Engineering Journal
issn: 0125-8281

Article

Durability Characteristics and Microstructure Analysis of Zeolite and Graphene Oxide induced Self-Compacting Concrete: An Experimental Study

Jagadeep K.[1,2,a,*], **Dhevasenaa P. R.**[1,b], **Sivagamasundari R.**[1,c] **and Jodhi C.**[1,d]

1 Department of Civil & Structural Engineering, Annamalai University, Chidambaram, India
2 Department of Civil Engineering, S.R.K.R Engineering College, Bhimavaram, India
E-mail: [a,*]jagadeep.kankatala@gmail.com (Corresponding author), [b]senaadheva@gmail.com, [c]siva_1667@yahoo.com, [d]jee.ezhiljodhi@gmail.com

Abstract. This study aims to examine the influence of incorporating zeolite (Z) and graphene oxide (GO) on the efficiency of self-compacting concrete (SCC). Conventional tests are employed to assess the influence of the change on the microstructure, mechanical properties and durability of the alteration. There is a stronger focus on studying the long-lasting nature of waste expulsion. The chosen tests to investigate durability are the Rapid Chloride Penetration Test (RCPT), the rebound hammer test, the acid, alkaline and sulfate resistance test, the Ultrasonic Pulse Velocity (UPV) test, the SEM and XRD examinations of the mineral composition and microstructure. The identified optimum mix Z10G2 (Zeolite 10% and Graphene oxide 0.02%) mixture exhibited superior chemical resistance and mechanical integrity in comparison to conventional concrete (CC). This enhanced both the microscopic arrangement and the physical characteristics of the material. Based on these discoveries, it seems that identified mixes have the capacity to enhance the effectiveness and durability of concrete constructions. The overall findings indicate that inducing identified mix into concrete mixtures has the potential to enhance durability and performance in various environmental conditions. To accurately assess the potential benefits of enhancing the longevity of concrete structures, further investigation is needed to examine the long-term effects on these structures.

Keywords: Zeolite, graphene oxide, rapid chloride penetration test, ultrasonic pulse velocity, SEM and XRD.

ENGINEERING JOURNAL Volume 28 Issue 12
Received 23 May 2024
Accepted 23 November 2024
Published 31 December 2024
Online at https://engj.org/
DOI:10.4186/ej.2024.28.12.41

1. Introduction

The construction and upkeep of civil infrastructure both need the utilization of cementitious materials heavily. In addition to providing durability and lifespan for a longer amount of time, they are important for a wide variety of endeavours [1]. In the meantime, the concrete industry is continuously investigating new ways to enhance the properties of cementitious materials and reduce the impact that they have on the environment [2]. This entails the incorporation of alternative fiber alternatives, nanomaterial additives, and supplemental cementitious materials (SCMs) in order to reduce carbon emissions and improve the qualities of strength and durability. [3-4]. Approximately 7% of global carbon dioxide emissions are attributed to the cement industry. Therefore, it is crucial to explore different solid waste materials for use in cementitious composite materials [5]. Common waste products may consist of slag, fly ash, silica fume, nanomaterials, and others. They have inspired numerous research studies aimed at comprehending their impact and implementing mixture design specifics to effectively harness their wide range of advantages [6–11]. Naturally occurring alternatives like natural zeolite are attractive for their low energy requirements during manufacture. Their production comprises a straightforward procedure of extraction and grinding. Partially substituting cement with supplementary cementitious materials (SCM), such as natural zeolites, might lead to the following overall advantages [12, 13]: (1) Reduced manufacturing costs in comparison to traditional Portland cement; (2) Decrease in energy consumption and CO_2 emissions; (3) Enhancement in the mechanical characteristics of concrete products, particularly over time; and (4) Improved durability and lifespan.

Natural zeolites are used in several industries such as wastewater treatment, gas purification, and construction. They are notably used as pozzolanic admixtures in concrete [14]. Using a zeolitic additive with high water absorption capacity in low water-to-binder ratio concrete mixtures can help decrease permeability and improve the durability of cement paste and concrete. Zeolite is utilized as an aggregate in the production of lightweight concrete [15]. Additionally, concretes that contain natural zeolite have demonstrated increased durability in the face of sulphate assault and freeze-thaw cycles. The production of concrete frequently makes use of volcanic ash from the Black Forest that contains forty-five percent zeolite [16]. This ash is also exploited in various European locations, including Germany, Switzerland, and France. Concrete constructions that make use of high-strength components, such as paving stones, slabs, and pipes, have been made with the help of this concrete [17]. Multiple nations have shown a great amount of interest in the utilization of zeolite as a pozzolanic material. The utilization of natural zeolite in the concrete industry is restricted due to its rarity and the availability of more cost-effective substitutes. As a result, its application is restricted to several locations across the world [18]. The consequences of introducing natural zeolite into the qualities of concrete have been the subject of many research investigations, and these investigations have contrasted this pozzolanic material with other goods that are extremely similar [19]. It is common practice to use natural zeolite rather than Portland cement to improve durability. This is mostly due to the pozzolanic qualities of natural zeolite. It is possible that experimental research will not always produce consistent results because of the differences in the shapes, structures, and purities of natural zeolite. There have been instances where contradictory observations have been recorded [20]. Several studies have been conducted to investigate the effects of varying concentrations of natural zeolite on the properties of concrete [21]. Research that has been done in the past has focused mostly on the mechanical properties, alkali-silica reactions (ASR), and transport characteristics of concrete and mortar compositions that contain zeolite [22]. Despite valuable study, information on further durability aspects like resistance to sulphates is scarce. The study found that silica vapor is more beneficial than zeolite in enhancing the load resistance and decreasing the initial surface absorbency and chloride ion diffusion in concrete [23]. Cementitious composites are commonly utilized in construction, however some issues like low durability and the requirement for regular inspection and maintenance have been documented. Additionally, certain cementitious composites exhibit low tensile strength and are prone to cracking when subjected to stress [24].

The idea of using nanoparticles in cementitious composites originated as a result. Several significant nanoparticles were included into cementitious composites, yielding excellent outcomes. Graphene oxide is one of the choices. Graphene oxide (GO) is a nanomaterial that is smaller than 100 nm and contains an extra hydroxyl group attached to the hexagonal carbon structure. GO is a monolayer material composed of carbon, oxygen, and hydrogen, produced through the oxidation of graphite crystals [25]. The structure of GO consists of graphene sheets that are oxygenated, containing hydroxyl (OH) and epoxy (-O-) groups on their basal planes, and carboxyl (COOH) and carbonyl (C=O) groups on their sheet edges [26, 27]. The presence of active groups causes a change in van der Waals force between GO particles, enhancing dispersion and reactivity. Sonication disrupts the surface of GO, leading to its reduction in size from the micro to nano scale. Removing the oxygen groups attached to GO can partially transform it into graphene [28]. An r-graphene oxide, commonly referred to as functionalized graphene or chemically modified graphene, is a reduced graphene oxide (rGO) [19]. Introducing functional groups to graphene can reduce its mechanical properties, as seen in references [29-33]. GO has an advantage as a reinforcement in cement composite because it is more efficient at controlling crack development and propagation at the nano scale level compared to traditional reinforcement methods [34, 35].

GO stands out because of its exceptional characteristics, including a high tensile strength of 130 GPa, a huge specific surface area of 2630 m2/g, and a high thermal conductivity of 5300 W/mK. Carbon nano fibers and nano tubes have a physical role in cement composites, while GO is involved in the hydration and chemical modification of cement, resulting in a composite with enhanced qualities compared to traditional cementitious composites [36]. Prior research on incorporating GO in cement composites has shown that GO strengthens the composites through its nano material filling ability and chemical interaction with the cement matrix, resulting in a strong covalent bond [37]. This bond enhances load transfer efficiency from the matrix to the GO sheets, leading to increased compressive strength. Moreover, the many functional groups on GO's surface create a space for water molecules and cement components to adhere, which accelerates the cement hydration process [38–41]. Similarly, some literature has highlighted the limitations of using GO in a cementitious composite. According to literature, GO enhances the hydration rate in cement by creating additional attachment sites for the C-S-H gel [42]. However, the reduction of GO functional groups in alkali cementitious environments can weaken the bond between GO and C-S-H, diminishing GO's reinforcing properties. The replacement rate of GO is over 0.03%, leading to an increase in pore capacity through flocculation [43-48]. This results in a decrease in compressive strength. GO causes a rupture in the PVA fiber before complete debonding from the matrix, impacting the mechanical performance of the strain-hardening cementitious composite. Graphene has the potential to enhance the performance of cement mortar, however its limited dispersibility inside the cement matrix is a significant drawback [49, 50]. The strong van der Waals interactions between the graphene sheets reduce aggregation and adherence to the matrix, leading to failure.

1.1. Objectives

This study paper investigates the use of zeolite and graphene oxide in conjunction with one another as a partial replacement for concrete. Specifically, the Cement is replaced with zeolite and graphene oxide. In order to investigate whether or whether this combination is beneficial in terms of lowering the carbon footprint in SCC, the findings are being analyzed. Findings of [51] suggests that use of PETE fibers as fiber- reinforced concrete have increased strength parameters, the study suggests 1.3 denier fibers are optimal among the planned others. Another study has utilised the recycled aggregate and carbon fiber and showed notable improvements from CC [52]. Also, another study where the focus given to SCM materials such as steel fibers, hooked –end steel fibers and milled steel fibers and undergone with both strength and internal structure analysis and found hooked end steel fibers are best suited compared to other materials in the study [53]. Another similar study where the researchers have utilized both graphene nano platelets and geopolymer concrete as SCM and identified the mix with 10% crub rubber and 0.3% graphene nano platelets have improved strength an found mass loss after exposure to fire [54].

