Research Article GU J Sci, Part A, 12(2): 583-607 (2025) 10.54287/gujsa.1647353

Gazi University
Journal of Science
PART A: ENGINEERING AND INNOVATION
http://dergipark.org.tr/gujsa

Strength and Microstructural Analysis of Nano Powder and Basalt Fibre Reinforced RCC Pavement Concrete

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Keywords

Roller Compacted Concrete

SEM and BET Analyses

Nanopowders

Basalt Fibre

Abstract

Nowadays, durability and longevity represent the main issues in the field of road concrete. Roller Compacted Concrete (RCC) is a sustainable option for road pavements due to its low binder content, fast application and high strength. Nevertheless, there is a necessity for the improvement of RCC road concretes through the incorporation of various additives to enhance their performance. The present study investigates the mechanical and microstructural properties of RCC road concretes containing Fe_2O_3 and TiO_2 nano powders and basalt fiber additives. Three distinct mixtures were formulated, and a series of compressive strength, flexural strength and abrasion resistance tests were conducted. The results were verified by BET (Brunauer-Emmett-Teller) and SEM (Scanning Electron Microscope) analyses. The experimental findings demonstrated that the incorporation of nano powder and basalt fiber additives was effective in increasing the durability of concrete. The third mixture demonstrated optimal performance, exhibiting a compressive strength of 61.20 MPa, a flexural strength of 8.80 MPa, and a mass loss of 2.5 g. BET analysis revealed that the incorporation of nanopowders enhanced the matrix density by increasing the surface area. Furthermore, the SEM images demonstrated that the nanopowders were uniformly dispersed within the matrix, and the basalt fibres exhibited robust interfacial interactions. In conclusion, the combined use of Fe_2O_3 and TiO_2 nanopowders with basalt fibre additive is considered as an effective approach to improve the performance of RCC road concretes.

Cite

Sünbül, Ş. & Tortum, A. (2025). Strength and Microstructural Analysis of Nano Powder and Basalt Fibre Reinforced RCC Pavement Concrete. *GU J Sci, Part A*, *12(2)*, 583-607. doi:10.54287/gujsa.1647353

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Article Process

Submission Date	26.02.2025
Revision Date	24.03.2025
Accepted Date	28.05.2025
Published Date	30.06.2025

1. INTRODUCTION

The incorporation of nano powder and fibre additives into RCC road concrete has emerged as a pivotal subject in contemporary construction research, particularly regarding enhancing strength and durability. RCC has garnered significant attention as a sustainable alternative due to its reduced binder content and energy requirements in comparison to conventional concrete. The preference for RCC is particularly pronounced in the domain of road construction, owing to its cost-effectiveness, rapid construction time, and environmental benefits. The water-cement ratio employed in the production of RCC differs from that of traditional concrete, resulting in a drier concrete with zero slump rate. This concrete can be opened to light traffic without any damage. Additionally, RCC coatings offer minimize construction time and labour costs. The present study aims to investigate the effects of nano powder and basalt fiber additives used in RCC road concrete on the mechanical properties of concrete. The incorporation of nano powder and fibre into RCC road concretes

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represents a significant development in contemporary construction industry, particularly regarding the enhancement of strength and durability. RCC technology is distinguished by its ability to withstand substantial traffic loads and the deterioration that results from environmental effects. The material's distinctiveness is evidenced by its enhanced sustainability, as evidenced by its production with reduced binder content and energy consumption when compared to conventional road concretes. The utilizations of RCC, particularly in the context of road construction, is experiencing a notable increase in prevalence, primarily due to its distinct advantages, namely its capacity to expedite construction processes while maintaining a low cost (Choi & Groom, 2001). Rigid roller compactable pavements are essentially like conventional concrete pavements, but the cement content used is less than that used in conventional concrete. The utilizations of a reduced cement content in the concrete mixture has been demonstrated to engender a concomitant increase in the economic efficiency of the material. The addition of various additives to the concrete can further enhance its strength. These types of coatings are characterized by a higher level of dryness in comparison to traditional coatings, exhibiting minimal propensity for collapse (Mardanı et al, 2020). This issue, which impacts workability, is addressed by utilizing high compression energy. The transportation, placement and compaction of RCC is analogous to that of bituminous pavements. Consequently, RCC can be applied expeditiously and economically. RCC coatings, which were previously preferred in industrial field floors where heavy loads were carried and travelled at low speeds due to their high surface roughness, have also started to be used in urban roads and intercity highways in recent years. The production and construction of roller-compacted concrete is a more practical approach when compared with traditional concrete methods and can be utilised following the compaction process (Menekşe, 2020). The material is laid and compacted in layers. It is imperative that adequate and effective compaction is provided in each layer. The term used for this process is 'vibratory rolling', which involves the utilization of vibratory rollers for the compaction of the concrete (Öztürk, 2018). The production of roller-compacted concrete roads involves the integration of several characteristics found in both conventional concrete roads and asphalt roads. These common features can be classified in accordance with the following criteria: the utilizations of materials analogous to those employed in the construction of traditional concrete roads; discrepancies in mixing ratios; and variations in curing requirements. The similarities with asphalt roads are that the equipment types such as aggregate grading, placement, compaction, etc. are the same. Furthermore, RCC pavements are typically utilised in contexts characterized by low-speed heavy traffic, and in areas where factors such as strength, durability and cost-effectiveness are of paramount importance, such as in the case of airport runways and taxiways (Huang, 2004; Mallick & Tahar, (2018). Roller compactable concrete is a superstructure construction method for rigid roads that is characterized by its zero-slump concrete properties, which are derived from the process of consolidation. This new type of pavement is distinguished from traditional concrete pavements by its unique construction techniques, which draw parallels with those employed in the fabrication of flexible pavements. The materials utilized in the construction of RCC are analogous to those employed in the construction of traditional roads, namely water, binder, aggregate, and so forth. Nevertheless, the water-cement ratio utilized in the construction of RCC pavements deviates from that employed in conventional road design. Due to its drier composition, RCC exhibits no tendency to slump. The water/cement and air void ratio of RCC pavements is lower than that of conventional concrete pavements. This is due to the compaction method. Furthermore, it has been demonstrated that high load-bearing capacity can be attained immediately following the compaction process. Consequently, the RCC pavement can be opened to light traffic without incurring any damage after the compaction process. Moreover, the use of RCC pavements eliminates the necessity for formwork, reinforcement, dowels or joints present in conventional concrete pavement, consequently leading to a reduction in labour costs and construction time for pavement construction of similar length (ACI Committee, 2014). Furthermore, given that the cementitious content of RCC is lower than that of conventional concrete, it is more environmentally friendly (LaHucik et al, 2017). As the application of RCC coatings is analogous to that of asphalt coatings, the construction time and labour costs are comparable. However, it has been demonstrated that RCC pavements exhibit superior strength and durability in comparison to asphalt pavements. Furthermore, RCC pavements exhibit a high resistance to rutting, and do not typically exhibit significant cracking under the turning or braking forces of vehicles. It is notable for its stability at elevated temperatures, a property that renders it resistant to degradation by several chemicals, including fuels (Prusinski, 1997). A thorough examination of these situations reveals that, despite certain disadvantages associated with RCC, it offers numerous benefits for rigid pavements. Moreover, it is more environmentally friendly than other coating materials and is regarded as one of the ideal building materials for road construction. RCC pavements are produced by utilizing the same materials in the traditional concrete pavement mixture, albeit in different proportions. They are produced by using coarse and fine aggregates, binding materials (cement, fly ash, slag, etc.), water and chemical additives when necessary. In the present study, the focus is on the utilizations of nano powder additives in the context of RCC design, with particular emphasis on their impact on the microstructure and the effectiveness of crack prevention in fibres. The incorporation of nano-additives into concrete has been demonstrated to enhance the mechanical and durability properties of the material. This is achieved by creating a dense matrix through the filling of micropores that form during the process of cement hydration. A significant amount of research is currently being conducted on the various applications of nanomaterials in the field of building materials, with a particular focus on cement-based materials (Kawashima et al., 2013). Nanotechnology is an area of research that is currently undergoing rapid development and expansion. It has been identified as one of the most active research domains in contemporary academia, with a wide range of potential applications across a broad spectrum of disciplines. These include, but are not limited to, the following areas: energy, defence, information and technology, agriculture, environmental protection and health (Sanchez & Sobolev, 2010). The applications of nanoscience and nanotechnology in cement and concrete systems can be categorised under the following four headings. These are as follows:

