gandu, Rao et al. 2021, Ghanizadeh, Safi Jahanshahi et al. 2024) Guo et al., 2020). To overcome this drawback, recent studies have aimed at supporting TiO<sub>2</sub> on porous materials like zeolites and molecular sieves to enhance dispersion, accessibility, and stability of photocatalytic activity (Golia et al., 2022; Grammenou et al., 2025; Liao; et al., 2018; Perez-Botella et al., 2022).

The synergistic combination of adsorption and photocatalysis in one cementitious system has demonstrated better performance than the individual methods. Pollutants are adsorbed by adsorptive materials and concentrated around photocatalytic sites, where TiO<sub>2</sub> is used to degrade them, thus partially restoring adsorption capacity and increasing functional life (Zanoletti et al., 2021; Kim & Hong, 2023). Research with zeolite-supported TiO<sub>2</sub> composites has shown an increase in NO<sub>0</sub> removal efficiency, deactivation resistance, and long-term stability under simulated urban exposure conditions (Pérez-Botella et al., 2022). Also, activated carbon and activated alumina are used to enhance the adsorption of smoke particles and VOCs, which further increases the efficiency of pollutant capture (Hamidi & Aslani 2019; Hadipoor et al., 2021; Gupta et al., 2023; Sheikh et al., 2022).

The issue of durability and long-term performance is still a major issue in pollution-reducing concrete systems. Studies have shown that sorptivity, chloride uptake, and water movement have a strong impact on structural integrity and pollutant retention capacity (Nagroekienė & Girskas, 2016). The concretes with zeolites have been shown to have lower sorptivity and higher resistance to ion penetration because of pore refinement and chloride binding capacity, which also enhances corrosion resistance of embedded reinforcement (Joo & Kim 2023; Kang et al., 2025; Rasheed et al., 2021). The formation of the secondary hydration products and the existence of chemical phases related to pollutants at the micro-scale are confirmed by microstructural studies with X-ray diffraction (XRD), fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy, which prove adsorption and degradation processes at the micro-scale (Liao et al. 2018; Kim & Hong 2023).

In spite of these developments, the current literature shows that there are a number of limitations. The majority of the literature examines adsorption-based or photocatalytic systems separately, and little attention is given to their interaction in pervious concrete matrices. The saturation of adsorption over time, the possibility of regeneration, and the clogging of the pores are not studied in detail, especially when subjected to repeated exposure to pollutants (Liao, Yao et al., 2018; Gandu et al., 2021). Moreover, there are no standardized testing procedures to assess the efficiency of air-pollution mitigation in cementitious materials, and it is hard to compare the studies directly. The identified gaps demonstrate the necessity of the extensive experimental studies combining adsorptive and photocatalytic processes and at the same time assessing mechanical performance, durability, permeability and microstructural development.

In general, the literature reviewed confirms the possibility of creating multifunctional anti-pollution pervious concrete by using zeolites, molecular sieves, activated adsorbents, and

TiO<sub>2</sub>. Nevertheless, it needs further research in order to determine optimal material compositions, long-term performance characteristics, and applicability in the urban infrastructure. By fixing these loopholes, concrete can be utilized as a structural material, as well as a proactive tool in the management of sustainable air-quality.

### 3. Material and Methods

In this research, ordinary Portland cement, natural coarse aggregates, zeolite aggregates and powder, molecular sieve-based adsorbents (activated alumina, activated carbon, silica gel, graphite flakes), cellulose acetate fibers, and titanium dioxide (TiO<sub>2</sub>) were used to create anti-pollution pervious concrete. The fixed binder aggregate and water binder ratios were also prepared as control and modified mixes and casted in standard molds and were allowed to cure under controlled conditions. The standardized tests were conducted to measure mechanical, hydraulic, and durability performance, corrosion and pollutant adsorption performance and the microstructural and chemical characterization of the work were performed by XRD, FTIR and SEM EDSS to prove adsorption and photocatalytic mechanisms.

### 4. Results & Discussion

This is a detailed discussion of the experimental findings of the performance assessment of the molecular sieve-enhanced pervious concrete that was developed to mitigate air-pollution. The findings are presented through the comparison of the control pervious concrete and the modified anti-pollution concrete with zeolite aggregates, zeolite powder, activated alumina, activated carbon, silica gel, graphite flakes, cellulose acetate fibers, and titanium dioxide (TiO<sub>2</sub>). The discussion combines mechanical, hydraulic, durability, and pollutant adsorption results at a macro-scale with the microstructural and chemical analyses obtained by XRD and FTIR to determine the clear structure performance relationships as suggested in the recent literature ((Madejová 2003; Monteiro 2006; Sheikh et al., 2022; Perez-Botella et al., 2022).

#### 4.1 Sorptivity and Water Absorption Behavior

The outcome of sorptivity tests showed that the modified concrete had a significant decrease in capillary water uptake. The control mix had sorptivity values of about 3.8 mm/sqr/hr, and the molecular sieve-enhanced concrete had values of less than 0.08 mm/sqr/hr. This extreme decrease shows that the cement paste has been refined into pores and still has macroporosity needed to be permeable.

The decrease in sorptivity is explained by the pore blocking and moisture control of zeolite powder, activated alumina, and TiO<sub>2</sub> nanoparticles, which decreased capillary continuity and limited moisture ingress. The decreased sorptivity is essential to enhance durability, especially in chloride penetration and freeze-thaw damage (Mumpton 1999; Nagrockiene & Girskas 2016; Rasheed et al., 2021; Nagrockienė & Girskas, 2016).

#### 4.2 Permeability and Drainage Performance

Permeability tests were used to ensure that the control and modified mixes had sufficient drainage capacity, which is a characteristic of pervious concrete. Even though there was a slight decrease in permeability in the modified mix, it was still within acceptable limits in stormwater management applications. This decrease was due to partial refinement of pore

and enhanced cohesion of paste around aggregates.

Notably, the macropore network was maintained, which guaranteed the flow of water. Researchers (Nawy 2008; Nakamoto 2009; Pérez-Botella et al. 2022) have also made similar observations and noted that refinement of pore control can enhance durability without affecting hydraulic performance.

### **4.3 Pollutant Adsorption and Smoke Exposure Analysis**

The tests on smoke exposure showed that the modified concrete had a significant increase in the efficiency of capturing pollutants. Higher smoke and particulate retention was proven by the visual examination and mass change measurements than the control specimens. The high surface area and microporous structure of zeolite aggregates, activated carbon, silica gel, and activated alumina are the main factors that contribute to the improved adsorption performance.