2. Research Methodology

2.1. Materials

An ASTM Type I Portland cement (C) [55] was used to produce the plain SCC mixtures, and the chemical and physical properties are shown in Table 1. In addition, the mineral admixtures namely Zeolite (Z), Graphene Oxide (GO) were used in partial replacement with cement by weight in different combinations of cementitious blends. Zeolite (Z) is used as a mineral admixture collected from Innovare Biopharma LLP, Rangareddi, Telangana-500094, India. The Graphene Oxide is used as a nanomaterial collected from AD-NANO Technologies, Shimoga, Karnataka- 577222, India. The specific surface area of the GO is 121 m^2/g. The coarse aggregate used was nominal size of 10 and 20 mm; the fine aggregate used was natural river sand and superplasticizer (SP) used was a poly carboxylic-ether (PCE) type and is collected from Astrra Chemicals, Chennai, India. The cement was partially replaced with namely Zeolite (Z) and Graphene Oxide (GO) with different combinations to form binary, ternary blends and to identify optimum mix.

Table 1. Chemical and physical properties of OPC and Zeolite.

Component	**Composition (%)**	
	OPC	**Zeolite**
CaO	65.89	4.5
SiO_2	19.5	70
Fe_2O_3	4.92	1.2
Al_2O_3	4.61	20.65
SO_3	2.53	2.2
MgO	0.9	0.91
K_2O	0.42	0.5
Na_2O	0.13	-
Loss of ignition	1.1	-
Size	90µ	1-10µm
Specific gravity	3.15	2.47
Specific surface area	0.2 m^2/g	360 m^2/g

2.2. Mix Proportions

In this study, the mix proportions are achieved by the trial-and-error method as per EFNARC recommendations [56]. Initially, mix proportions are prepared to check the influence of W/B ratio and SP dosage. Followed by selection of optimum W/B ratio of 0.43 and SP dosage of 0.9%. For the fresh, harden and durability properties for conventional SCC mixes with five different Zeolite (Z) percentages are examined. From the results, the further examination of optimum percentage replacement of Zeolite (Z) in SCC mixes is fixed. To achieve these five mixes are prepared with zeolite replacement percentages of 5%, 10%, 15%, 20% and 25% respectively. To achieve the further mix, cement with Graphene Oxide were prepared with added percentage of 0.01%, 0.02%, 0.03%, 0.04% and 0.05% respectively and their fresh, harden and durability properties are thoroughly studied. Based on the finding's optimum percentage of Zeolite with Graphene Oxide is selected. As per the procedure explained above the experiments are carried out in the laboratory for the conventional concrete (CC), Zeolite (Z) and Zeolite with Graphene Oxide (ZG) mixes were prepared. The conventional and zeolite-based SCC mixes are named CC, Z5, Z10, Z15, Z20, Z25 and zeolite with graphene oxide-based SCC were named as Z10G0, Z10G1, Z10G2, Z10G3, Z10G4 and Z10G5 as shown in table 2.

Table 2. Mix proportions of all mixes along with their mix IDs.

Mix ID	**Z**	**GO**
	(%)	**(%)**
CC	0	0
Z5	5	0
Z10	10	0
Z15	15	0
Z20	20	0
Z25G0	25	0
Z10G1	10	0.01
Z10G2	10	0.02
Z10G3	10	0.03
Z10G4	10	0.04
Z10G5	10	0.05

2.3. Experimental Method

In the present study, nondestructive and durability tests were examined. The non-destructive methods such as rebound hammer, ultrasonic pulse velocity; durability tests such as rapid chloride penetration test, sulphate resistance, acid resistance and alkaline resistance were conducted. In the fresh state, slump flow diameter, V-funnel time, L-box ratio and T50 times of the SCC mixtures were measured according to the EFNARC standards [56]. Non-destructive and durability were performed for the harden concrete at 28, 56 and 90 days. The sulphate exposure testing procedure was conducted by immersing concrete specimens after the specified initial curing in a water tank containing 5% $MgSO_4$, 5% H_2SO_4 and 5% NaOH solutions at 23 ± 2°C according to ASTM C1012-04 standard [57]. The pH range of 6.0 to 8.0 for the solution was ensured each week. After the completion of curing period, the samples were subjected to chemical curing for 28, 56 and 90 days the specimens are taken out from the solution, surface dried, weighed and the value is recorded as final weight i.e., after immersion of above-mentioned solutions. Finally, the cube specimens are subjected to a compression test and the results are compared with conventional specimens. Based on the initial, final weight and compressive strength the percentage loss of weight and strength are obtained.

According to [58], the deterioration of the SCC cube specimens was investigated by determining the compressive strength loss as given in equation (1), which was calculated as follows:

$$\text{Compressive strength loss (\%)} = ((A-B))/A \times 100 \qquad (1)$$

where A is the average compressive strength of SCC specimens cured in tap water (MPa) and B is the average compressive strength of SCC specimens immersed in test solutions (MPa) for the same period.

The materials used in this experimental investigation, Z and GO are two potential alternatives to conventional concrete that are the focus of this research endeavor, which aims to find viable alternatives to the conventional materials used for producing concrete. The two materials selected for this study are expected that Z will enhance the longevity of concrete and that its influence will become increasingly apparent over time and GO shall enhance strength. In situations where a persistent lifespan is of utmost importance, this study suggests that Z may prove to be a helpful supplement. The addition of GO to mixtures of Z-concrete results in a substantial improvement in both the initial and long-term compressive strength. Situations that necessitate swift construction or where exceptional strength is critical may

Within the scope of this investigation, some different concrete mixtures were examined. These included conventional concrete (CC) as well as concrete mixtures that contained a variety of additive combinations of Z and GO. The findings unveil thought-provoking observations and benefits. Long-term compressive strength is significantly improved without a substantial compromise in early strength, even when Z is present in higher concentrations (up to 25%). Additionally, adding GO to Z-concrete mixtures greatly speeds up both the early and long-term strength development, making them stronger than regular concrete at all curing times. As a result of this synergistic effect, rapid construction and solid buildings are possible. In addition to enhancing performance, the integration of Z and GO into concrete production processes has the potential to mitigate the ecological consequences by partially substituting cement, reducing carbon emissions, and possibly prolonging the operational lifespan of structures. In general, this study highlights the potential of sustainable and innovative concrete technology approaches, which have positive ramifications for environmental sustainability and construction efficiency. This research paper explores the combinations of both Z and GO as a partial replacement of concrete by replacing cement with zeolite and graphene oxide. The findings are considered to explore this amalgamation as advantageous towards reducing carbon footprint in SCC [59]. The experimental investigation encompasses durability assessments, including RCPT, sulphate resistance, acid resistance, and alkaline resistance examinations [60, 61]. After that, non-destructive tests are conducted, including ultrasonic pulse velocity and rebound hammer. In addition, cement is utilized to partially replace Z and GO in the study. At first, cement was utilized to replace Z with 0% to 25%. Subsequently, a 10% constant was maintained with additional replacements with GO. Also, another replacement GO is adopted with percentage from 0.01% to 0.05%.

3. Results and Discussions

3.1. RCPT Result Explanation

In the study of the rapid chloride penetration test, this section will discuss the chloride ion penetrability results for the planned concrete mixtures after 28, 90, and 180 days. The results revealed significant differences between composition and performance. The CC has high chloride penetrability and exhibits values of 4,689, 3,825, and 2,017, indicating chloride ingress for 28, 90, and 180 days, as shown in figure 1. Mix Z10G2, on the other hand, emerges as the optimal blend, exhibiting significant enhancements in chloride ion penetrability in comparison to CC. After 28 days, Z10G2 recorded a penetrability level of 2,230, qualifying it as moderate. The pozzolanic activity of Z and the hydration of calcium hydroxide work together to make C-S-H gel, which makes concrete stronger and less porous. As a result of its large surface area and high mechanical strength, GO strengthens the cementitious matrix and stops the diffusion of chloride ions. Out of all the mixtures that were tested, Z10G2 has the best mechanical performance and resistance to chloride ions. This is because its internal structure has been optimized, resulting in a smaller pore network and better bonding between surfaces. This makes it ideal for long-term, eco-friendly concrete projects. At 90 days, the trend continues with a penetrability value of 1,154, and at 180 days, it drops even further to 788. The low penetrability rating of Z10G2 at 90 and 180 days indicates its increased chloride ingress resistance. Taking into account the compressive, flexural, and split tensile strengths reveal the advantage of Z10G2. These improvements can be attributed to the distinctive characteristics and internal configuration of Z10G2, which set it apart from CC [62]. They likely enhance the cementitious matrix by incorporating natural Z and GO, resulting in a denser microstructure and less obvious connections between pores.

Natural Z and GO enhance the ion resistance of the Z10G2 chloride mix. As per the literature, Z are minerals made from aluminosilicate that possess a porous structure and a high capacity for cation exchange. Mixing Z particles into concrete reacts with the calcium hydroxide that forms after cement hydration, resulting in the formation of more calcium silicate hydrate (C-S-H) [1]. This process reduces concrete matrix porosity and permeability and densifies it. Consequently, increased resistance impedes the diffusion of chloride ions through the concrete, leading to diminished penetrability values. Additionally, GO enhances Z10G2 concrete. Being a 2-dimensional tiny substance, GO has high tensile strength and rigidity. Some GO sheets blend into the cementitious matrices, and these sheets physically block the pathways that chloride ions typically require to move. The large surface area of GO connects to the hydration products of cement, making the microstructure denser and less permeable. [2].