- Research and modification of the nanostructure of calcium silicate-hydrate (C-S-H) gel,

- Controlled release of chemical additives into the concrete mixture,

- Cement-based composite materials containing carbon nanotubes,

- Cement systems containing nanoparticles (Raki, 2010).

The utilizations of nanoparticles in the field of building materials is a subject that is garnering increasing attention daily. The common application areas of nanotechnology in the construction sector can be classified as follows: new production techniques, devices and controls; nanostructured arranged materials; high-performance structural materials; smart structures and use of micro/nano sensors; special coatings, paints and thin films; multifunctional materials and components; energy-saving lights; fuel cells; and communication and computer devices (Zhu et al, 2010). Advancements in the domain of nanotechnology have facilitated enhanced resilience of concrete, nanomaterial, to environmental stress and chemical agents (e.g., deicing salts) (Öcal et al, 2018). This progress has led to the emergence of self-healing smart concretes, which exhibit remarkable resilience to external damage. The following three points summarise the problems related to the applications of nanotechnology in road engineering: The determination of current needs that cannot be effectively addressed using existing technology, the identification of applicable nanotechnology solutions in the field of road engineering, and the determination of nanotechnology solutions that will achieve the highest benefit/cost ratios by combining two concepts (Steyn, 2011). In recent years, a significant body of research has been dedicated to investigating the diverse applications of nanotechnology in the domain of building materials, with a particular focus on those containing nano-SiO_2, nano-Al_2O_3, nano-TiO_2, nano-Fe_2O_3, nano-$CaCO_3$, nanoparticles, carbon nanotubes, and nano-clay, among others. The behaviour of these materials is primarily influenced by the chemical reactions that occur at the interface. Consequently, the employment of nanoparticles in cement-based materials has been demonstrated to yield superior outcomes by modifying their behaviour in both fresh and hardened states (Sanchez & Sobolev, 2010; Senff et al, 2012). The fibres utilised in concrete serve the primary function of preventing the propagation of stress within the concrete matrix by means of a crack bridging effect, thereby enhancing the flexural strength and mitigating the fragility of the concrete. Among these fibres, basalt fibres are distinguished by their strength and environmental resistance properties. As demonstrated in the extant literature, basalt fibres, in addition to steel, glass and polypropylene fibres, have been shown to be effective in increasing the durability of concrete (Bolat, 2009). However, the environmental compatibility and thermal resistance properties of basalt fibres render this material more attractive. A plethora of studies have been conducted on the utilisation of fibres as road pavement. Bolat (2009) conducted a large-scale study in which he determined the performance of polyester (PYTB), and polypropylene fibre-reinforced concrete (PPTB) compared to steel fibre-reinforced (ÇTB) and non-fibre reinforced concrete. This was achieved by conducting fresh and hardened concrete tests and investigating the usability of the mixtures as highway superstructure. The study encompassed a comprehensive array of tests, extending beyond the conventional physical assessments of concretes. This encompassed plate splitting tensile strength, approximate compressive strength ascertained through surface hardness, beam flexural, compressive and elastic modulus, ultrasonic transmission speed, abrasion, capillary water absorption, and carbonation depth. As a result, when the wire-reinforced concretes were compared to the unreinforced concretes; it was determined that the collapse was reduced, the resistance to cracking was increased, the flexural strength was increased, the tensile strength in splitting was increased, and the compressive strength was relatively low. Consequently, it was deduced that the produced wire-reinforced concrete could be utilised in highway superstructures (Bolat, 2009). In a separate study, an attempt was made to enhance the mechanical properties of concrete utilised in road superstructure through the reinforcement of the material with polyamide and steel fibres. The study concluded that the most effective parameter in compressive strength and flexural strength was the use of polyamide fibre. It was observed that as the percentage of polyamide fibre incorporated into the mixture increased, a concomitant decrease in strength was recorded. It has been determined that material ratios have a significant effect on the design of road concrete using polyamide and steel fibres. Furthermore, the applicability of the Taguchi method has been envisaged to determine the optimum amount (Asatekin, 2019). In a separate study, the utilisation of basalt fibres in concrete roads was examined. The objective of this study was to enhance the flexural and compressive strength of concrete by incorporating basalt fibres into the concrete mixture. Furthermore, improvements in the mechanical properties of concrete using different types and amounts of fibres were comparatively studied. Consequently, the mechanical properties of the concrete samples containing fibre additives exhibited an enhancement in comparison with the unreinforced control samples. A comparative analysis was conducted to assess the usability of these materials in concrete roads, and it was observed that the addition of steel fibre, basalt fibre and polypropylene fibre resulted in optimal performance (Çevik, 2014).

The object of this study is to examine the microstructure of RCC road concrete with nano powder and basalt fibre additives by BET and SEM analysis, with a view to revealing the effects of these additives on road concrete in detail. BET analysis is a widely utilised technique in the field of materials science, with applications including the comparison of pore structures across diverse material types. It serves as a valuable tool for examining the impact of additives on enhancing the specific surface area of materials. Additionally, it facilitates the evaluation of the influence of these structural modifications on the mechanical properties of the material, offering insights into the relationship between material design and performance. For instance, studies evaluating the impact of nano-additives on the microstructure of concrete have underscored the significance of BET analysis in the filling of micropores [20]. Additionally, it is extensively utilised in the investigation of the effects of innovative nano-additives, such as carbon nanotubes (Seis et al, 2022). On the other hand, SEM analysis facilitates the visualisation of the microstructure of the material, thereby enabling a more detailed examination of cracks, fibre distributions and filling effects. SEM analysis is a frequently employed technique in the evaluation of microstructural features, including the distribution of fibres and the observation of cement hydration products. In academic literature, the SEM images provide valuable insights into the distribution of nanomaterials within the cement matrix, and the synergistic effects they create with fibres. The present study focuses on the pore-filling ability of nano powder and the role of basalt fibres in crack control. The aim is to reveal their contributions to the strength and longevity performance of the material. In this context, the connections between microstructure and material performance will be discussed in depth, and inferences that will guide future applications will be made in the light of the findings. The results of the BET and SEM analyses obtained in the present study will be compared with those of similar studies in literature by correlating them with compressive, flexural and abrasion tests. This approach will facilitate a more comprehensive evaluation of the impact of nanoadditives and basalt fibres on microstructure and macro performance.