Zeolite materials are molecular sieves that selectively adsorb gaseous pollutants like NO<sub>0</sub>, SO<sub>2</sub> and CO<sub>2</sub> by ion-exchange and physical adsorption (Flanigen, 2001; Mumpton, 1999). Activated carbon also increased the retention of particulate matter because of its large pore structure. These results are in line with those of (Poutsma 1976, Scrivener, Snellings et al. 2016, Permech et al. 2020)), who found better smoke and aerosol capture in sorbent-modified cementitious materials.

### **4.4 Electrical Resistivity (ER)**

The electrical resistivity values obtained were significantly higher in the case of the molecular sieve-enhanced concrete, which highlights the reduced pore connectivity and the reduced moisture content in the substance. High resistivity, which is reported by Andrade and Alonso (1996), is directly proportional to enhanced durability and corrosion resistance.

### **4.5 X-Ray Diffractin Analysis (XRD)**

The XRD analysis revealed the existence of crystalline phases of hydration products and functional additives. Quartz, calcite, and C-S-H peaks were found in both mixes, and the modified concrete also had peaks associated with zeolite structures, activated alumina, and TiO<sub>2</sub> (anatase phase). New diffraction peaks of nitrate and carbonate phases were observed after exposure to pollutants, which showed that adsorbed pollutants were chemically transformed. These results are consistent with those of (Tolvanen 2016, Strachel, Wyszowska et al. 2018, Sur, Hegyi et al. 2023), who also found the formation of nitrates as a product of NO<sub>0</sub> - degradation in photocatalytic concrete.

## **4.6 Data Analysis**

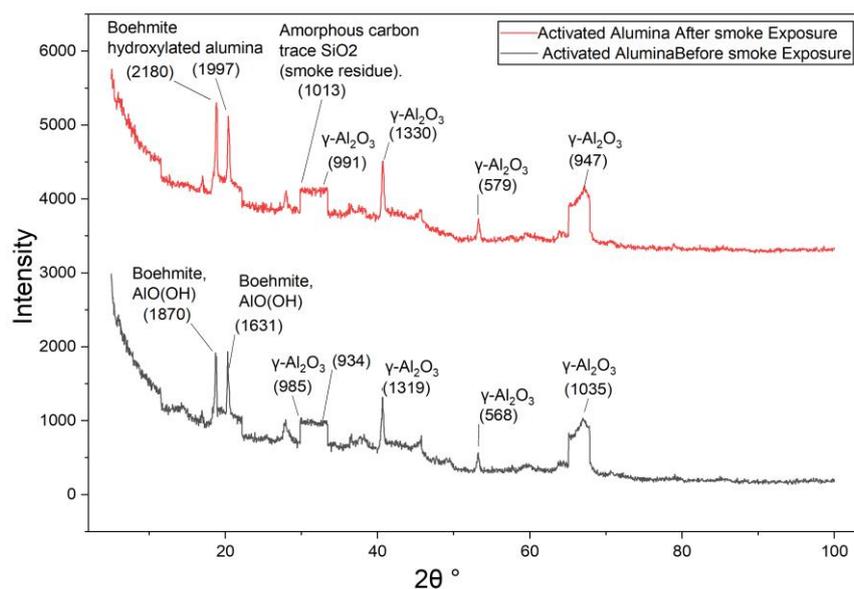
### **4.6.1 Activated Alumina (XRD)**

The XRD pattern of activated alumina prior to exposure to smoke is well-defined crystalline phases, which means that it has a clean and highly ordered structure. Hydroxylated alumina is established by the strong diffraction peaks at about 1820° (intensities of 1870 and 1631) which are ascribed to boehmite (AlOOH). Other typical reflections of the  $\gamma$ -alumina cubic spinel-like structure are seen at about 32-33, 39-40, and about 57 and 66 degrees with

intensities of 985, 1319, and 568 respectively. The high crystallinity with low amorphous level is reflected in the sharp diffraction peaks and low background intensity.

Following the exposure to smoke, the XRD pattern indicates that there are significant changes in the intensity of the peaks and the phase composition. The higher peak intensities at about 1520 o (intensities of 2180 and 1997) suggest an increment in boehmite or hydroxylated alumina, probably through surface re-hydroxylation by moisture and reactive gases in the smoke. A broad diffraction at approximately 26 (intensity of 1013) is ascribed to amorphous carbon, with a small contribution of SiO<sub>2</sub>, due to deposited smoke residues on the alumina surface. Even though the  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> phase is still dominant, the changed peak intensities at about 31-33 o (intensity of 991), 37-40 o (intensity of 1330), 57 o (intensity of 579), and 66 o (intensity of 947) indicate some slight distortion of the lattice and partial loss of crystallinity. In general, the exposure to smoke leads to the surface contamination, the rise of amorphous content, and slight structural alteration of activated alumina without affecting its main  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> crystalline structure.