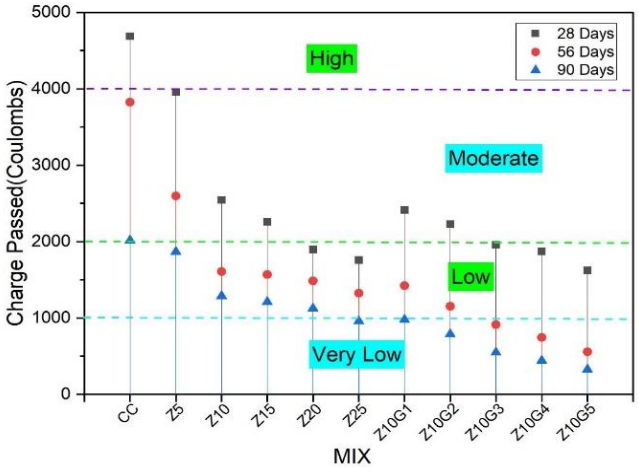

Fig.. 1. RCPT results of CC with Z and GO.

3.2. Sulphate Resistance

Sulphate resistance (SR) studies on concrete mixtures in severe sulphate-rich settings are crucial to assessing their practicality. Z concentration levels are beneficial because data analysis demonstrates different patterns and contrasts with the CC. Z-modified mixtures experience distinct losses in weight and compressive strength when compared to CC. Particularly noteworthy is the fact that certain mixtures, such as Z10, have very little weight loss while maintaining or slightly improving their compressive strength during the testing period as shown in Fig. 2a. With lower and higher Z concentrations, Z5 and Z25 lose mass and have lower compressive strengths, which may be an issue. The compression strength evaluations at various time periods show how Z inclusion and resistance to sulfate affect mix performance.

It is crucial to understand how concrete mixes react to sulphates to assess their long-term durability. The GO with Z is also tested to understand the SR. Z10G2 is identified as the best composition for SR. The time period taken little longer for Z10G2 to lose weight than it does for the CC, which loses 2.12%. Z10G2 maintains its weight loss percentage lead over subsequent durations. In addition, Z10G2 has very good resilience; its starting compressive strength at 28 days was 58.53 N/mm², which was higher than CC's 52.88 N/mm². Overall, all mixtures lose strength over time, but Z10G2 has the least amount, only losing 6.7% of its strength after 90 days compared to 15.0% for CC as shown in Fig. 2b. We found that the addition of graphene oxide (G) indeed enhances durability up to an optimal concentration of 0.02%. At this level, G contributes to a denser matrix, likely reducing micro voids and enhancing resistance to environmental factors. However, as the G content increases beyond 0.02%, durability declines, which may be attributed to particle agglomeration and interference with the cement hydration process. This excess can create weak points within the matrix, resulting in a higher percentage of loss and decreased overall durability. This amazing performance of Z10G2 is due to pl hey abhinetaanned mix of materials and internal structure. Adding natural Z and GO refines the microstructure by reducing pore connectivity and improving interfacial bonding. Z's pozzolanic activity improves matrix strength and permeability by forming C-S-H gels, while GO prevents sulphate ion ingress. The exceptional mechanical characteristics of Z10G2, such as its optimized internal structure, manifest in increased durability and longevity when compared to conventional concrete. These characteristics include compressive strength, flexural strength, and split tensile strength. However, Z10G2 is clearly the best option for places with a lot of sulphates because it has advanced SR and shows how new materials and mix designs can help concrete engineering progress for long-lasting infrastructure development.

By synergizing natural Z and GO, the combination possesses unique properties that increase SR. During cement hydration, pozzolanic natural Z reacts with calcium hydroxide to form C-S-H gel. The concrete microstructure becomes denser, pore connectivity decreases, and sulfate ion ingress is limited. Z's porous structure protects concrete from sulfate attack. GO, on the other hand, is perfect for reinforcing partially replaced concrete because it has a large surface area, and it is only two dimensions. A blend of consistently spread of GO sheets in the cementitious matrix improves concrete's mechanical properties and inhibits sulfate ion diffusion. Cement hydration products improve GO microstructure density and imperviousness. This improves the durability of concrete and SR. The dense, impermeable microstructure and enhanced interfacial bonding of Z10G2 make it SR. Sulfur reduces weight and strength loss in Z10G2 compared to the CC, which lacks GO and Z. In high-sulphate areas, concrete mixtures must be fortified with GO and natural Z to improve their resistance and longevity. Z10G2 is sulphate-resistant because natural Z and GO densify, reinforce, and impermeabilize the concrete matrix. This scientific understanding shows that novel substances and mixed designs up to certain mix proportions can improve concrete structure durability and toughness.

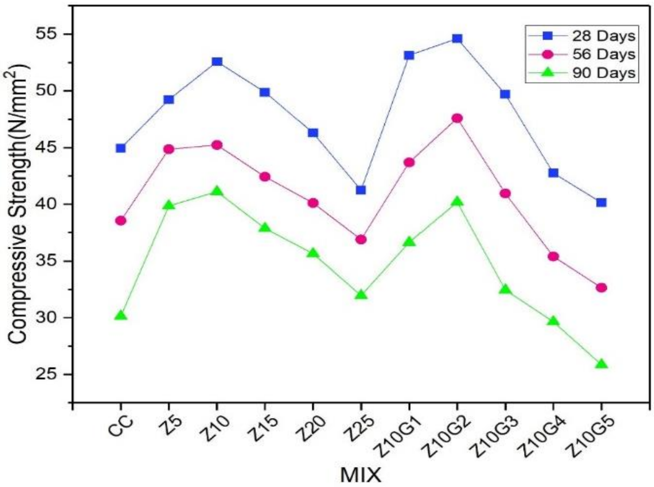

Fig. 2a. Sulphate Resistance results of CC with Z and GO.

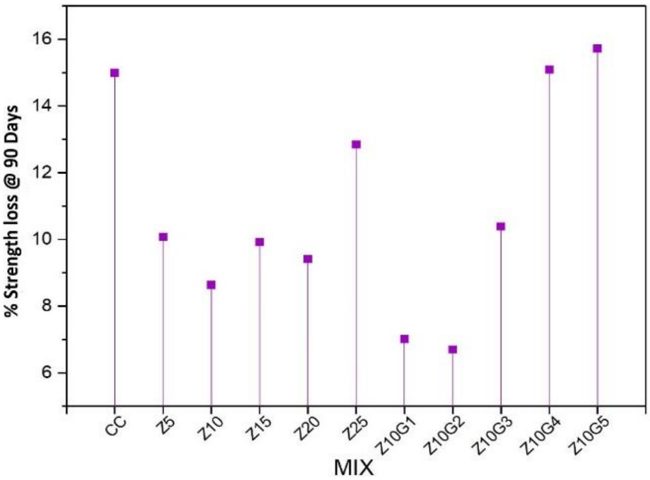

Fig. 2b. % Strength loss @ 90 days in Sulphate Resistance of CC with Z and GO.

3.3. Acid Resistance Test

Acid resistance tests reveal important information about concrete mixes' durability and resilience in acidic environments. Comparing the data to the CC shows trends and the effectiveness associated with various Z content levels. Comparing the tested mixes to the CC shows decreases in weight and compressive strength differences as shown in Fig. 3a. Compared to Z5 and Z25, Z10 and Z15 show less weight loss and similar compressive strength throughout the examination period. Z inclusion and acid resistance are interconnected, with different mix compositions producing different results.

Evaluating concrete mixture durability in harsh conditions, acid resistance test results provide valuable insights for both Z and GO with exceptional acid resistance, Z10G2 is the best composition tested. Weight loss with Z10G2 starts out very low, at 3.10 percent. This is a lot less than the 5.6 percent loss seen with the CC. Z10G2 consistently loses less weight than CC over subsequent durations. Additionally, Z10G2 shows exceptional resilience in compressive strength analysis; at 28 days, the initial compressive strength was 58.53 N/mm², which is higher than CC's 52.88 N/mm. In particular, all of the mixtures lose strength over time, but Z10G2 loses the least, only 14.66% at 90 days compared to 23.22% for CC as shown in Fig. 3b. The durability is increases with increase with addition of G upto 0.02% and there after it decreases with the addition of G.

GO's single layer of carbon atoms arranged in a hexagonal lattice and poor dispersion on concrete will result in failure beyond the optimum mix.

The distinctive content and inner structure of Z10G2, especially the combined benefits of natural Z and GO, explain its outstanding performance. The incorporation of natural Z into concrete results in an increased density of the microstructure, which in turn restricts acid penetration by decreasing pore connectivity. While this is going on, GO strengthens the structure, stopping acid from spreading and making the concrete last longer. Z10G2 is more acid-resistant than CC, which lacks Z and GO. It loses less weight and strength under acidic conditions. For concrete mixtures to increase acid resistance and guarantee the long-term durability of structures exposed to aggressive environments, additional materials including natural Z and GO must be incorporated. Z10G2 is clearly the best option for uses that need to be resistant to acidic environments. It also demonstrates how the development of new materials and mix designs can contribute to the advancement of concrete engineering for the development of long-lasting infrastructure.