2. MATERIAL AND METHOD

2.1. Material

In this study, CEM I 42.5R type cement produced by Aşkale Çimento company, which complies with TS EN 197-1 standards, was used as the binder (TS EN 197-1, 2012). The mixing water was obtained from the municipal drinking water supply, complying with TS EN 1008 standards (TS EN 1008, 2003). Aggregates of three different sizes (0-5 mm, 5-12 mm, and 12-22 mm) were sourced from Mazlumoğlu Construction in accordance with TS 3530 EN 933-1 (TS 3530 EN 933-1, 2012). Granulometry curves of aggregates are shown in Figure 1.

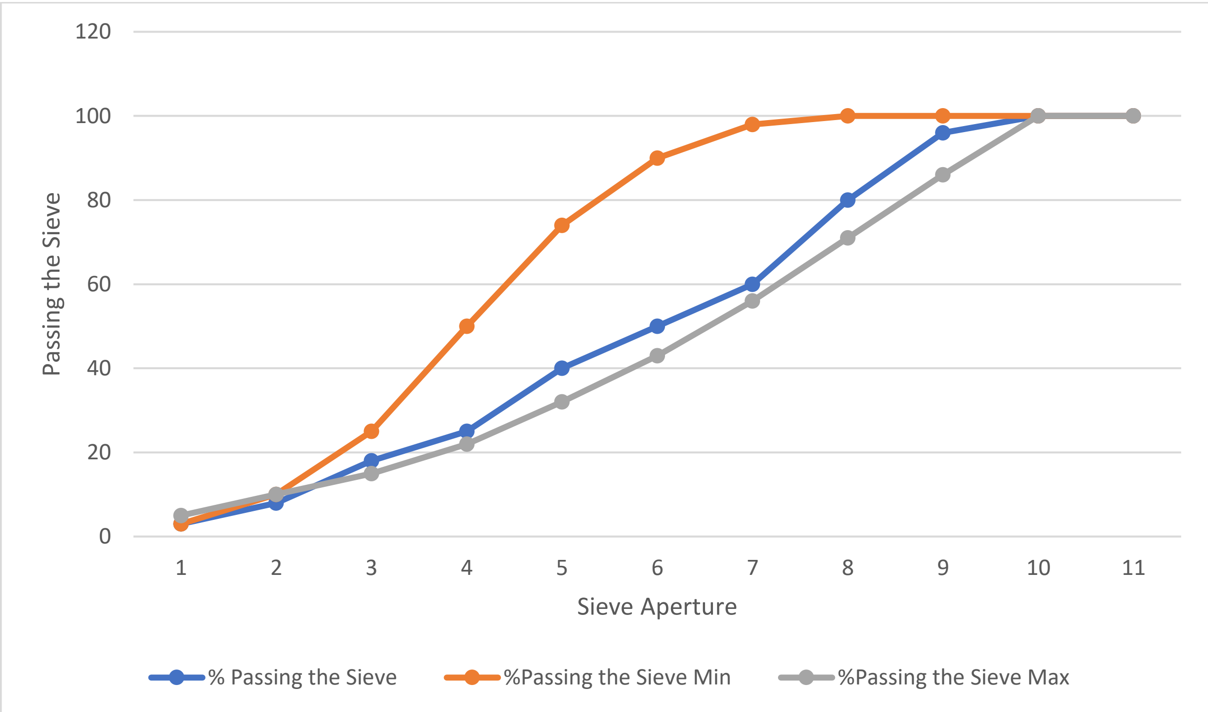

***Figure 1.** Granulometry Curves*

Basalt fibre, procured from Dost Chemistry Industry, was utilized to enhance the mechanical properties of the concrete. Nano Fe_2O_3 and nano TiO_2 powders, supplied by Nanografi Nano Technology, were incorporated into the mix to improve the microstructure and durability characteristics. Fly ash obtained from Yatağan Thermal Energy Production Corporation was used as a supplementary cementitious material in accordance with TS EN 450-1 (TS EN 450-1, 2013). Additionally, a plasticizer (Master Pozzolith-515) from Master Builders Solutions, complying with the TS EN 934-2+A1 standard, was included to increase the workability of the concrete (TS EN 934-2+A1, 2013).

2.2. Method

2.2.1. Mixture Calculation

Three mixtures were prepared using the optimum mixture calculation determined in the studies of Sünbül and Tortum (2024), and the proportions of these mixtures are given in Table 1 (Sünbül & Tortum, 2024). Following a 28-day period of curing, the prepared mixtures were subjected to a series of mechanical tests, including compressive, flexural and abrasion. The optimum values were thus evaluated separately, and the most ideal mixture was determined.

Table 1. *Optimum Mixture Proportions*

Mixture No.	Cement (kg)	Fly Ash (kg)	Nano Fe_2O_3 (kg)	Nano TiO_2 (kg)	Basalt Fibre(kg/m^3)
Mixture-1	322	17.5	0	10.5	0
Mixture-2	339.5	0	10.5	0	0
Mixture-3	329	0	7	14	2.5

2.2.2. Slump Test

The slump test is typically conducted using a truncated cone, known as a slump cone (Clayton et al, 2003; Roussel & Leroy, 2005; Bayar, 2019). It is expected that the slump value will be within certain limits. Concrete with slumps greater than the limit value demonstrate a decrease in strength, whilst those with slumps less than the limit value exhibit a decrease in workability.

Given that the concrete designed in this study is RCC, it is anticipated that the slump value will be approximately zero. The utilisation of a roller for the placement of the concrete is expected to mitigate any potential issues arising from the low slump value, ensuring optimal workability. The slump test was conducted independently on three distinct mixtures, in accordance with the provisions of the TS EN 12350-2 standard (Figure 2) (TS EN 12350-2, 2019). The slump values were found to be in the range of 0.3-0.5 mm.

Figure 2. *Applied Slump Test*

2.2.3. Abrasion (Bohme) Test

The phenomenon of abrasion is associated with the aggregate's resistance to abrasion. The aggregate demonstrating the greatest resistance to abrasion also exhibits a similar effect in concrete and exhibits a high level of compressive strength (Bayar, 2019). The addition of nano or fibrous materials to concrete has been demonstrated to result in a variation in the abrasion resistance, depending on the ratio of the materials. Consequently, under conditions where the appropriate proportion and uniform distribution of these materials can be accomplished, an enhancement in abrasion resistance may be observed (Seis et al, 2022). A variety of test methods are available for the purpose of determining abrasion. To ascertain the abrasion resistance of RCC, the subject of this study, the Böhme abrasion test was selected as the abrasion test. The samples prepared for the test were then subjected to the test using the Baz Makine brand Böhme (abrasion) test device in accordance with the TS 2824 EN 1338 standard (TS 2824 EN 1338, 2005). In the Böhme test, a device with a horizontally placed rotating abrasive disk of approximately 750 mm diameter, rotating at a speed of 30 rpm ± 1 rpm, was utilised on cube samples with side lengths of 70 mm (Figure 3). A quantity of 20 g ± 0.5 g of abrasive powder was dispensed onto the friction strip, which was then loaded with 294 ± 3 N by means of a steel lever. The test, which consists of 22 cycles for each sample, was applied to sample 16 times.