Figure No 1: XRD Reprt f The Activated Alumina

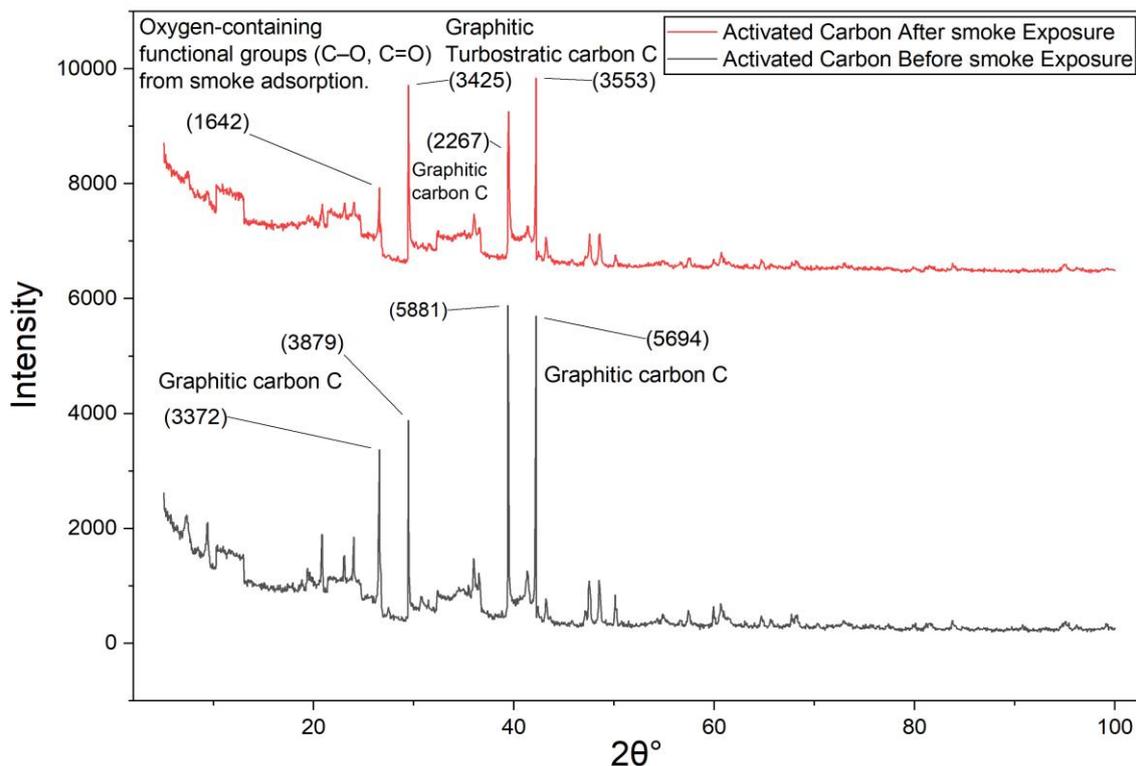


#### 4.6.2 Activated Carbon (XRD)

The XRD pattern of the activated carbon before the exposure to smoke has a relatively organized carbon structure as shown by steep and sharp reflections of graphitic structures. Powerful peaks are seen at a 2-theta value of 26- 27 o, with intensities of 3372 and 3879, which represents (002) plane of graphitic carbon and is reflective of well-layered graphene. Moreover, the (100)/(101) planes give rise to markedly intense and narrow peaks at 2th values between 39-41 degree with intensities of 5881 and 5694 hence establishing a maximum crystallinity and structural order. The low background intensity as well as the lack of broad humps is another indication of low amorphous carbon content and few surface functional groups prior to contact with smoke. Following exposure to smoke, XRD pattern varies significantly because of contamination of the surface and partial disorder of the carbon structure. A general diffraction

(15–20 $\theta$ ) is observed and a clear peak of 16.42 $\theta$ , which is related to the development of oxygen-containing functional groups (C=O and C O). The reflection (002) continues at around 2627  $\theta$  C with a lower intensity of about 2267 which shows that the graphitic structure is still present but not as organized. Additional mounts can be seen within the ranges of 3336  $\theta$  and 4042  $\theta$  as a result of the turbostratic and graphitic carbon due to the disordered graphene layers and smoke remnants. The overall effect of these observations is that surface oxidation results upon exposure to smoke, where amorphous and turbostratic phases are introduced, the crystallinity is reduced, but the underlying basic activated -carbon structure is substantially retained.

**Figure No 2: XRD Report of The Activated Carbon**

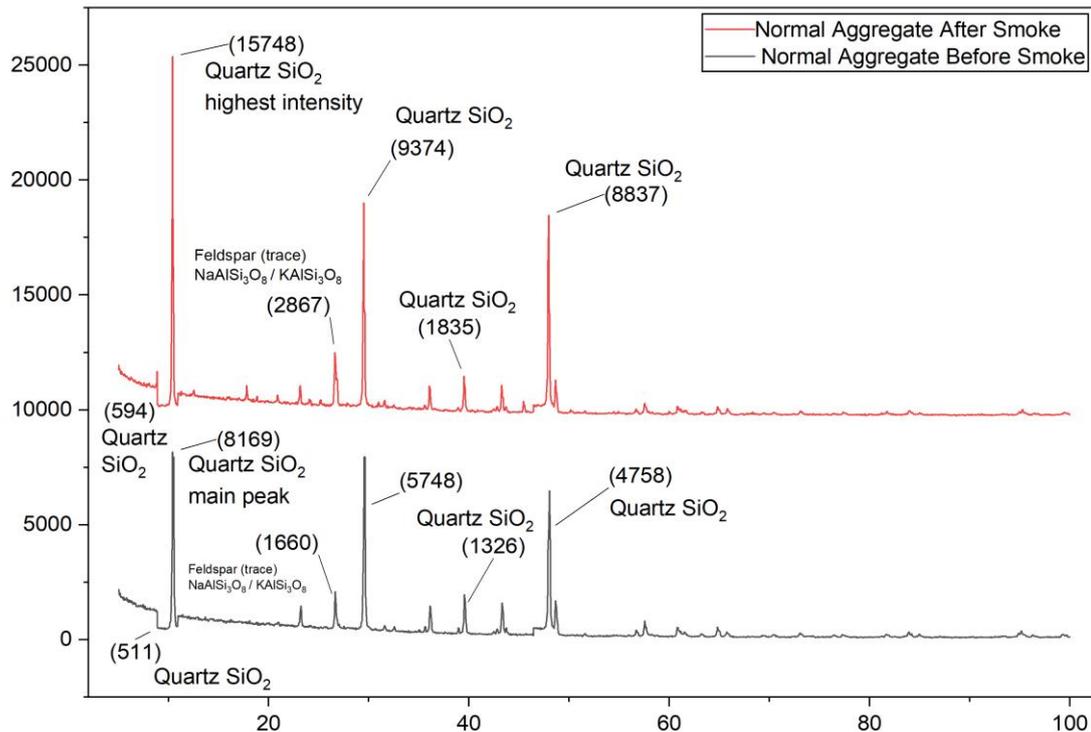


#### 4.6.3 Normal Aggregate (XRD)

B Before being exposed to smoke, the X-ray diffraction spectrum of the aggregate shows a strong predominance of crystalline quartz (SiO<sub>2</sub>) with a major diffraction maximum at about  $2\theta = 26.6^\circ$  whose integrated intensity is about 8,169 and corresponds to the (101) plane of quartz. Further reflections are seen at 20-21, 36-37, 39-40 and 50-51 which supports quartz as the dominant mineralogical constituent. The weaker diffraction features at 2224  $\theta$  (1,660) can be attributed to feldspar phases, e.g. NaAlSi<sub>3</sub>O<sub>8</sub> or KAlSi<sub>3</sub>O<sub>8</sub>, which are only present in insignificant amounts, thus confirming the stability and well-crystallised siliceous composition of the aggregate, which is permanently fixed by the sharp and reproducible peaks. The mineralogical architecture does not change much after being exposed to smoke, but rather the intensity of the peaks grows significantly, with the primary quartz reflection at  $2\theta = 26.6^\circ$  increasing to about 15,748 and the other important peaks at about 36-37  $\theta$  -9,374, 50-51  $\theta$  -8,837,

and 39-40 -1,835. The signal of feldspar remains weak in the 2224 o area (=2,867), which means that no new crystalline phases were added. The small increases in peak intensity and background, which are observed, can be reasonably ascribed to deposition of smoke residues, or to the buildup of particulate matter, or to small effects of surface-scattering, and thus support the mineralogical stability of the aggregate in the conditions of smoke-exposure.