Z10G2 is a concrete matrix that possesses distinctive characteristics due to the synergistic effect of natural Z and GO, which enhance acid resistance. During the process of cement hydration, the pozzolanic substance known as Natural Z forms a C-S-H gel that contains calcium hydroxide particles. During this process, the microstructure of the concrete is densified, which results in a reduction in pore connectivity and a limitation of acid penetration pathways. Through absorbing and neutralizing acidic ions, Z's excellent capacity for the exchange of cations helps to reduce the amount of corrosion that occurs on the surface of concrete. Since GO strengthens the cementitious matrix and prevents acid penetration, Z10G2 is acid resistant. A network of high-surface-area two-dimensional GO sheets is evenly distributed throughout the concrete matrix to improve its mechanical properties and impermeability. GO and the hydration of cement processes produce a microstructure that is compact and dense, making it impossible for acidic ions to flow through both of these processes. One factor that contributes to the acid resistance of Z10G2 is the optimization of its internal structure. Having a microstructure that is dense and impermeable helps to strengthen the interfacial bonds in this structure. Z10G2 loses less weight and strength in acidic conditions than the CC, which lacks Z and GO. Adding natural Z and GO to concrete mixtures improves its acid resistance, extending its lifespan. In summary, Z10G2's increased acid resistance is due to the combined effects of naturally occurring Z and GO, which strengthen, densify, and neutralize the concrete matrix. This discovery underscores the significance of the potential by discovering novel substances and mix compositions that can enhance the performance and longevity of concrete structures exposed to corrosive environments.

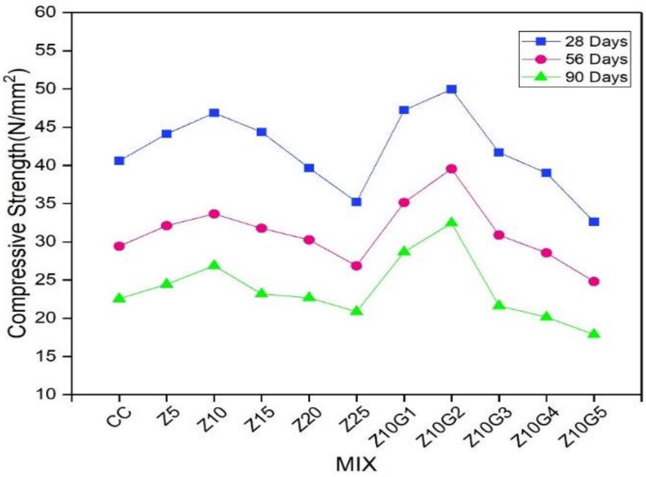

Fig. 3a. Acid Resistance results of CC with Z and GO.

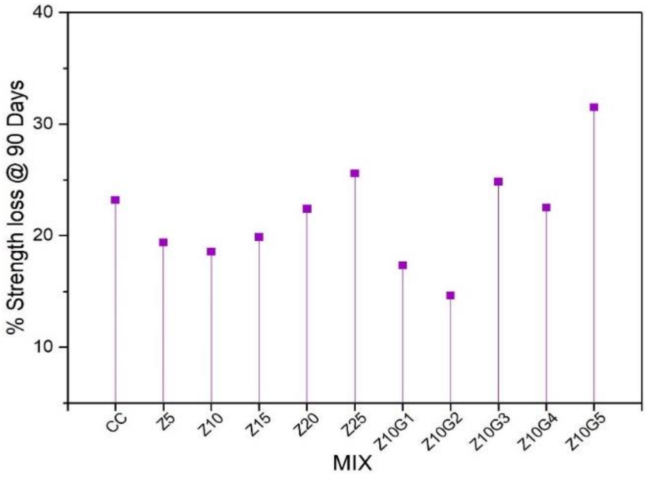

Fig. 3b. % Strength loss @ 90 days in Acid Resistance of CC with Z and GO.

3.4. Alkaline Resistance Test

Alkaline resistance tests can determine concrete mix durability in harsh alkaline environments. The data shows patterns and comparisons with the CC, revealing the efficacy associated with various Z content levels. The Z - modified mixes lose weight and compressive strength differently than the CC. From Z5 to Z25, weight loss increases, suggesting that Z may make concrete more susceptible to alkaline attack. However, compressive strength evaluations at different times show mixed results as shown in Fig. 4a. The compressive strength of Z10 and Z15 is comparable or slightly higher than the CC, but Z20 and Z25 are significantly lower, suggesting potential drawbacks of higher Z induced content as shown in Fig. 4a. Z has the unique properties and connection to the concrete matrix explain these observations. Since it has a high surface area and cation exchange capacity, Z can absorb and retain alkalis from the environment. Extreme Z incorporation may increase concrete matrix porosity and interconnected voids, compromising structural integrity and alkaline resistance. The intricate interplay between advantageous alkali absorption and deleterious impacts on concrete properties is underscored by the distinction in internal structure between Z-modified mixes and the CC.

The further results were adopted with Z with GO to determine the durability of a concrete mixture once it has been exposed to alkaline environments. Z10G2 is the best alkaline-resistant composition tested. Z10G2 initially loses 0.62%, compared to 0.99% for the mix (CC). Z10G2 consistently loses less weight than CC over subsequent durations. Additionally, Z10G2 has very high compressive strength, measuring 58.53 N/mm^2 at 28 days, which is higher than CC's 52.88 N/mm^2. It is worth mentioning that although all mixtures undergo a gradual decline in strength, Z10G2 exhibits the least strength loss, amounting to merely 8.68% after 90 days, in contrast to CC's 10.85% as shown in Fig. 4b. This can be attributed to particle agglomeration and interference with the cement hydration process. This excess can create weak points within the matrix, resulting in a higher percentage of loss and decreased overall durability. The exceptional performance exhibited by Z10G2 can be ascribed to its distinctive internal structure and composition, particularly the synergistic effects resulting from the presence of natural Z and GO. Natural Z facilitates the densification of the microstructure of concrete, thereby obstructing alkaline penetration and reducing pore connectivity. The structure is reinforced by GO, which prevents alkaline diffusion and increases concrete durability. Z10G2 is more resistant to alkaline attack than CC, which lacks Z and GO. It loses less weight and strength under alkaline conditions. To increase alkaline resistance and concrete structure durability in harsh environments, natural Z and GO should be added to concrete mixtures. Z10G2 is the best choice for alkaline-resistant applications, demonstrating its durability and the possibility of novel substances and mixed designs to advance concrete engineering to promote environmentally friendly infrastructure development.

Figure 4c shows the variation of weight loss at 28 days in Alkaline, Acid & Sulphate Resistance of CC with Z and GO. From the experimental investigation it was observed that the percentage of weight loose was significant for acid resistance, it is moderate for Sulphate resistance and mild for Alkaline resistance.

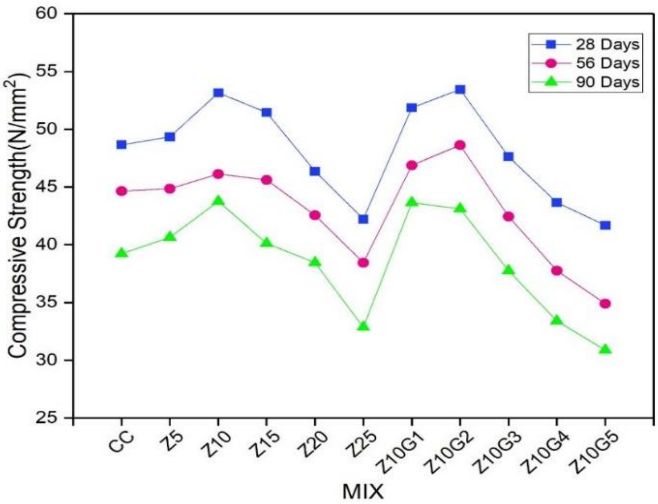

Fig. 4a. Alkaline Resistance results of CC with Z and GO.

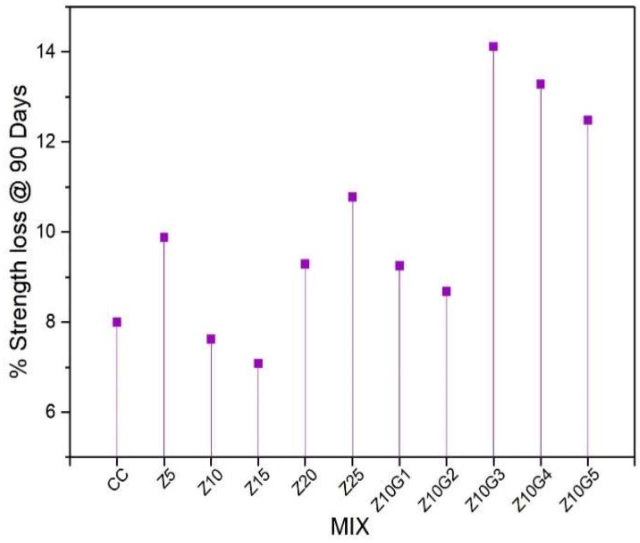

Fig. 4b. % Strength loss @ 90 days in Alkaline Resistance of CC with Z and GO.