Figure 3. *Abrasion Application to The Sample*

After the meticulous cleansing of the test sample, its dimensions were measured with a precision caliper and weighed on a precision balance. Consequently, the initial and final weights of the sample were measured, and volume losses were calculated.

Total volume loss was calculated according to Equation 1 below:

$$\Delta v = \Delta m / d \quad (1)$$

Here;

Δv: Total volume loss after 16 cycles (mm3)

Δm: Total mass loss after 16 cycles (g)

d: Sample density (g/mm3)

The visual appearance of the test samples prior to and following abrasion is illustrated in Figure 4.

Figure 4. *Condition of the Sample Before and After Abrasion*

2.2.4. Compressive Strength Test

In the context of RCC roads, the compressive strength of concrete assumes significant importance. To ensure that the road can safely and efficiently accommodate the anticipated traffic loads, with minimal deterioration, it is imperative that the compressive strength of the concrete is sufficiently high. The findings of the studies indicated that the mean of the 7- and 28-day compressive strength test results were met for RCC mixtures (Öztürk, 2018; Abut, 2017; Yağtu, 2019). The compressive strength test was conducted utilising the Besmak brand compressive strength test device, in accordance with the requirements of the TS EN 12390-5 standard (TS EN 12390-5, 2019). The samples upon which the test was applied have dimensions of 150x150x150 mm. The cube samples were positioned in a manner that ensured the load application direction was perpendicular to the concrete casting direction. The experiment was conducted by transferring the load to the sample without impact effect with a constant loading rate of 0.2 MPa/s (N/mm2.s). In accordance with the established protocol, the load was applied at a constant velocity until the maximum load that could be applied to the sample was attained (Figure 5). At this point, the reading of the load from the indicator was documented.

Figure 5. *Applying Compressive Strenght Test to Concrete*

2.2.5. Flexural Strength Test

In the cross-section of samples in flexural state, compressive stresses occur in the region proximate to the inner surface and tensile stresses occur in the region proximate to the outer surface (Luther-Davies, 2014). The samples that were produced for the flexural strength test were then subjected to three-point flexural testing using a Besmak brand sample flexural testing device in accordance with the requirements of the TS EN 12390-5 standard (TS EN 12390, 2019). The test was applied to 40x100x100 mm beam samples from the midpoint of the opening using the simple beam method on concrete samples (Figure 6).

Figure 6. *3-Point Flexural Strenght Test Application*

2.2.6. Scanning Electron Microscopy Method (SEM)

The first electron microscope to be developed was the Transmission Electron Microscope (TEM). The scanning electron microscope (SEM) was first commercialised in the 1960s and began to spread with the development of technology (Karaduman, 2017). In the last 20-30 years, the use of high-tech instruments such as SEM and TEM, which are used to determine the properties of nanomaterials and their use, has opened the doors of the nano world to researchers (Arivalagan et al. 2017). Scanning electron microscopy (SEM) is a type of electron microscope that acquires images by scanning the sample surface with a focused beam of electrons. Scanning electron microscopy (SEM) is a technique used to visualise the morphological, topographic, component structures and dimensions of the sample and its surface. The utility of SEM extends to the examination of a wide range of non-conductive samples, provided they do not possess liquid properties or conduct electricity. The use of the scanning electron microscope (SEM) allows for the examination of a wide range of materials, including metals, textiles, fibres, plastics, polymers, and particles such as sand, gravel, and pollen. The examination of non-conductive samples can be facilitated through the application of a conductive coating. The EDX (Energy Dispersive X-ray Spectrometer) detector enables the relative amounts of elements and compounds to be obtained as percentages. The mapping method facilitates the identification of elements concentrated in the target region on the SEM image. It is possible to obtain crystallographic information from the sample using the electron backscatter diffraction detector. The utilisation of multiple detectors in conjunction with SEM has been demonstrated to enhance the comprehensiveness of the resulting data. The SEM setup comprises an electron gun, condenser lenses that function to collect and direct the electron beam, mechanical apertures that serve to control the diameter of the electron beam and scanning coils that deflect electrons to scan the sample surface. The sample chamber, which is maintained under vacuum, contains holders and detectors into which the samples are placed (Karaduman, 2017; Acharya, 2023).

2.2.7. Gas Adsorption (Brunauer and Emmett) Method

The Brunauer and Emmett methods, predicated on the adsorption-desorption process, are the most common methods employed in practice. The BET method was developed by three researchers who, in a seminal paper, employed multilayer adsorption theory to determine the specific surface area of solid materials. In this method, two adsorbents (nitrogen and water vapour) are utilised, and a drying process is a prerequisite for the preparation of samples (Skalny & Hearn, 2001; Beaudoin & Marchand, 2001; Odler, 2003). However, in samples containing CSH phase, BET N_2 value is generally lower than BET H_2O value. This phenomenon can be attributed to the smaller size of water vapour, which consequently enters smaller voids and between CSH layers, resulting in elevated values (Odler., 2003). BET analysis, an adsorption isotherm model, consists of the incremental addition of a new adsorbed molecular layer to the layer beneath it. The BET gas adsorption theory forms the basis for the measurement of surface area in materials with high specific surface area. Remarkably, the BET method gives a higher specific surface area for a fine-grained sample than for a coarse-grained sample (Brunauer, 1938). It has been established that, due to the inability of N_2 gas to reach the inner surfaces in the BET method, the measurement of N_2 gas adsorption is limited to the outer surfaces (Su, 2019). A typical graph obtained from gas adsorption in general is shown in Figure 7. This representation facilitates the determination of the volumes of the voids in the sample according to their diameters (Lange & Grasley, 2007).

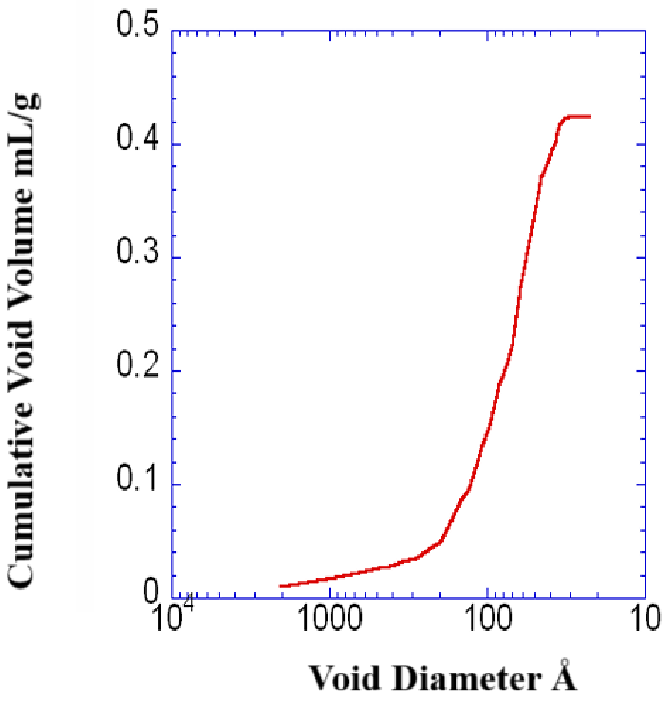

Figure 7. *The Graph Obtained as A Result of Gas Adsorption*

The equation developed for the BET isotherm is given in equation 2 (Noorimotlagh et al, 2014).

$$\frac{c_e}{(c_s - c_e)} = \frac{1}{BQ^0} + \left[\frac{B-1}{BQ^0}\right]\left(\frac{c_e}{c_s}\right) \tag{2}$$

Here;

Cs: Saturation concentration of adsorbate (mg/L)

Qo: Amount of adsorbate adsorbed on all layers on the surface of the adsorbent (mg/g)

B: BET constant (gives the energy relationship between the adsorbent surface and the adsorbate).