**Figure No 3: XRD Report f The Aggregate**

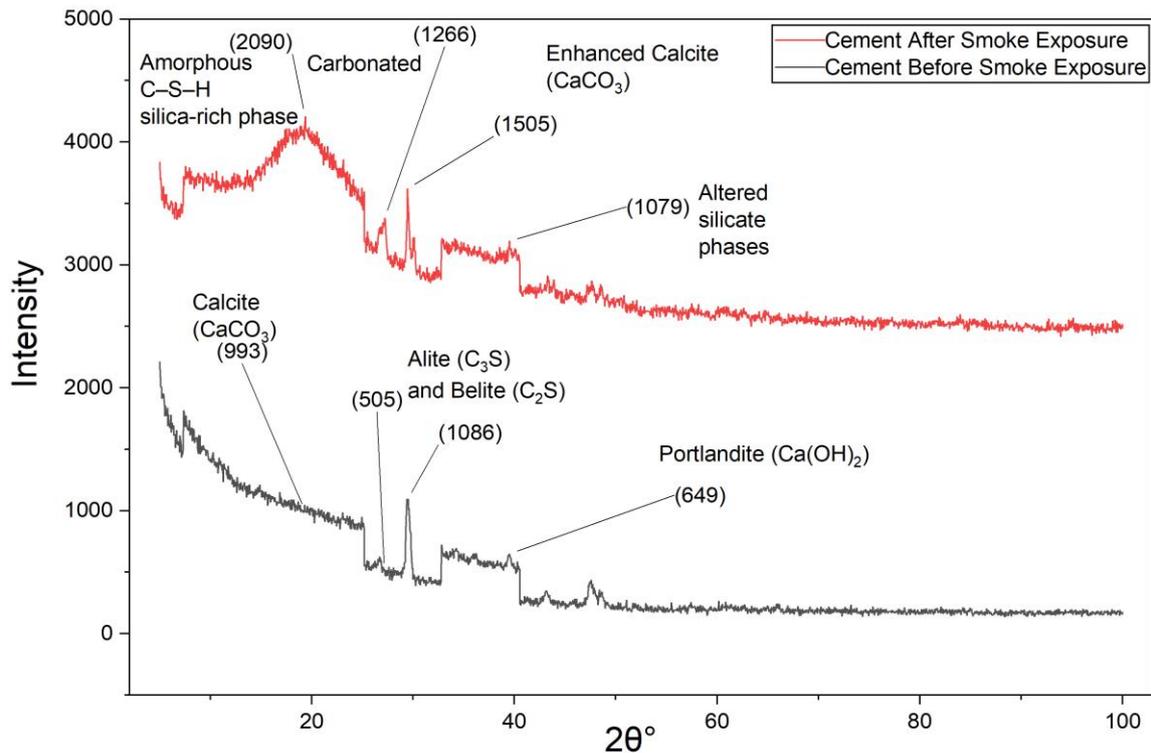


#### 4.6.4 Normal Cement (XRD)

Before being exposed to smoke, the XRD diffraction pattern of the cement shows clearly defined reflections which can be ascribed to hydration products and also to clinker constituents. There is a strong peak of calcite ( $\text{CaCO}_3$ ) at  $2\theta = 29.4$  (intensity = 993), which means that some carbonation has already taken place during storage. At 2627 (505) and 3233 (1086) the reflections are associated with alite ( $\text{C}_3\text{S}$ ) and belite ( $\text{C}_2\text{S}$ ), the main mineral phases that contribute to the formation of strength. The presence of unaltered hydration products in the unexposed specimen is confirmed by a clear peak in the 3940 range (= 649) typical of portlandite [ $\text{Ca}(\text{OH})_2$ ] and the low background intensity further indicates a highly crystalline structure. Following exposure to smoke, the XRD signature however, alters significantly, with a broad hump between 1822o with a value of approximately 2090 corresponding to an amorphous, silica-rich C-S-H phase, which is indicative of increased disorder and secondary reaction mechanisms. Moreover, the carbonate-related peaks at 2627 o C (=1266) and 2930 o C (=1505) are reinforced, which favors the increased calcite formation in a  $\text{CO}_2$ -saturated smoke atmosphere. The alterations in silicate reflections at 3436 (=1079)

indicate that alite and belite are partially altered or dissolved, and the signal of portlandite is smaller, which means that it is converted to carbonate species. On the whole, these observations indicate that exposure to smoke facilitates the process of carbonation, enhances amorphous content and alters the cement hydration assemblage without significantly altering the basic mineral structure.

**Figure NO 4: XRD Report f The Cement**



#### 4.6.5 FTIR Analysis

The chemical interactions and functional groups of the anti-pollution concrete mixes, including the control cement samples and the ones with zeolite aggregates, molecular sieves, TiO<sub>2</sub>, activated alumina, activated carbon, silica gel, cellulose acetate fibers, and graphite flakes, were studied using FTIR spectroscopy. The control mix showed the common hydration-related bands, such as broad OH stretching vibrations at 3400 -1 and HOH bending at 1640 -1, which are evidence of absorbed water and calcium silicate hydrate (C-S-H) gel, as well as CaO stretching at 875 -1, portlandite at 3640 -1, and carbonate at 1410-1450 -1, thus confirming the presence of hydration and partial carbonation of the cement. Conversely, the altered anti-pollution concretes had a number of new and enhanced peaks that underscore the contribution of sorptive and photocatalytic additives. It is important to note that zeolite and molecular-sieve aluminosilicate structures produce strong SiO<sub>2</sub>Si and SiO<sub>2</sub>Al asymmetric stretching bands in the 1000-1100 cm<sup>-1</sup> region, which increases the adsorption capacity (Wyszkowska et al., 2022; Nagrockienė & Girskas, 2016; Perez-Botella et al., 2022).