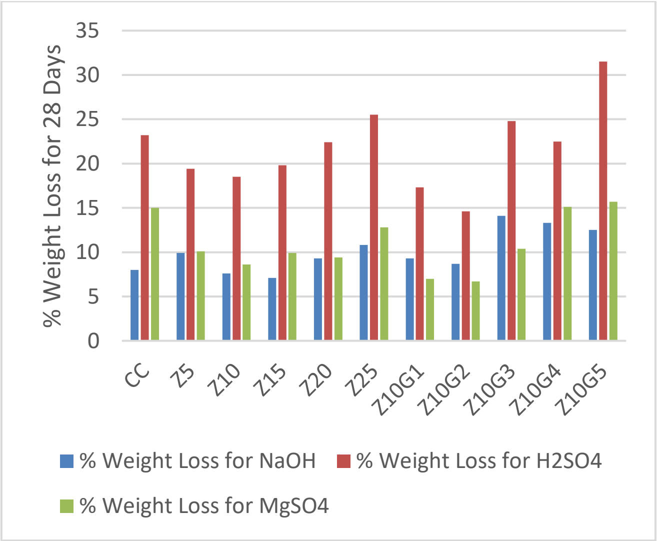

Fig. 4c. % Weight loss @ 28 days in Alkaline, Acid & Sulphate Resistance of CC with Z and GO.

3.5. Rebound Hammer Test (Non-Destructive Test)

For structural integrity and durability, rebound hammer test results reveal concrete mix hardness and quality. Compared to the CC, the recovery values of the different combinations show interesting trends. Low rebound mixes, like Z25, may have softer concrete due to insufficient compaction or compressive strength. Higher rebound mixes like Z10, Z15, and Z5 have harder concrete, indicating better compaction and compressive strength. The most significant rebound value of the tested mixes is mix Z10, showing outstanding toughness and mechanical quality. Its high compressive strength supports the rebound-concrete strength correlation. Figure 5 shows the quality of concrete with definite layers with good and very good. Most of the tested mixes rebound to a "very good hard layer," indicating robust, long-lasting concrete appropriate for a variety of uses in construction.

The results of the Rebound Hammer test provide valuable information concerning the strength and characteristic qualities of concrete specimens, specifically those in which components such as GO, and Z were partially substituted. Among all the combinations of both individual mix of Z from 5 to 25% have possessed the range of compressive strength varying from 48% to 45%, but, Z25 had marked 47.33 N/mm² lowest among the other combinations as shown in Fig. 5. It is observed, different rebound values directly relate to variations in strength at compression and general concrete quality for all tested mixes, even the CC. Z10G2 is the best mix, with a rebound value of 55, graph value of 56.32 and a compressive strength of 56.32 N/mm² is mapped, outperforming CC and other mixtures. The concrete's exceptional compressive strength is consistent with the extremely hard layer denoted by this high rebound value. While Z10G5 has a rebound value of 40 with graph value of 42.56 N/mm², making it a "Good layer," it still has a sufficient compressive strength of 42.56 N/mm². This finding implies that although rebound values are typically correlated with the quality of concrete, additional variables can impact the ultimate characteristics. The Rebound Hammer test shows that adding GO and Z to concrete, especially Z10G2, strengthens and lasts. Consequently, this advancement holds promise for reliable and environmentally friendly infrastructural alternatives.

Rebound Hammer test results provide a complete assessment of concrete specimen structural quality and integrity for partial substitution of components like GO and Z. This evaluation is thorough. The rebound values tell us about the concrete's surface hardness and robustness, which show us its compressive strength. GO/Z replacement mixtures rebound and compress harder than the CC, according to the study. The ideal mix is Z10G2, which yields a hard concrete layer with a compressive limit of 56.32 N/mm² and a rebound value of 55 and graph value is with 56.32. GO and Z improve concrete compressive resistance and strength, as shown by these excellent results. Though Z10G5's compressive strength is still deemed acceptable despite having a lower rebound value, a slight discrepancy was noted, indicating the intricate interplay of numerous factors influencing concrete's characteristics. The Rebound Hammer test shows that modern concrete additives like GO and Z work. This enables environmentally friendly and long-lasting construction solutions.

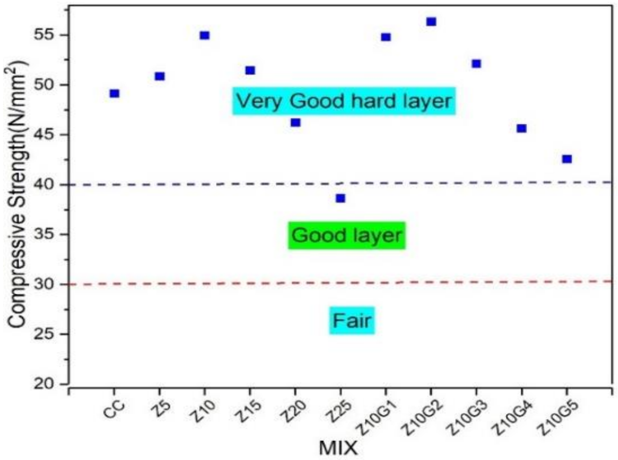

Fig. 5. Rebound Hammer test results of CC with Z and GO.

3.6. UPV Test Results (Non-Destructive Test)

Our Ultrasonic Pulse Velocity (UPV) test outcomes can tell you a lot regarding the quality and consistency of the concrete mixes that were tested. By comparing the velocity values of each mix to those of the CC, trends reveal themselves as shown in Fig. 6. Improved solidity and consistency indicate denser, more uniform concrete in Z10, Z15, and Z20 mixes. These combinations range in speed from 4483 to 4661 m/s, which is considered "Very good to excellent." Mix Z25, at 3945 m/s, is "Good to very good." Possible causes for the concrete's reduced velocity include slight flaws or variations in density that fall within a suitable range. The majority of the mixes tested were of good quality and consistency, according to the UPV results; however, mix Z10 exhibited the greatest velocity and strongest concrete structure.

Tests measuring UPV are used to evaluate concrete samples, particularly those with GO and Z replaced. Analysis of the data shows that UPV values depend on concrete density and structural integrity. The highest UPV mix, Z10G2, has superior density and quality at 4841 m/s. This exceeds the CC UPV at 4056 m/s, showing how GO and Z improve efficiency. Z10G2 has a higher UPV value because GO and Z work together, which means its internal structure is denser and more uniform. These materials may improve concrete interfacial bonding, increasing density and integrity. On the flip side, conventional concrete's shortcomings are brought to light by CC's lower UPV value, which suggests weaker density and potentially more porosity in the building. Because of its remarkable efficiency, Z10G2 is a good choice for applications that call for robustness and reliability of the highest possible standard. Resilience and long-term dependability are provided. Through the exploitation of innovative elements and mix designs, experienced professionals can modify concrete mixtures to fulfill the severe requirements of modern infrastructure projects. In this way, the lifetime of building techniques is ensured. According to the results of the UPV test, GO and Z both improve the quality and performance of concrete.

When concrete samples are subjected to Ultrasonic Pulse Velocity (UPV) examinations, the structure and quality of the samples are revealed, particularly those that include GO and Z. The UPV through concrete is determined by the density of the concrete as well as the inner framework of the concrete. At 4841 meters per second, Z10G2 has the greatest UPV of any of the mixes. Because of this, its construction is quite robust and it has a high density. It was observed that GO and Z enhance the interfacial bonding and porosity of the concrete matrix in a synergistic manner. the UPV is 4056 meters per second, the interior structure of the CC might be less dense and more permeable. Modern substances affect concrete properties, as shown by Z10G2's high densities and durability, as shown by its UPV differences. Infrastructure projects are more durable and structurally sound with GO and Z-optimized concrete. Advanced Z10G2 internal structure minimizes deterioration and improves resilience to outside forces, making infrastructure solutions resilient and beneficial to the environment. These findings demonstrate the importance of material invention in improving concrete understanding and meeting construction needs.

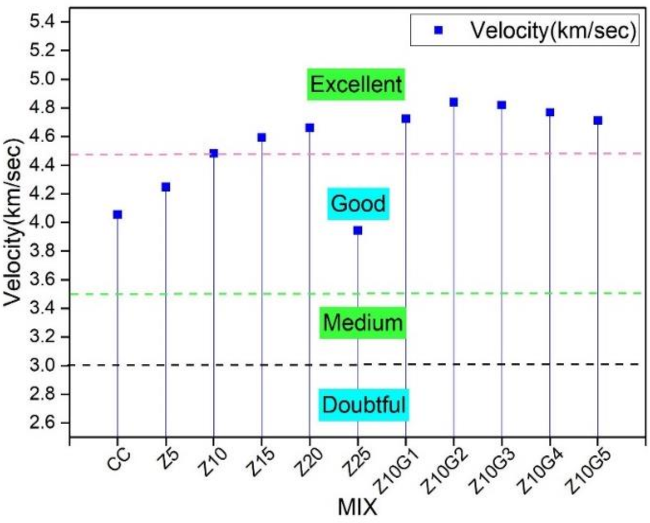

Fig. 6. Ultrasonic Pulse Velocity test results of CC with Z and GO.

3.7. Microstructure Investigation

The microstructure, mechanical properties, and mineral content of self-compacting concrete (SCC) with Z and GO all show that the material's longevity and performance are affected by a variety of factors. The images captured with a scanning electron microscope (SEM) show the numerous architectural elements found in the different mixes [63]. In addition to minuscule fissures and apertures, typical concrete exhibited intricate Ca(OH)2, ettringite, and CSH gel. With only slight differences, the results achieved by introducing Z to Z10G0 were comparable. Z's influence on the crystalline phases is supported by the XRD analysis of Z10G0, which revealed the existence of quartz and ettringite. This could improve the mechanics. Figures 7 and 8 show the outcomes of the SEM and XRD after a ninety-day period. All the images have shown visible traces of adopted materials for this study, eventually leading to the formation of essential elements that match the CC structure. The combination of 10% Z and 0.02% GO Z10G2 altered the microstructure. The mechanical performance was improved by ettringite, CSH, and fractures.