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Compression, Flexural and Abrasion Test Results

To conduct a mixture calculation, three test samples were prepared for each calculation. These samples were then subjected to a series of tests, including compressive, flexural and abrasion tests. The mean values of the test results were calculated to obtain the average compressive, flexural strength and abrasion strength values. The compressive strength of mixture 1 was determined to be 35.46 MPa, that of Mixture 2 was found to be 45.88 MPa, and mixture 3 was found to be 61.20 MPa. It is evident from the data presented in Figure 8 that mixture 3 exhibited the highest compressive strength. The primary cause of this increase is the enhancement of pozzolanic reactions by nano Fe_2O_3 and TiO_2, the improvement of matrix density, and the limitation of crack propagation of basalt fibres. The presence of nanoscale materials has been demonstrated to support the formation of C-S-H (calcium silicate hydrate), thereby providing a more compact and durable structure.

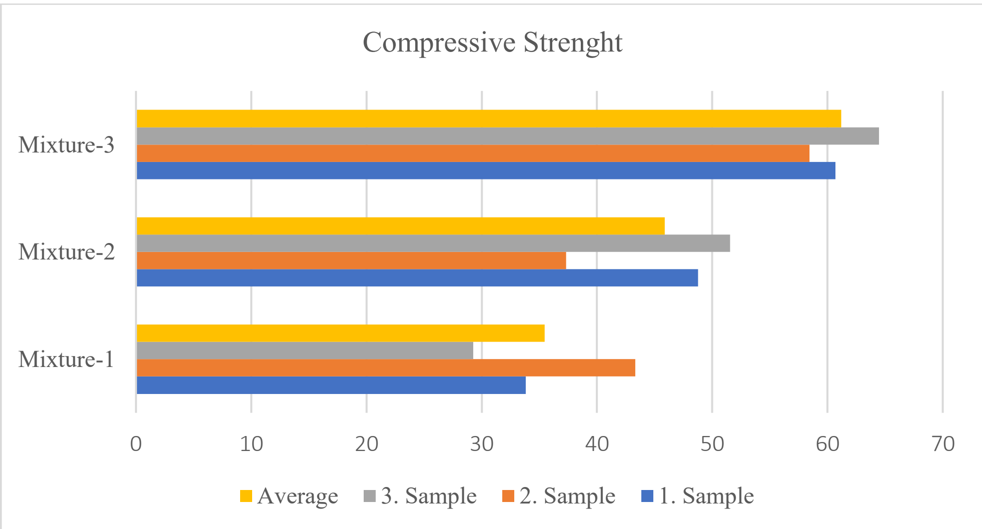

Figure 8. *Compressive Strength Data*

During the flexural strength test, the mean flexural strength of Mixture 1 was determined to be 7.25 MPa, that of mixture 2 was found to be 6.95 MPa and that of mixture 3 was established to be 8.80 MPa. It was determined that mixture 3 exhibited the highest flexural strength (Figure 9). This result is associated with an increase in crack resistance capacity of the basalt fibre additive and a strengthening of the bond structure of the nano powders within the matrix. The increase in bond strength, attributable to the filling of the voids within the nano particles, and the contribution of the basalt fibres to the load carrying capacity, resulted in an enhancement of the flexural strength.

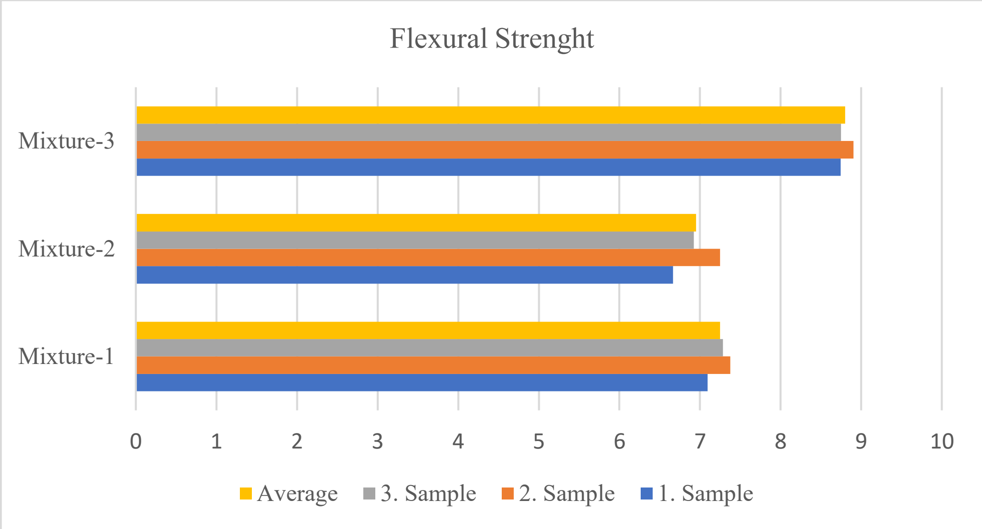

Figure 9. *Flexural Strength Data*

The weights of the samples that were subjected to the abrasion test were measured prior to and following the test, and the average mass and volume losses were calculated at the conclusion of the test. The average mass loss of mixture 1 was determined to be 3.9 g, the volume loss was 1.81 g, the average mass loss of mixture 2 was determined to be 3.2 g, the volume loss was 1.48 g, and the average mass loss of mixture 3 was determined to be 2.5 g, the volume loss was 1.12 g. Consequently, the mixture that exhibited minimal abrasion loss was identified as the third mixture (Figure 10). This phenomenon can be attributed to the presence of nano particles, which fill the interstices within the matrix, thereby enhancing its resistance to abrasion. The basalt fibres, in turn, contribute to the maintenance of mechanical integrity. The matrix, characterised by a denser and more compact bond structure, exhibits reduced loss when subjected to abrasive loads.