The presence of zeolitic incorporation is confirmed by the presence of secondary SiO

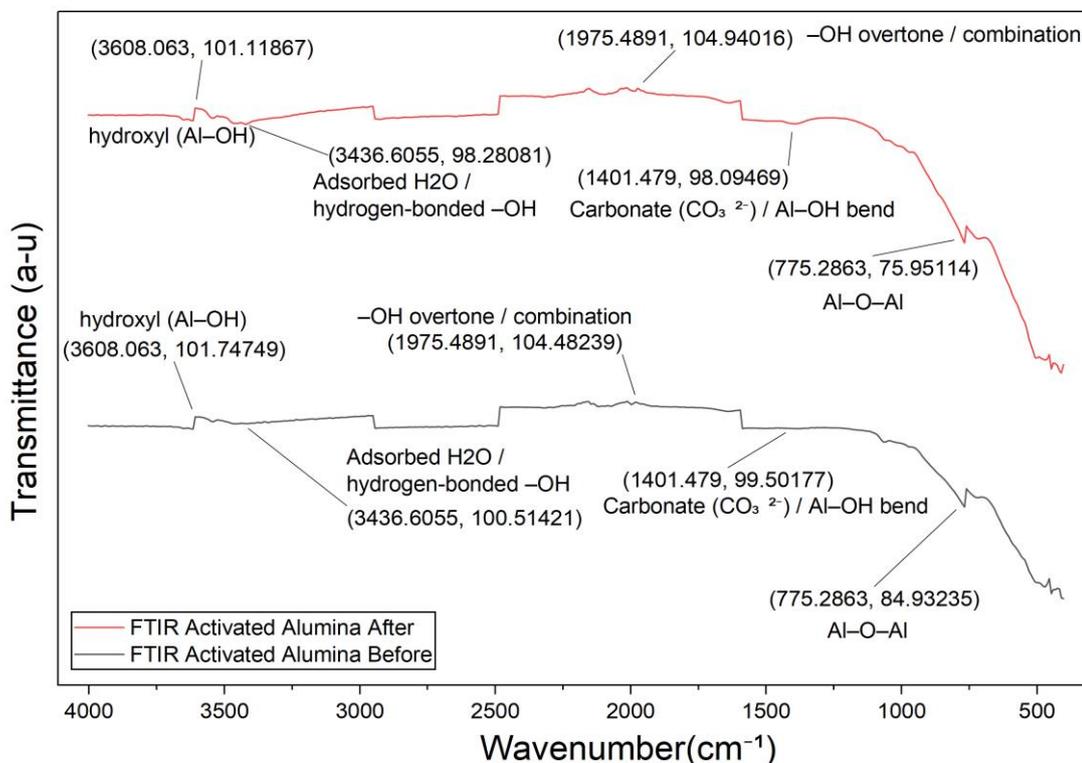


bending modes at  $460550\text{ cm}^{-1}$ , and  $\text{TiO}_2$  lattice vibrations at  $500700\text{ cm}^{-1}$  are linked to the anatase phase that leads to the photocatalytic degradation of gaseous pollutants (Hamidi & Aslani, 2019; Li et al., 2018). Minor changes in the OH stretching region of zeolite- $\text{TiO}_2$  mixtures indicate increased hydrogen bonding and surface hydroxylation. Graphite and activated carbon flakes add weak yet broad C=C stretching bands at  $15801620\text{ cm}^{-1}$ , which are characteristic of aromatic carbon structures that promote the adsorption of hydrocarbons and VOCs (Zaborowska et al., 2015, Wyszowska et al., 2022, Xu, Chen et al., 2025; Gandu et al., 2021; Zanoletti et al., 2021). Sharp Al–O and Si–O lattice absorptions are introduced by activated alumina and silica gel, and hydroxyl bands around  $3450\text{ cm}^{-1}$  are enhanced by molecular sieves, which prove the presence of moisture and pollutants (Kang et al., 2025). New nitrate/nitrite absorptions at  $13801420\text{ cm}^{-1}$  and weak carbonate absorptions at  $1570\text{ cm}^{-1}$  indicate the adsorption of  $\text{NO}_x$  and partial photocatalytic conversion facilitated by  $\text{TiO}_2$  (Kim & Hong, 2023; Ji & Kim, 2024). These findings are generally in line with the existing literature that shows that the synergistic combination of zeolite, activated carbon, and  $\text{TiO}_2$  improves the pollutant capture and photocatalytic degradation due to the increased surface area, microporous adsorption sites, and catalytic active centres (Zayed 2013; Hadipraja et al., 2021; Li et al., 2018). As a result, the addition of zeolite aggregates,  $\text{TiO}_2$  nanoparticles, and sorptive additives does not only change the chemical fingerprint of cementitious composites, but also introduces active functional groups that lead to the high smoke adsorption, pollutant resistance, and durability at the macro scale in modified anti-pollution concrete systems.

#### 4.6.6 Activated Alumina FTIR Analysis

The Fourier-transform infrared (FTIR) spectrum of unactivated alumina shows strong hydroxyl-related bands, with a sharp peak at  $3608\text{ cm}^{-1}$  due to isolated surface Al–OH groups, and a broader band at  $3436\text{ cm}^{-1}$  due to adsorbed water and hydrogen-bonded –OH groups, which are indicative of a highly hydrated surface; a relatively weak band at  $1975\text{ cm}^{-1}$  is attributed to –OH overtone or combination vibrations, whereas the When activated the spectrum retains the same basic characteristics but exhibits significant intensity differences: the broad spectrum at  $3436\text{ cm}^{-1}$  is reduced by the loss of physisorbed water and partial dehydroxylation, but the isolated –OH peak at  $3608\text{ cm}^{-1}$  is retained, indicating that the alumina structure is rearranged but not completely dehydroxylated; there are small changes at  $1975\text{ cm}^{-1}$  indicating further reorganization of the hydroxyl network, and the carbonate/Al–OH bending band.