There was a visible increase in the strength of compression of Z10G0 because of an increase in the Z concentration. As a consequence of the presence of GO, the compressive strength of Z10G2 was improved. An X-ray diffraction (XRD) study of Z10G2 indicated the presence of quartz and ettringite, both of which contributed to the strengthened durability and mechanical properties of the material. The significance of GO in maintaining the mechanical strength of concrete is demonstrated by the fact that it showed the greatest improvement in features in Z10G2. An X-ray diffraction (XRD) study was performed, and the results showed that the changes in the mineral composition that were responsible for the modifications and the higher durability were determined to be more important. [64] supports the discussion for microstructural analysis.

4. Conclusion

This study demonstrates that Z and GO exert a substantial influence on the mechanical properties and microstructure of SCC. Consequently, Z and GO have a variety of impacts when combined in SCC. Scanning electron microscopy images showed unique architectural elements, with Z-GO combinations, especially Z10G2, showing improved microstructure. Enhancement of mechanical properties and durability was facilitated by modifications in the mineral composition, which were disclosed by XRD analysis. It has been established that adding Z and GO to a material increases its compressive strength based on the outcomes of mechanical property testing. Of all the combinations evaluated, the Z10G2 combination had the most promise since it outperformed the others in terms of mechanical features. The mechanical and durability qualities of SCC mixes including Z and GO were shown to be more durable. Z10G2 demonstrated exceptional resistance to numerous detrimental chemicals. Based on the material's durability, mechanical qualities, and microstructure, the results indicate that Z10G2 is the best combination. This combination, when combined with conventional concrete (CC), can improve the performance and longevity of concrete constructions. For optimization solutions to be investigated and tested in practical settings, more research is needed.

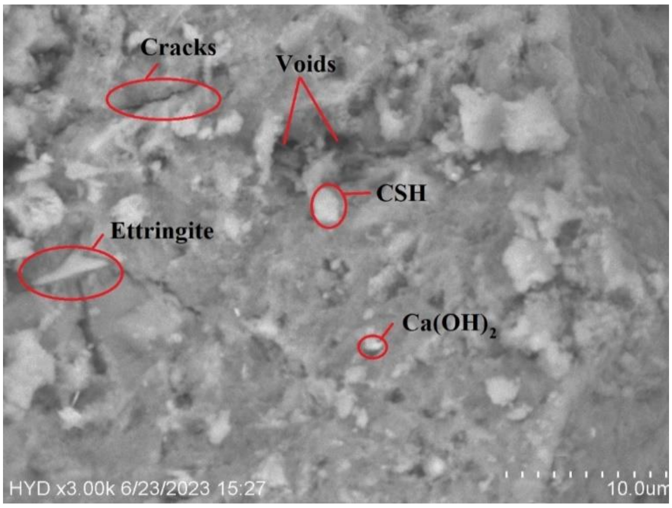

Fig. 7a. SEM results - Conventional Concrete.

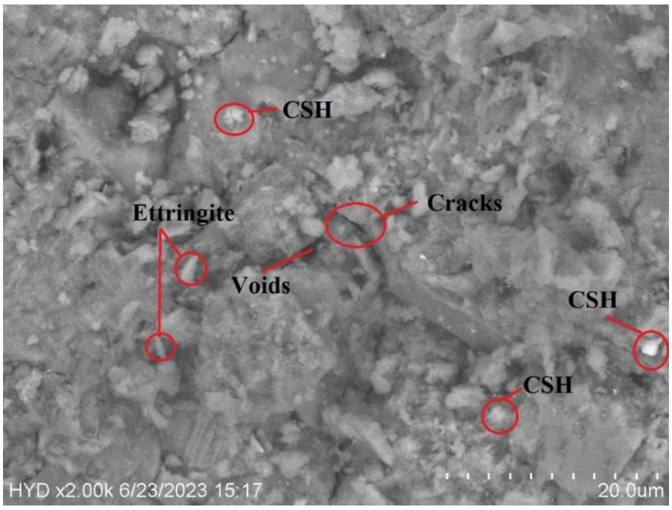

Fig. 7b. SEM results - Z10G0.

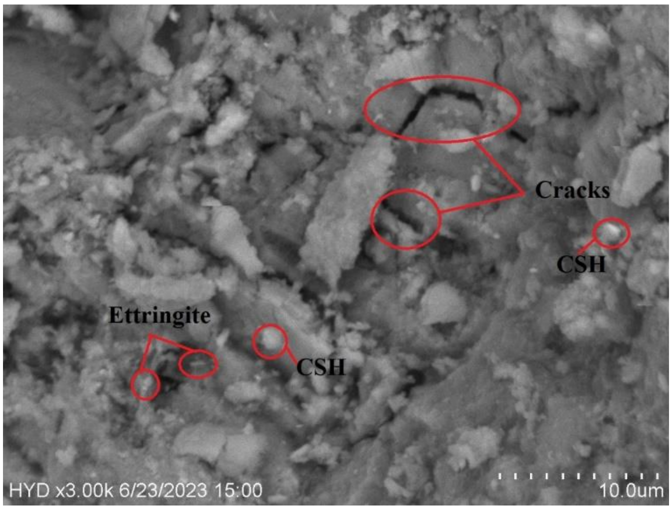

Fig. 7c. SEM results - Z10G2.

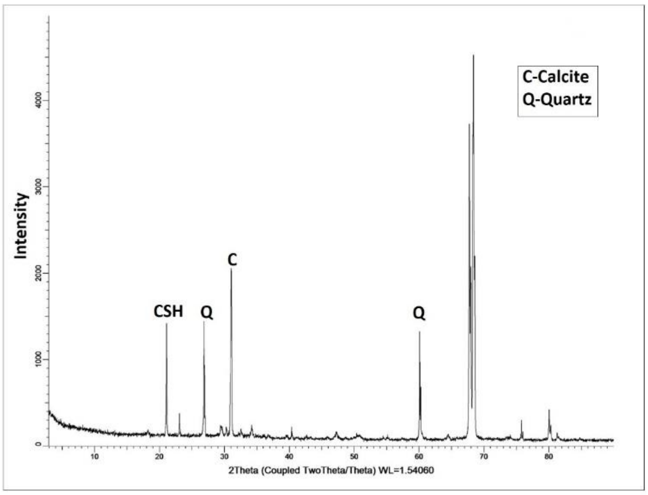

Fig. 8a. XRD results - Conventional Concrete.

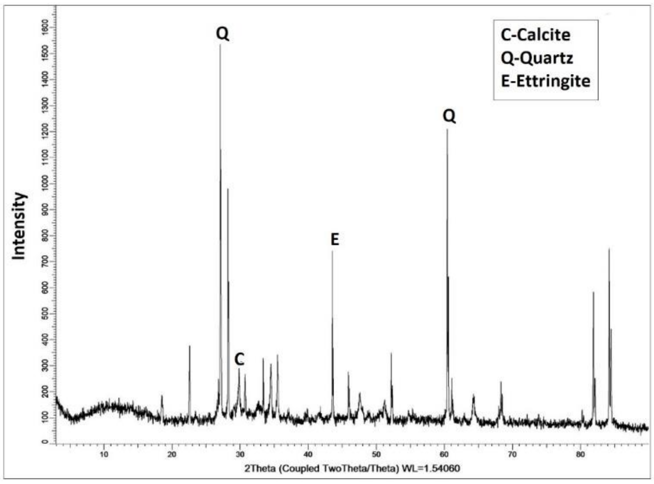

Fig. 8b. XRD results - Z10G0.

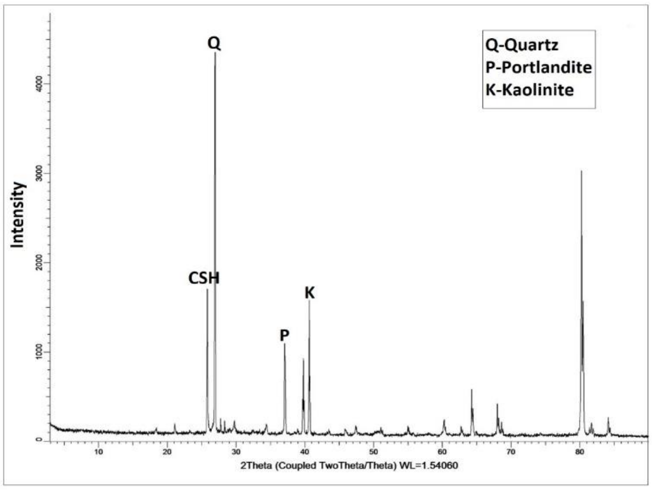

Fig. 8c. XRD results - Z10G2.

DOI:10.4186/ej.2024.28.12.41

Conflict of interest

The authors declare that they have no conflict of interest.

Authors contributions:

Jagadeep K: Writing – Original Draft, Methodology & Editing; **Dhevasenaa P R**: Supervision & Reviewing; **Sivagamasundari R & Jodhi C**: Reviewing.

Acknowledgment:

The authors are grateful to the staff of Structural Engineering laboratory for conducting the experiments and tests.

References

[1] D. Fan, L. Lue, and S. Yang, "Molecular dynamics study of interfacial stress transfer in graphene-oxide cementitious composites," *Computational Materials Science*, vol. 139, pp. 56–64, 2017. doi: 10.1016/j.commatsci.2017.07.034.

[2] E. Cuenca, L. D'Ambrosio, D. Lizunov, A. Tretjakov, O. Volobujeva, and L. Ferrara, "Mechanical properties and self-healing capacity of ultra high performance fibre reinforced concrete with alumina nano-fibres: Tailoring ultra high durability concrete for aggressive exposure scenarios," *Cement and Concrete Composites*, vol. 118, 2021. doi: 10.1016/j.cemconcomp.2021.103956.