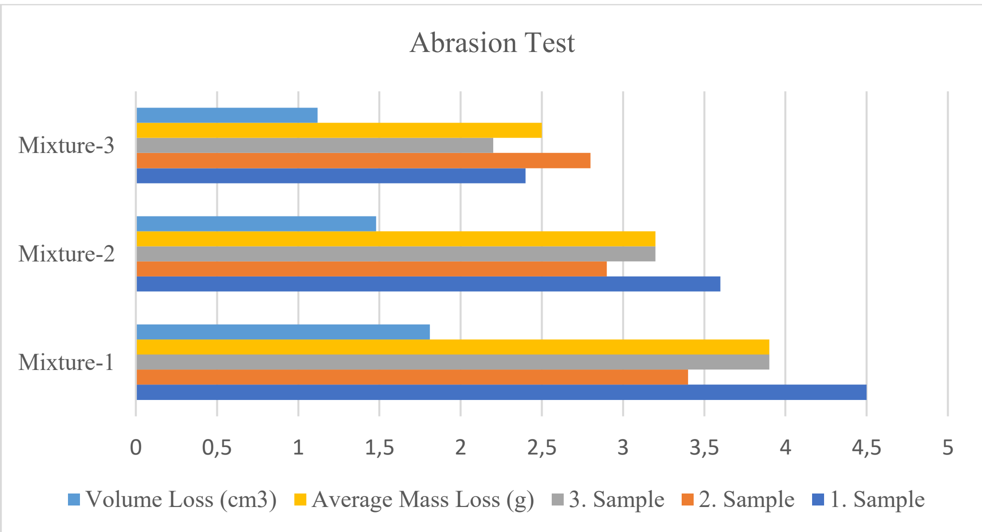

Figure 10. *Abrasion Test Data*

3.1.2. SEM-EDX Analysis Results

SEM imaging was performed on the optimum calculation samples that had been produced, with three growth amounts — 5k, 10k and 20k — to obtain a high-resolution internal structure view and elemental analysis with EDX. The samples were different, so there were big elemental analysis results differences. The samples were found to contain CH (calcium hydroxide) crystals, which exhibited a distinct plate-like surface morphology. These crystals are the result of the hydration process of cement, and the presence of C-S-H (calcium silicate hydrate) gels was also identified. These gels have been identified as a primary contributing factor to the strength of concrete.

Figure 11 presents the 5k, 10k and 20k magnification SEM images of the samples produced with the 1st mixture calculation. Using fly ash and nano-TiO_2 in concrete makes the structure smaller than with cement, as the particles fill the voids. A more thorough examination of the image revealed the presence of smaller voids. This finding indicates that fly ash and nano TiO_2 are inadequate in filling the voids. Consequently, it can be deduced that the compressive strength of the initial verification specimen will be lower than that of the other mixtures due to the presence of voids. The compressive strength tests also corroborate this situation. The presence of CH crystals and C-S-H gels in the mixture was also observed. Furthermore, fly ash was found to be present within the microvoids that had originated from the C-S-H or other microvoids.

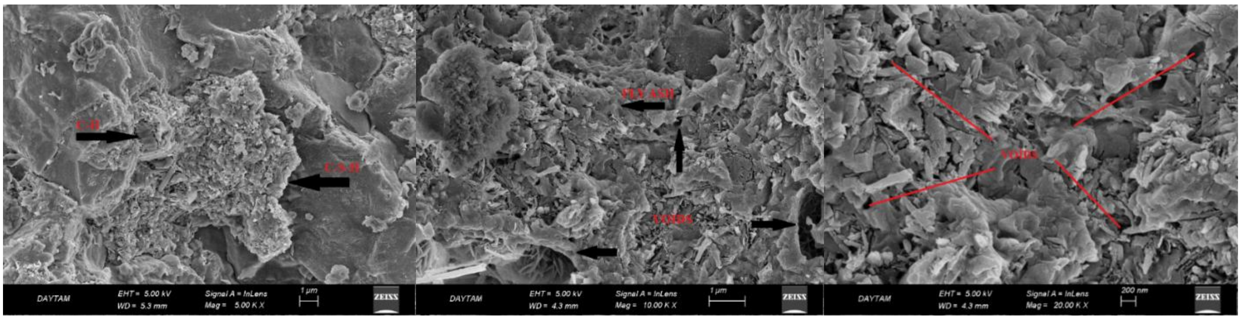

***Figure 11**. SEM Image of Mixture-1*

Figure 12 presents the SEM images of the samples produced with the second mixture calculation at 5k, 10k and 20k magnifications. A comparison of the two mixtures reveals that the void ratio in the latter is less. The presence of a small, porous structure was attributed to the incorporation of nano-Fe_2O_3 material within the concrete. The presence of CH products has been observed at the interfaces of pores in various materials. Moreover, CH crystals and C-S-H gels have also been observed in concrete. The nanomaterial utilised in the mixture contributed to the strength of the material by forming additional C-S-H gel. Furthermore, an increase in reactions with the seeding (nucleation) effect was observed, which also resulted in an increase in strength with the filling effect. This hypothesis was corroborated by the findings of compressive strength tests.

Figure 13 presents the 5k, 10k and 20k magnification SEM images of the samples produced with the 3rd mixture calculation. Upon examination of the images depicting the mixture in which basalt fibre was incorporated, it was observed that the void structure was significantly reduced, and the C-S-H gel formations

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were more intense. It is evident that, under typical conditions, basalt fibre exhibits a porous structure, thereby hindering the anticipated level of adhesion between the fibre and cement. However, the incorporation of nanomaterials into concrete has been shown to enhance adhesion. In 20k images, the presence of materials and the formation of C-S-H gels on the basalt fibre is more clearly discernible. A homogeneous structure is observed in the mixture upon examination in general. It is understood that a good adherence relationship is formed in the aggregate-cement-water reaction. Furthermore, analysis of the images indicates that the addition of basalt fibre to concrete does not result in the formation of a new phase. While there are minor voids present, the fibres appear to be well amalgamated and distributed homogeneously within the mixture. The reinforcement effect created by the homogeneous distribution of basalt fibres in the concrete has been demonstrated. Consequently, the addition of fibre to concrete is understood to enhance its mechanical properties. It has been determined through the implementation of flexural strength tests that this structure increases strength.

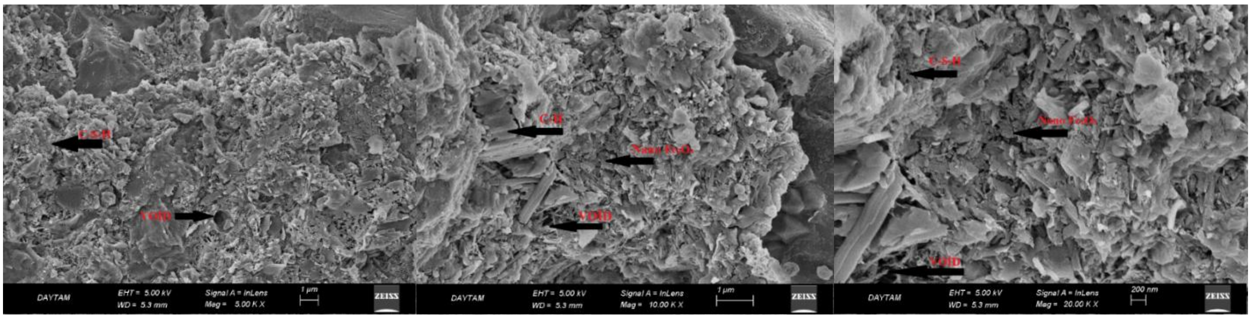

Figure 12. *SEM Image of Mixture-2*

The incorporation of two distinct nanopowder types in the third mixture resulted in a substantial augmentation in the amount of C-S-H formed in the concrete and the seeding effect. The primary distinction between the samples devoid of nanomaterials or comprising a solitary nanomaterial and those containing two types of nanomaterials in the SEM images pertained to the dough matrices of the samples containing nanomaterials, which exhibited increased density and a higher proportion of crystalline structure in comparison to the samples devoid of nanomaterials. Therefore, it is anticipated that the mechanical properties of the sample will undergo enhancement. The superior mechanical properties of the third sample were further substantiated by compressive strength tests. Concurrent studies by other researchers have yielded analogous results (Adak et al, 2014; Deb et al, 2015; Ramachandran & Beaudoin, 2000). The findings of the analyses support these researchers.