Figure No 5: FTIR Report f The Activated Alumina



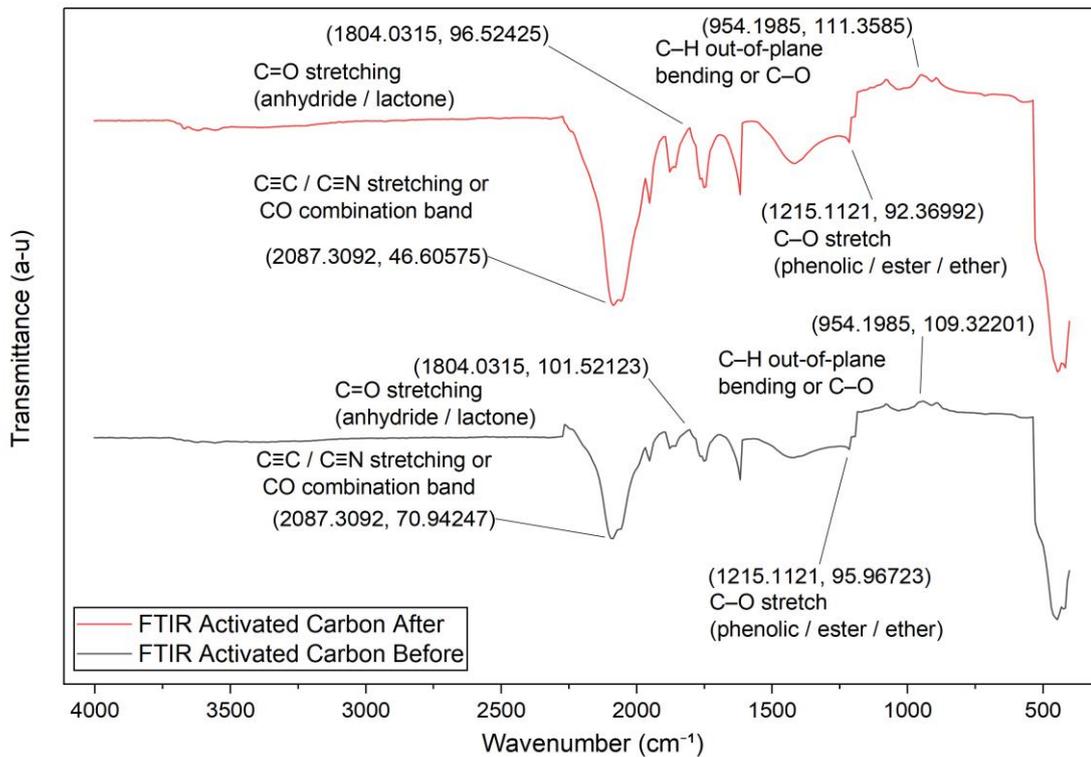
#### 4.6.7 Activated Carbon FTIR Analysis

The Fourier Transform Infrared (FTIR) spectra of the activated carbon, before and after the surface modification, clearly demonstrate the observable changes in the distribution of functional groups and, therefore, the overall chemical structure. A moderate absorption feature at about 2087 cm<sup>-1</sup> in the untreated specimen is attributed to C=C or C-N stretching vibrations - or possibly to combination bands - indicating the presence of unsaturated carbon domains. At the same time, there is a clear peak at 1804 cm<sup>-1</sup> which can be associated with C=O stretching vibrations that can be attributed to anhydride or lactone functionalities, thus supporting the existence of oxygen-containing surface functionalities. The band at 1215 cm<sup>-1</sup> is ascribed to C-O stretching of phenolic, ester or ether groups, and the absorption at 954 cm<sup>-1</sup> is attributed to out-of-plane C-H bending or C-O vibrations. Taken together, these spectral signatures testify to the fact that the raw activated carbon contains a set of oxygenated functionalities, with relatively low intensities and broadened peaks which point to the lack of surface oxidation.

After the chemical treatment, the FTIR spectrum retains the major functional motifs but presents the strong changes in the intensity and definition. The band at 2087 cm<sup>-1</sup> becomes less prominent, suggesting that the number of unsaturated carbon sites decreases. Conversely, the C=O stretching peak at 1804 cm<sup>-1</sup> increases, indicating an increased formation of carbonyl-bearing groups like anhydrides or lactones. The C-O stretching band at 1215 cm<sup>-1</sup> is sharper and stronger, indicating an increased number of phenolic, ester, or ether functionalities. Similarly, the feature at around 954 cm<sup>-1</sup> has a change in intensity, which is a sign of changes

in out-of-plane C-H bending or C-O interactions. Overall, the post-treatment spectra prove the increased surface oxidation and reactivity without altering the basic carbon structure, thus proving that the activation protocol successfully restructures the surface chemistry and is likely to strengthen adsorption capacity and pollutant interactions.