[3] M. Kazemian and B. Shafei, "Effects of supplementary cementitious materials on the hydration of ultrahigh-performance concrete," *Journal of Materials in Civil Engineering*, vol. 35, 2023. doi: 10.1061/JMCEE7.MTENG-16173.

[4] A. Sadrmomtazi, Z. Noorollahi, B. Tahmouresi, and A. Saradar, "Effects of hauling time on self-consolidating mortars containing metakaolin and natural zeolite," *Construction and Building Materials*, vol. 221, pp. 283–291, 2019. doi: 10.1016/j.conbuildmat.2019.06.037.

[5] A. Sadeghi-Nik, J. Berenjian, S. Alimohammadi, O. Lotfi-Omran, A. Sadeghi-Nik, and M. Karimaei, "The effect of recycled concrete aggregates and metakaolin on the mechanical properties of self-compacting concrete containing nanoparticles," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 43, pp. 503–515, 2019. doi: 10.1007/s40996-018-0182-4.

[6] K. K. Ma Mousavi, A. Sadeghi-Nik, A. Bahari, and A. Ashour, "Cement paste modified by nano-montmorillonite and carbon nanotubes," *ACI Materials Journal*, vol. 119, 2022. doi: 10.14359/51734612.

[7] P. Farnood Ahmadi, A. Ardeshir, A. M. Ramezanianpour, and H. Bayat, "Characteristics of heat insulating clay bricks made from zeolite, waste steel slag and expanded perlite," *Ceramics International*, vol. 44, pp. 7588–7598, 2018. doi: 10.1016/j.ceramint.2018.01.175.

[8] A. M. Sabziparvar, E. Hosseini, V. Chiniforush, and A. H. Korayem, "Barriers to achieving highly dispersed graphene oxide in cementitious composites: An experimental and computational study," *Construction and Building Materials*, vol. 199, pp. 269–278, 2019. doi: 10.1016/j.conbuildmat.2018.12.030.

[9] M. M. Ali, S. A. Osman, A. Z. Aw, M. Y. M. Yatim, F. Alatshana, and S. J. Hilo, "Concrete-filled twin-layer steel-sheet CWs system: A systematic review of the literature," *Latin American Journal of Solids and Structures*, vol. 18, no. 6, 2021. doi: 10.1590/1679-78256622.

[10] A. U. Rehman and J. H. Kim, "3D concrete printing: A systematic review of rheology, mix designs, mechanical, microstructural, and durability characteristics," *Materials*, vol. 14, no. 14, 2021. doi: 10.3390/ma14143800.

[11] S. Lawson, X. Li, H. Thakkar, A. A. Rownaghi, and F. Rezaei, "Recent advances in 3D printing of structured materials for adsorption and catalysis applications," *Chemical Reviews*, vol. 121, no. 10, pp. 6246–6291, 2021. doi: 10.1021/acs.chemrev.1c00060.

[12] F. Friol Guedes de Paiva, J. R. Tamashiro, L. H. Pereira Silva, and A. Kinoshita, "Utilization of inorganic solid wastes in cementitious materials – a systematic literature review," *Construction and Building Materials*, vol. 285, 2021. doi: 10.1016/j.conbuildmat.2021.122833.

[13] J. Xie, S.-C. Kou, H. Ma, W.-J. Long, Y. Wang, and T.-H. Ye, "Advances on properties of fiber reinforced recycled aggregate concrete: Experiments and models," *Construction and Building Materials*, vol. 277, 2021. doi: 10.1016/j.conbuildmat.2021.122345.

[14] G. Iswarya and M. Beulah, "Use of zeolite and industrial waste materials in high strength concrete —A review," *Materials Today: Proceedings*, vol. 46, pp. 116–123, 2021. doi: 10.1016/j.matpr.2020.06.329.

[15] A. Ates and G. Akgül, "Modification of natural zeolite with NaOH for removal of manganese in drinking water," *Powder Technology*, vol. 287, pp. 285–291, 2016. doi: 10.1016/j.powtec.2015.10.021.

[16] L. Wu, N. Farzadnia, C. Shi, Z. Zhang, and H. Wang, "Autogenous shrinkage of high performance concrete: A review," *Construction and Building Materials*, vol. 149, pp. 62–75, 2017. doi: 10.1016/j.conbuildmat.2017.05.064.

[17] S. Xu, Q. Wang, N. Wang, Q. Song, and Y. Li, "Effects of natural zeolite replacement on the properties of superhydrophobic mortar," *Construction and Building Materials*, vol. 348, p. 128567, 2022. doi: 10.1016/j.conbuildmat.2022.128567.

[18] T. Markiv, K. Sobol, M. Franus, and W. Franus, "Mechanical and durability properties of concretes incorporating natural zeolite," *Archives of Civil and Mechanical Engineering*, vol. 16, pp. 554–562, 2016. doi: 10.1016/j.acme.2016.03.013.

[19] N. C. Thang, N. Van Tuan, K.-H. Yang, and Q. T. Phung, "Effect of zeolite on shrinkage and crack resistance of high-performance cement-based concrete," *Materials*, vol. 13, p. 3773, 2020. doi: 10.3390/ma13173773.

[20] D. Kriptavičius, G. Girskas, and G. Skripkiunas, "Use of natural zeolite and glass powder mixture as partial replacement of Portland cement: The effect on hydration, properties and porosity," *Materials*, vol. 15, p. 4219, 2022. doi: 10.3390/ma15124219.

[21] M. Pekgoz and I. Tekin, "Microstructural investigation and strength properties of structural lightweight concrete produced with Zeolitic tuff aggregate," *Journal of Building Engineering*, vol. 43, p. 102863, 2021. doi: 10.1016/j.jobe.2021.102863.

[22] F. Pacheco-Torgal and S. Jalali, "Nanotechnology: Advantages and drawbacks in the field of construction and building materials," *Construction and Building Materials*, vol. 25, no. 2, pp. 582–590, 2011. doi: 10.1016/j.conbuildmat.2010.07.009.

[23] H. Grajek, J. Jonik, Z. Witkiewicz, T. Wawer, and M. Purchala, "Applications of graphene and its derivatives in chemical analysis," *Critical Reviews in Analytical Chemistry*, vol. 50, no. 5, pp. 445–471, 2020. doi: 10.1080/10408347.2019.1653165.

[24] H. Kim, et al., "Graphene/polyethylene nanocomposites: Effect of polyethylene functionalization and blending methods," *Polymer*, vol. 52, no. 8, pp. 1837–1846, 2011. doi: 10.1016/j.polymer.2011.02.017.

[25] H. Yang, H. Cui, W. Tang, Z. Li, N. Han, and F. Xing, "A critical review on research progress of graphene/cement-based composites," *Composites Part A: Applied Science and Manufacturing*, vol. 102, pp. 273–296, 2017. doi: 10.1016/j.compositesa.2017.07.019.

[26] J. Silvestre, N. Silvestre, and J. de Brito, "Review on concrete nanotechnology," *European Journal of Environmental and Civil Engineering*, vol. 20, no. 4, pp. 455–485, 2015. doi: 10.1080/19648189.2015.1042070.

[27] J. Zhang, et al., "Graphene oxide/polyacrylonitrile fiber hierarchical-structured membrane for ultra-fast microfiltration of oil-water emulsion," *Chemical Engineering Journal*, vol. 307, pp. 643–649, 2017. doi: 10.1016/j.cej.2016.08.124.

[28] K. Al-Jabri and H. Shoukry, "Use of nano-structured waste materials for improving mechanical, physical and structural properties of cement mortar," *Construction and Building Materials*, vol. 73, pp. 636–644, 2014. doi: 10.1016/j.conbuildmat.2014.10.004.

[29] K. Yang, J. Wang, and B. Chen, "Facile fabrication of stable monolayer and few-layer graphene nanosheets as superior sorbents for persistent aromatic pollutant management in water," *Journal of Materials Chemistry A*, vol. 2, no. 43, pp. 18219–18224, 2014. doi: 10.1039/c4ta04300f.

[30] K. S. Novoselov, et al., "Electric field effect in atomically thin carbon films," *Science*, vol. 306, no. 5696, pp. 666–669, 2004. doi: 10.1126/science.1102896.

[31] L. Lu, P. Zhao, and Z. Lu, "A short discussion on how to effectively use graphene oxide to reinforce cementitious composites," *Construction and Building Materials*, vol. 189, pp. 33–41, 2018. doi: 10.1016/j.conbuildmat.2018.08.170.

[32] L. Wang, et al., "Effect of graphene oxide (GO) on the morphology and microstructure of cement hydration products," *Nanomaterials (Basel)*, vol. 7, no. 12, 2017. doi: 10.3390/nano7120429.

[33] M. Şahmaran, M. Lachemi, K. M. A. Hossain, and V. C. Li, "Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking," *Cement and Concrete Research*, vol. 39, no. 10, pp. 893–901, 2009. doi: 10.1016/j.cemconres.2009.07.006.

[34] M. Wang, R. Wang, H. Yao, S. Farhan, S. Zheng, and C. Du, "Study on the three-dimensional mechanism of graphene oxide nanosheets modified cement," *Construction and Building Materials*, vol. 126, pp. 730–739, 2016. doi: 10.1016/j.conbuildmat.2016.09.092.