In order to facilitate the investigation of the C, O, Fe and Ti densities during the EDX analysis, the ratios of these elements are presented. SEM images of the third mixture with the highest strength values were examined and compared with EDX images, which provided information about the elemental composition of the sample (Figure 14). Accordingly, it can be concluded that the SEM images agree with the EDX results. A thorough examination of the EDX spectra of the third mixture reveals that the levels of carbon and oxygen in the environment exceed those observed in the other mixtures. According to the resultant data, most of the phases formed in the third verification sample, that is, as a percentage by weight in the sample, consist of compounds of these elements. The carbon density of the material under investigation is attributable to the presence of cement and fly ash. The data obtained in this study are consistent with those reported in similar studies (Ramachandran & Beaudoin, 2000; Erdoğan, 2011). Consequently, a comparison of the three prepared verification samples revealed that the mechanical properties of the third mixture, the basalt fibre and nano powder concrete sample, would exceed those of the other concrete samples. This is attributable to the low amount of voids, the good adhesion relationship between the phases, and the formation of a homogeneous structure. The outcomes of the compressive and flexural strength assessments further substantiate this phenomenon.

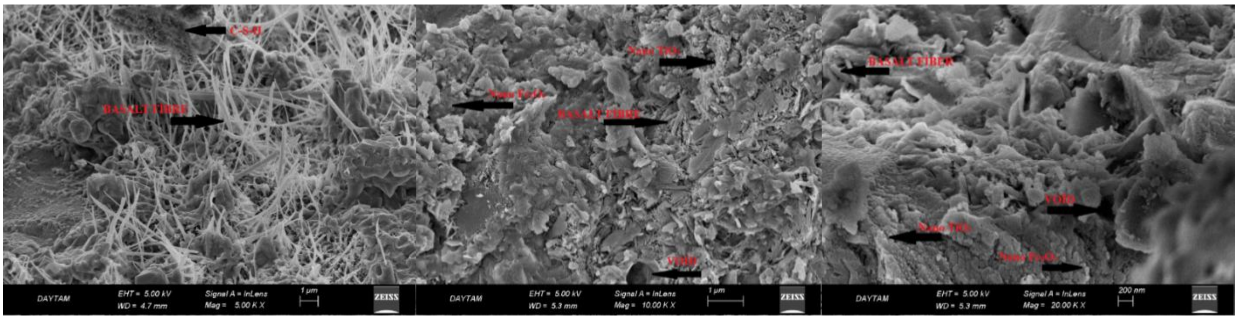

Figure 13. *SEM Image of Mixture-2*

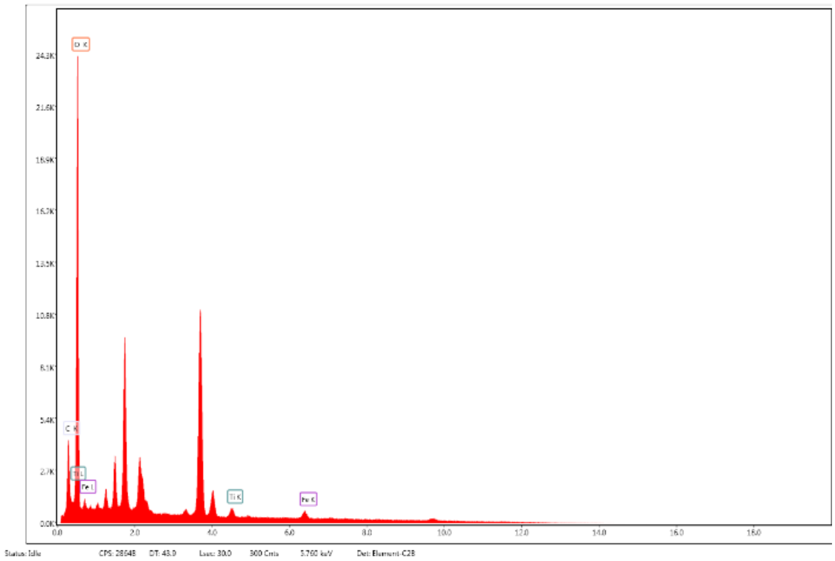

Figure 14. *Third Mixture EDX Chart*

3.1.3. BET Analysis Results

The BET method was applied to determine the surface area and the width of the pores of the material. The adsorption process was facilitated by the utilisation of nitrogen gas. The Barrett, Joyner and Halenda (BJH) method was utilised to ascertain the pore sizes. The BJH method, a computational procedure developed by Barrett, Joyner and Halenda in 1951, has emerged as the most prevalent technique for determining the mesopore (multipore) size distribution (Rouquerol et al, 1999; Rouquerol et al, 2002). The specific surface area and adsorption-desorption pore sizes, calculated by the BET method, and the cumulative pore width, obtained by the BJH method, are presented in Tables 2 and 3, respectively.

Table 2. *Material Surface Areas*

Surface Area (m²/g)			
Mixture No	Mixture-1	Mixture -2	Mixture -3
Single Point Surface Area (p/p° = 0,35)	11.42	10.59	5.68
BET Surface Area	11.51	11.25	6.72
Cumulative Surface Area of BJH Adsorption Pores	14.90	15.91	8.36
Cumulative Surface Area of BJH Desorption Pores	18.18	19.08	9.91
Cumulative Surface Area of D-H Adsorption Pores	19.59	20.34	12.44
Cumulative Surface Area of D-H Desorption Pores	18.88	20.18	15.11

It is anticipated that the surface area and pore size will be minimal due to the elevated density of nanomaterials in the sample derived from the third mixture, which was ascertained to be optimal. The analysis results also support this situation. Hysteresis loops are utilised in the characterisation of nanoporous materials. The International Union of Pure and Applied Chemistry (IUPAC) has determined the types of hysteresis loops, of which the first appeared in 1984 (Collet et al, 2008). Subsequently, the International Union of Pure and Applied Chemistry (IUPAC) categorised hysteresis loops into four distinct types and correlated them with pore structures (Figure 15) (Sing et al, 2004).

The analysis of the distribution of pore widths according to the hysteresis between the adsorption-desorption isotherms was conducted using hysteresis loop tables for the three mixture samples. In accordance with the UNAC classification, the hysteresis loops in all three mixtures are of the H3 type (Figure 16). As demonstrated in the tabular data, there is an absence of a discernible peak in the BJH desorption pore volume curves of the optimum mixture samples. This finding indicates that the pore size distribution of the sample is characterised by a high content, suggesting the absence of a uniform pore structure. Isotherms exhibiting H3 type hysteresis are indicative of the potential presence of interconnected micropores or mesopores within the samples (Kruk & Jaroniec, 2001).