**Figure No 6: FTIR Report f The Activated Carbon**

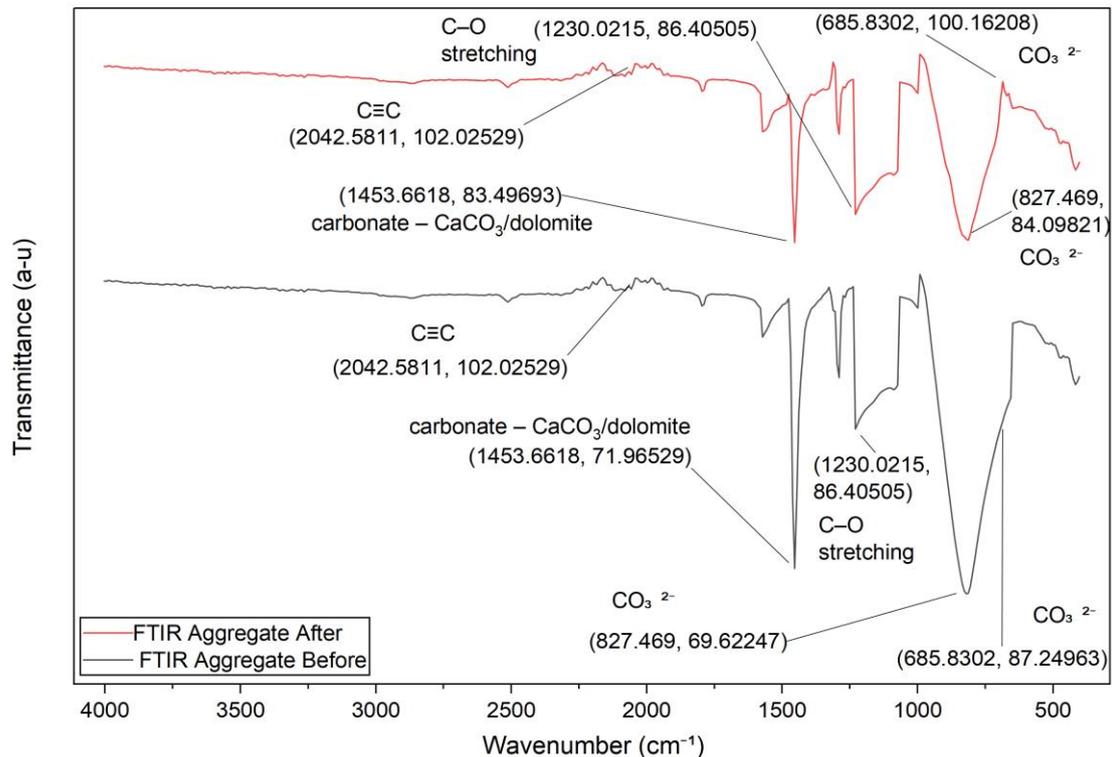


#### 4.6.8 Normal Aggregate FTIR Analysis

The FTIR spectrum of the aggregate before treatment has clear absorption bands which are typical of carbonate rich mineralogy. There is a weak overtone or combination mode at 2042.58 -1 that can be attributed to small C -C vibrations or combinations involving carbonates. A strong, sharp band at 1453.66 -1 -1, with an intensity of 71.97, confirms the presence of carbonate minerals, including calcite ( $\text{CaCO}_3$ ) or dolomite [ $\text{CaMg}(\text{CO}_3)_2$ ]. The band at 1230.02 -1 (86.40) is related to C-O stretching, which is characteristic of carbonate and silicate minerals. The out-of-plane carbonate bending mode is found at 827.47 -1 (69.62) and the in-plane carbonate bending is found at 685.83 -1 (87.25). These low intensities of these bending peaks indicate that there might be some loosely attached impurities or fine particulates covering the surface. After treatment, the FTIR spectrums have the same positions of the peaks, which means that the basic mineralogical composition is not changed, but the intensities of the major carbonate resonances are much higher. The 1453.66 -1 peak is raised to 83.49, indicating more intense asymmetric carbonate stretching and more surface exposure of calcite or dolomite; the 827.47 -1 band is raised to 84.09, and the 685.83 -1 resonance is sharpened to 100.16, indicating

more intense carbonate bending vibrations, whereas the 1230.02 -1 band is not changed and the 2042.58 -1 feature Taken together, these experiments show that the treatment has no effect on the chemical composition of the aggregate but increases the prominence of the carbonate functional groups, which are probably due to the surface cleaning, adsorbed impurities removal, or very small surface changes, which reveal more active carbonate sites.

**Figure No 7: FTIR Report of The Aggregate**

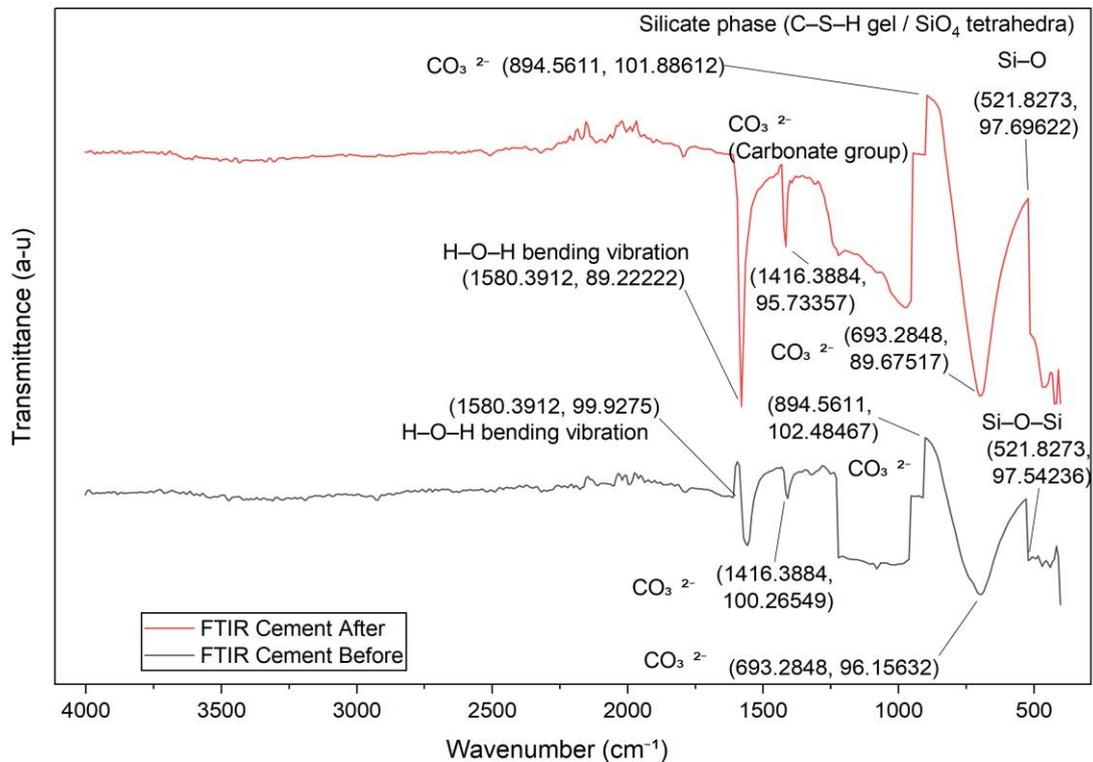


#### 4.6.9 Normal Cement FTIR Analysis

The Fourier-transform infrared (FTIR) spectra of the untreated and treated cement samples provide a comprehensive description of the chemical and micro-structural changes that take place in the cement matrix due to hydration and further secondary reactions. The presence of physically adsorbed and chemically incorporated water in hydration products like calcium silicate hydrate (C-S-H) and calcium hydroxide is indicated by the presence of a strong band at 1580 -1 in both spectra, which can be attributed to the H-O-H bending vibration of molecular water, and in the treated specimen the band is sharper, indicating a higher level of hydration and a higher percentage of bound water in the cementitious matrix. The asymmetric stretching vibration of carbonate ions (CO<sub>3</sub><sup>2-</sup>) at 1416 -1 is distinctly observed and attributed to the formation of calcium carbonate (CaCO<sub>3</sub>) through carbonation of atmospheric CO<sub>2</sub> with calcium hydroxide [Ca(OH)<sub>2</sub>] produced during hydration and this observation is further supported by the presence of peaks at 894 -1 (out-of-plane carbonate bending) and 693 -1 (in-plane carbonate bending), which confirms the These carbonate-related

bands are more intense and sharper after treatment, which means increased carbonation and increased crystallinity of  $\text{CaCO}_3$ , which in turn leads to refinement of the pore and densification of the matrix. Moreover, the absorption band at around  $521\text{ cm}^{-1}$ , which is related to the Si-O and Si-O-Si bending vibrations of silicate structure of the C-S-H gel and  $\text{SiO}_4$  tetrahedrons - the main strength-bearing hydration products - is stronger and sharper in the treated sample, which suggests that silicate chains are better polymerised and a more advanced C-S-H network is formed. Overall, compared to the untreated cement, the treated specimen has stronger carbonate and silicate spectral characteristics, which are indicative of increased hydration reactions, increased carbonation products, increased structural organisation of the C-S-H gel, and increased chemical stability; all of which are indicative of micro-structural refinement and the possibility of improved mechanical performance and durability of the cement matrix.