[35] N. Makul, "Modern sustainable cement and concrete composites: Review of current status, challenges and guidelines," *Sustainable Materials and Technologies*, vol. 25, 2020. doi: 10.1016/j.susmat.2020.e00155.

[36] M. F. Nuruddin, K. Y. Chang, and N. Mohd Azmee, "Workability and compressive strength of ductile self-compacting concrete (DSCC) with various cement replacement materials," *Construction and Building Materials*, vol. 55, pp. 153–157, 2014. doi: 10.1016/j.conbuildmat.2013.12.094.

[37] P. Dorin, et al., "Properties evolution of some hydraulic mortars incorporating graphene oxides," *Buildings*, vol. 12, no. 6, 2022. doi: 10.3390/buildings12060864.

[38] Q. Wang, J. Wang, C.-X. Lu, B.-W. Liu, K. Zhang, and C.-Z. Li, "Influence of graphene oxide additions on the microstructure and mechanical strength of cement," *New Carbon Materials*, vol. 30, no. 4, pp. 349–356, 2015. doi: 10.1016/s1872-5805(15)60194-9.

[39] Q. Zheng, Y. Geng, S. Wang, Z. Li, and J.-K. Kim, "Effects of functional groups on the mechanical and wrinkling properties of graphene sheets," *Carbon*, vol. 48, no. 15, pp. 4315–4322, 2010. doi: 10.1016/j.carbon.2010.07.044.

[40] S. Chuah, Z. Pan, J. G. Sanjayan, C. M. Wang, and W. H. Duan, "Nano reinforced cement and concrete composites and new perspective from graphene oxide," *Construction and Building Materials*,

vol. 73, pp. 113–124, 2014. doi: 10.1016/j.conbuildmat.2014.09.040.

[41] S. Kamel, M. El-Sakhawy, B. Anis, and H. A. S. Tohamy, "Graphene's structure, synthesis, and characterization; a brief review," *Egyptian Journal of Chemistry*, vol. 62, Special Issue (Part 2), pp. 593–608, 2019.

[42] S. Sagadevan, et al., "Functionalized graphene-based nanocomposites for smart optoelectronic applications," *Nanotechnology Reviews*, vol. 10, no. 1, pp. 605–635, 2021. doi: 10.1515/ntrev-2021-0043.

[43] S. C. Ray, "Application and uses of graphene oxide and reduced graphene oxide," *Applied Graphene and Graphene-Oxide Based Nanomaterials*, pp. 39–55, 2015.

[44] S. J. Lee, S.-H. Jeong, D.-U. Kim, and J.-P. Won, "Graphene oxide as an additive to enhance the strength of cementitious composites," *Composite Structures*, vol. 242, 2020. doi: 10.1016/j.compstruct.2020.112154.

[45] T. Kuila, S. Bose, A. K. Mishra, P. Khanra, N. H. Kim, and J. H. Lee, "Chemical functionalization of graphene and its applications," *Progress in Materials Science*, vol. 57, no. 7, pp. 1061–1105, 2012. doi: 10.1016/j.pmatsci.2012.03.002.

[46] T. Soltani and B. Kyu Lee, "A benign ultrasonic route to reduced graphene oxide from pristine graphite," *Journal of Colloid and Interface Science*, vol. 486, pp. 337–343, 2017. doi: 10.1016/j.jcis.2016.09.075.

[47] Y. T. Tran, J. Lee, P. Kumar, K.-H. Kim, and S. S. Lee, "Natural zeolite and its application in concrete composite production," *Composites Part B: Engineering*, vol. 165, pp. 354–364, 2019. doi: 10.1016/j.compositesb.2018.12.084.

[48] V. Palermo, I. A. Kinloch, S. Ligi, and N. M. Pugno, "Nanoscale mechanics of graphene and graphene oxide in composites: A scientific and technological perspective," *Advanced Materials*, vol. 28, no. 29, pp. 6232–6238, 2016. doi: 10.1002/adma.201505469.

[49] X. Yao, et al., "Graphene oxide-coated Poly(vinyl alcohol) fibers for enhanced fiber-reinforced cementitious composites," *Composites Part B: Engineering*, vol. 174, 2019. doi: 10.1016/j.compositesb.2019.107010.

[50] Z. Pan, et al., "Mechanical properties and microstructure of a graphene oxide–cement composite," *Cement and Concrete Composites*, vol. 58, pp. 140–147, 2015. doi: 10.1016/j.cemconcomp.2015.02.001.

[51] S. Khemngern, D. Wongsawaeng, P. Jongvivatsakul, and P. Nuaklong, "Mechanical and thermal neutron attenuation properties of concrete reinforced with low-dose gamma irradiated PETE fibers and sodium borate," *Engineering Journal*, vol. 24, no. 3, pp. 1–10, 2020. doi: 10.4186/ej.2020.24.3.1.

[52] P. Nuaklong, A. Wongsa, K. Boonserm, C. Ngohpok, P. Jongvivatsakul, V. Sata, P. Sukontasukkul, and P. Chindaprasirt, "Enhancement of mechanical properties of fly ash geopolymer containing fine recycled concrete aggregate with micro carbon fiber," *Journal of Building Engineering*, vol. 41, p. 102403, 2021. doi: 10.1016/j.jobe.2021.102403.

[53] G. Xing, Y. Xu, J. Huang, Y. Lu, P. Miao, P. Chindasiriphan, P. Jongvivatsakul, and K. Ma, "Research on the mechanical properties of steel fibers reinforced carbon nanotubes concrete," *Construction and Building Materials*, vol. 392, p. 131880, 2023. doi: 10.1016/j.conbuildmat.2023.131880.

[54] H. W. Iqbal, K. Hamcumpai, P. Nuaklong, P. Jongvivatsakul, S. Likitlersuang, T. Pothisiri, C. Chintanapakdee, and A. C. Wijeyewickrema, "Enhancing fire resistance in geopolymer concrete containing crumb rubber with graphene nanoplatelets," *Construction and Building Materials*, vol. 426, pp. 136115–136115, 2024. doi: 10.1016/j.conbuildmat.2024.136115.

[55] *Standard Specification for Portland Cement*, ASTM C150/C150M-21, ASTM International, West Conshohocken, PA, 2021.

[56] *Specification and Guidelines for Self-Compacting Concrete*, European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC), Norfolk, UK, 2005. [Online]. Available: http://www.efnarc.org.

[57] *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*, ASTM C1012-04, ASTM International, West Conshohocken, PA, 2004. doi: 10.1520/C1012-04.

[58] M. Uysal and M. Sumer, "Performance of self-compacting concrete containing different mineral admixtures," *Construction and Building Materials*, vol. 25, no. 11, pp. 4112–4120, 2011. doi: 10.1016/j.conbuildmat.2011.04.032.

[59] T. Chompoorat, S. Likitlersuang, and P. Jongvivatsakul, "The performance of controlled low-strength material base supporting a high-volume asphalt pavement," *KSCE Journal of Civil Engineering*, vol. 22, no. 6, pp. 2055–2063, 2018. doi: 10.1007/s12205-018-1527-z.

[60] T. T. Win, R. Wattanapornprom, L. Prasittisopin, W. Pansuk, and P. Pheinsusom, "Exploring ASEAN fly ash for enhancing cement hydration and service life prediction of Portland cement mortar," *Engineering Journal*, vol. 27, no. 9, pp. 1–13, 2023. doi: 10.4186/ej.2023.27.9.1.

[61] T. Chompoorat, T. Thepumong, P. Nuaklong, P. Jongvivatsakul, and S. Likitlersuang, "Alkali-activated controlled low-strength material utilizing high-calcium fly ash and steel slag for use as pavement materials," *Journal of Materials in Civil Engineering*, vol. 33, no. 8, 2021. doi: 10.1061/(ASCE)MT.1943-5533.0003798.

[62] P. Jitsangiam, K. Nusit, S. Likitlersuang, and J. Kodikara, "Using damage evaluation to assess the fatigue behaviour of cement-treated base material from laboratory and full-scale performance tests,"

Transportation Geotechnics, vol. 26, p. 100440, 2020. doi: 10.1016/j.trgeo.2020.100440.

[63] A. Nawaz, P. Julnipitawong, and S. Tangtermsirikul, "Effect of curing temperature and free lime content in fly ash on basic properties and autoclave expansion of fly ash mixtures," *Engineering Journal*, vol. 27, no. 10, pp. 67–79, 2023. doi: 10.4186/ej.2023.27.10.67.

[64] K. Jagadeep, P. R. Dhevasenaa, R. Sivagamasundari, and C. Jodi, "Investigation of mechanical properties of self-compacting concrete induced with zeolite and graphene oxide," *Journal of Building Pathology and Rehabilitation*, vol. 9, no. 2, 2024. doi: 10.1007/s41024-024-00455-x.

◆

Mr. Jagadeep K., Research Scholar, Department of Civil & Structural Engineering, Annamalai University, Chidambaram.
Assistant Professor, Department of Civil Engineering, S.R.K.R Engineering College, Bhimavaram.

E. Mail: jagadeep.kankatala@gmail.com

Dr. Dhevasenaa P R., Assistant Professor, Department of Civil & Structural Engineering, Annamalai University, Chidambaram.
E.Mail:senaadheva@gmail.com

Dr. Sivagamasundari R., Associate Professor, Department of Civil & Structural Engineering, Annamalai University, Chidambaram.
E. Mail: siva_1667@yahoo.com

Dr. Jodhi C., Associate Professor, Department of Civil Engineering, Annamalai University, Chidambaram.
E. Mail: jee.ezhiljodhi@gmail.com