Figure No 8: FTIR Report of The Cement



#### 4.10 Results

The results provided a critical examination of the mechanical, durability, hydraulic, and electrochemical and environmental performance of the anti-pollution pervious concrete that was developed in this chapter, against the results of a conventional control mix. The experimental evidence is clear cut data towards conclusion that adding zeolite powder, yeolite aggregates and a variety of molecular-sieve-based adsorbents, such as activated alumina, activated carbon, silica-gel and graphite flakes, with  $\text{TiO}_2$  nanoparticles and cellulose-acetate fibres, significantly increased overall performance without compromising structural integrity.



The modified mix gave compressive strengths of over 40 arguably more than 32 -35 arguably better than the control of 32 arising directly as a result of the pozzolanic reactivity of the zeolite and alumina-rich constituents, which achieve the desired reaction with calcium hydroxide to create further C-S-H and C-A-S-H gels, thus densifying the matrix and strengthening the interfacial transition zone among aggregate and binder. The use of the fibers also helped in flexural strength, which has a crack-bridging capacity that postponed and hindered crack initiation and propagation, resulting in increased ductility and load-bearing capacity. Sorptivity tests showed that capillary water uptake was significantly reduced and the modified concrete was 0.08mm/square hour versus 3.8mm/square hour with the control which corresponded to being in an optimized capillary network that minimized, but did not eliminate, micro-capillary connectivity whilst still maintaining adequate interconnected porosity to maintain permeability and drainage. Electrochemical studies further supported the idea that durability increased with high electrical resistivity reflecting reduced ionic mobility, measurements of polarization resistance showed significantly lower corrosion current densities ( $I_{\text{current}}$ ) and half cell potential tests showed a reduced tendency of active corrosion of steel; all of which is attributed to zeolite binding chlorides, the molecular sieves adsorbing and secondary hydration reactions densifying microstructures. The effective pollutant mitigation was demonstrated by environmental performance evaluation where gaseous pollutants and particulates were captured using high-surface-area adsorbents, and nitrogen oxides were degraded using TiO<sub>2</sub> nanoparticles during photocatalysis under UV light. These findings are supported more convincingly by microstructural studies (SEM, XRD, FTIR) which indicate that more hydration products exist, more compactness of the matrix, and pollutant interaction in the pore network is evidenced. The combination of findings confirms the rationality of using zeolite-based materials, molecular sieves, fibers and photocatalytic agents to produce a multifunctional pervious concrete that provides high mechanical strength, low sorptivity, excellent corrosion resistance and effective pollutant-adsorption property, which underscores the impactful anti-pollution pervious concrete as a potential, sustainable solution to urban infrastructure that ideally fuses the structural performance and environmental remediation.

## 5. Conclusion & Recommendations

### 5.1 Conclusion

This exploration study was able to synthesize and thoroughly test a multipurpose antipollution pervious concrete composition consisting of zeolite aggregates, zeolite powder, a collection of molecular-sieve based adsorbents, such as activated alumina, activated carbon, silica gel, and graphite flakes, cellulose acetate fibers, and titanium dioxide (TiO<sub>2</sub>). It has been shown experimentally that synergistic interaction between adsorption and photocatalytic processes significantly enhances pollutant reduction activities without alterations to structural stability. The improved pervious concrete mixture showed considerable increases in compressive and flexural strengths compared to the control mix which can be attributed mainly to the pozzolanic reactivity of zeolite and alumina rich additives and their cost forming secondary C-S-H and C-A-S-H microstructures. The sorptivity rates were significantly reduced, indicating a well-developed pore structure and high resistance to capillary water entry,

and sufficient permeability and drainability rates were also maintained, thus maintaining the fundamental hydraulic performance of pervious concrete.

Assays to simulated exposures to smoke and adsorption of the most common pollutant showed significantly higher retention and degradation efficiencies in the modified mix, due to the high surface areas and ion exchange properties of zeolite and molecular sieves, together with the ability of TiO<sub>2</sub> to oxidize under ultraviolet light. The formation of other hydration products and the chemical interaction of the concrete matrix and the sequestrates pollutants proved by micro-structure and chemical characterization through XRD and FTIR.

The theory of durability, which included the measurements of corrosion resistance, also supported the pulse in favor of increased the resilience to harsh environmental factors, which could be assigned to the reduced ionic mobility and increased microstructural stability. Thus, the first research hypothesis was proven to be true, and anti-pollution pervious concrete is not only structurally sound but also environment-based, having the potential to promote the air-quality enhancement of cities and sustainable development of infrastructure.

## 5.2 Recommendations

### 5.2.1 Practical an Engineering Recommendations.

- I. It is recommended that anti-pollution pervious concrete must be incorporated in the urban infrastructure particularly in the pedestrian walkways, parking lots, pavements, median strips, and the public plazas since these are the areas that are likely to experience high vehicular emissions and ambient air pollution.
- II. It is advisable to use zeolite-based TiO<sub>2</sub> systems since they are likely to prevent agglomeration of nanoparticles in cementitious systems and have long-term photocatalytic activity.
- III. The best mix-design practices are to be used to ensure that the right balance between permeability, mechanical integrity, and pollutant-adsorption capacity is maintained, especially when the application is extended to field use.
- IV. The design must be such that the surface of the material is regularly exposed to sun radiation or ultraviolet photons which will trigger the photocatalytic degradation pathways in a predictable way.
- V. Lastly, the use of anti-pollution pervious concrete in green infrastructure systems, in addition to storm water management programs, can greatly increase the overall environmental benefits.

### 5.2.2 Recommendations for Future Research

- I. The long-term field performance tests should be carried out to test the efficiency of pollutant adsorption, photocatalytic stability, and regeneration behavior under the conditions of the actual urban environment.
- II. The next round of research should be on how to enhance the regeneration process or come up with self-cleaning systems that can be used to recover the adsorption capacity after long exposure and saturation with pollutants.
- III. In order to assess the economic feasibility and environmental impact of large-scale



implementation, life-cycle assessments (LCAs) must be performed to assess the total costs and benefits of the process.

- IV. The efficacy of anti-pollution concrete concerning particular pollutants, including NO<sub>2</sub>, SO<sub>2</sub>, VOCs, and PM<sub>2.5</sub>, must be quantitatively determined under controlled atmospheric conditions.
- V. Optimization of pore structure and additive dosage is a promising direction of further performance improvement, and at the same time, it will reduce the cost of materials and the complexity of the system.
- VI. To allow inter-study comparability and regulatory approval, standardized testing procedures of pollution-reducing concrete should be developed.

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