Table 3. *Material Adsorption-Desorption Pore Sizes*

Pore Size (nm)			
Mixture No	Mixture-1	Mixture -2	Mixture -3
Adsorption Average Pore Diameter	8.43	9.93	6.06
Desorption Average Pore Diameter	11.47	13.60	7.83
BJH Adsorption Average Pore Width	8.75	10.34	4.51
BJH Desorption Average Pore Width	7.48	8.83	5.47
BJH Desorption Average Pore Width	7.57	9.06	4.27
D-H Desorption Average Pore Width	7.67	8.97	4.74

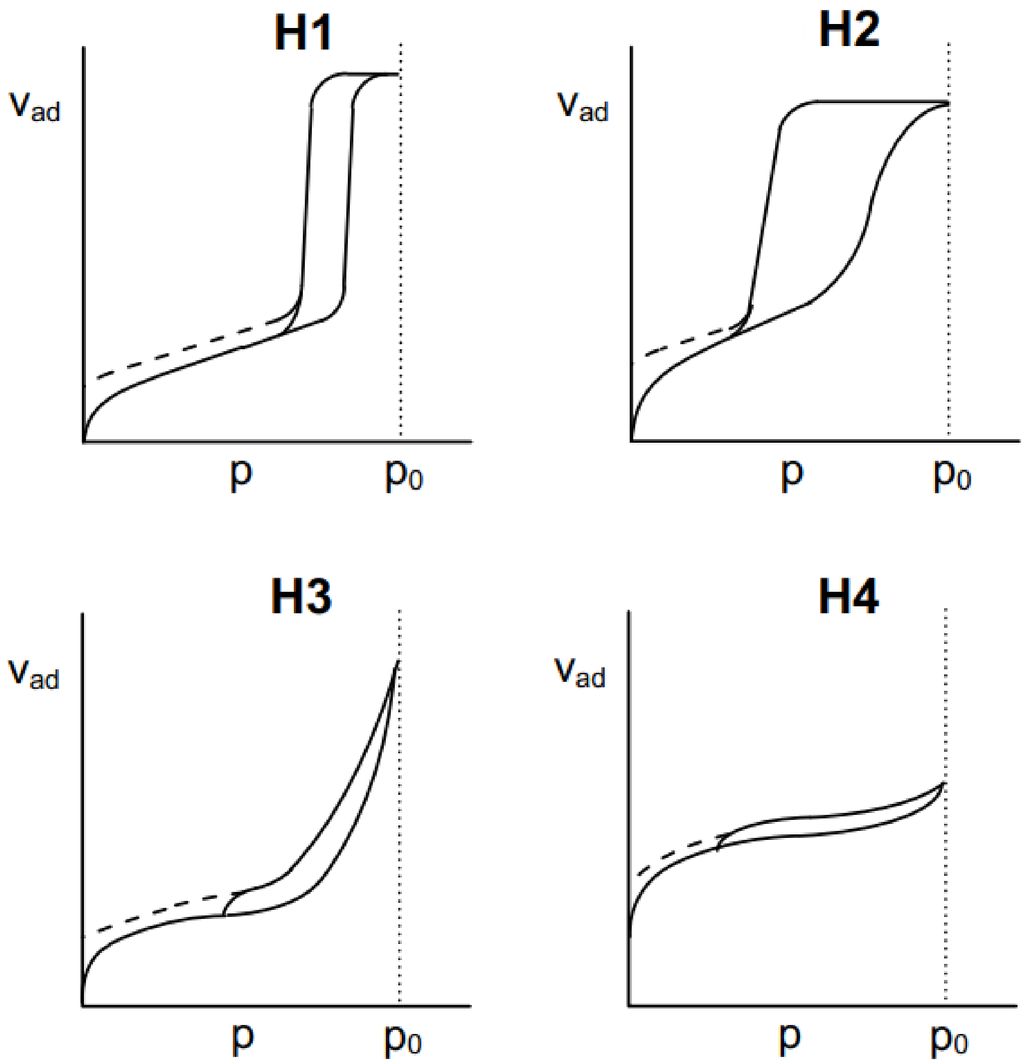

Figure 15. *IUPAC Hysteresis Loop Tables*

Following a thorough evaluation of the analyses, it can be concluded that the volume values of the pores in the samples are low. However, the pore type is not uniform. The findings from the analysis provide a robust rationale for the objective of reducing the void ratio, with the aim of enhancing the impermeability of concrete. Since changes in pore type depend on compression, good compression in practice will ensure that the void ratio is distributed evenly, and the pore type is not too diverse.

4. DISCUSSION

Roller compacted concrete (RCC) is characterised by a lower water/binder ratio, higher compaction requirements and a reduced void structure in comparison with conventional road concretes. The present study is an in-depth investigation into the microstructural and mechanical effects of nanomaterials and basalt fibres on RCC road concretes. SEM analysis demonstrated that nano-additive mixtures significantly reduced the voids and formed a more compact structure. It was observed that fly ash and nano-TiO_2 were present within the voids of the first mixture, but that they did not provide sufficient density. Research has demonstrated that nano-TiO_2 promotes the formation of calcium silicate hydrate (C-S-H) during cement hydration, thereby enhancing compressive strength. This finding was corroborated in the study by Wang et al. (2020), which demonstrated that nano-TiO_2 increased the density of cement paste and enhanced the pore structure (Wang et al, 2020). The utilisation of nano Fe_2O_3 in the second mixture resulted in the partial filling of the voids, thereby enhancing the concrete's compactness and increasing its strength through the acceleration of hydration reactions. Furthermore, the process resulted in a filling effect by demonstrating a nucleation effect, thereby enhancing the strength of the material. As stated in the extant literature, the presence of nano Fe_2O_3 in cement systems has been shown to induce a nucleation effect, thereby promoting the formation of the C-S-H phase and resulting in an increase in strength (Xing et al, 2018). In the third mixture, optimum results were obtained by using nano Fe_2O_3, nano TiO_2 and basalt fibre together. As demonstrated by SEM images, the void ratio is minimised in this mixture, resulting in the formation of a denser matrix. Furthermore, it was observed that basalt fibres were distributed homogeneously in concrete without creating a new phase and increased the flexural strength by bridging micro-cracks. The contribution of basalt fibres is a frequently emphasised benefit in the extant literature, and it is well-documented that these fibres positively affect the long-term performance of concrete due to their high thermal resistance and resistance to alkalis (Ulusoy, 2016). Moreover, in a separate study in which nano TiO_2 and nano Fe_2O_3 were utilised in conjunction, SEM images were referenced, and the beneficial impact of nano powders on the compressive strength of concrete was highlighted (Mutuk, 2013).

BET analyses were conducted to reveal the detailed changes that nano-additives and basalt fibres effect on the pore structure of concrete. In the third mixture, a significant decrease in surface area and pore volume was observed in comparison to the other mixtures. This finding indicates that the impermeability of RCC concrete increased, thereby rendering the road surface more resistant to the effects of water and chemicals. Various scholars have shown that adding nanomaterials to concrete can reduce how much water it absorbs and how permeable it is. This is because the nanomaterials change the concrete's pore structure (Senff et al, 2012). Increasing the impermeability of RCC concretes is a factor that improves the long-term performance of road concretes, especially by increasing their resistance to freeze-thaw cycles. Concretes with lower void ratios have been demonstrated to impede surface erosion and chemical deterioration by preventing water from seeping into the subsurface. In addition, studies have been conducted in which nano Fe_2O_3 and nano TiO_2 have been utilised in binary combinations with other nano powders. Oltulu (2014) obtained binary combinations by using nano Fe_2O_3 with nano Al_2O_3 and Nano SiO_2 and examined the void structure of the material with BET analysis. The study concluded that it was not possible to reach a definitive conclusion regarding the effect of increasing the nanopowder ratio on the variation in the samples' properties (Oltulu and Şahin, 2014). The findings of this study demonstrate that the amalgamation of nano Fe_2O_3 and nano TiO_2 yields highly favourable outcomes in this regard, thereby ensuring a substantial enhancement in the performance of RCC concretes.

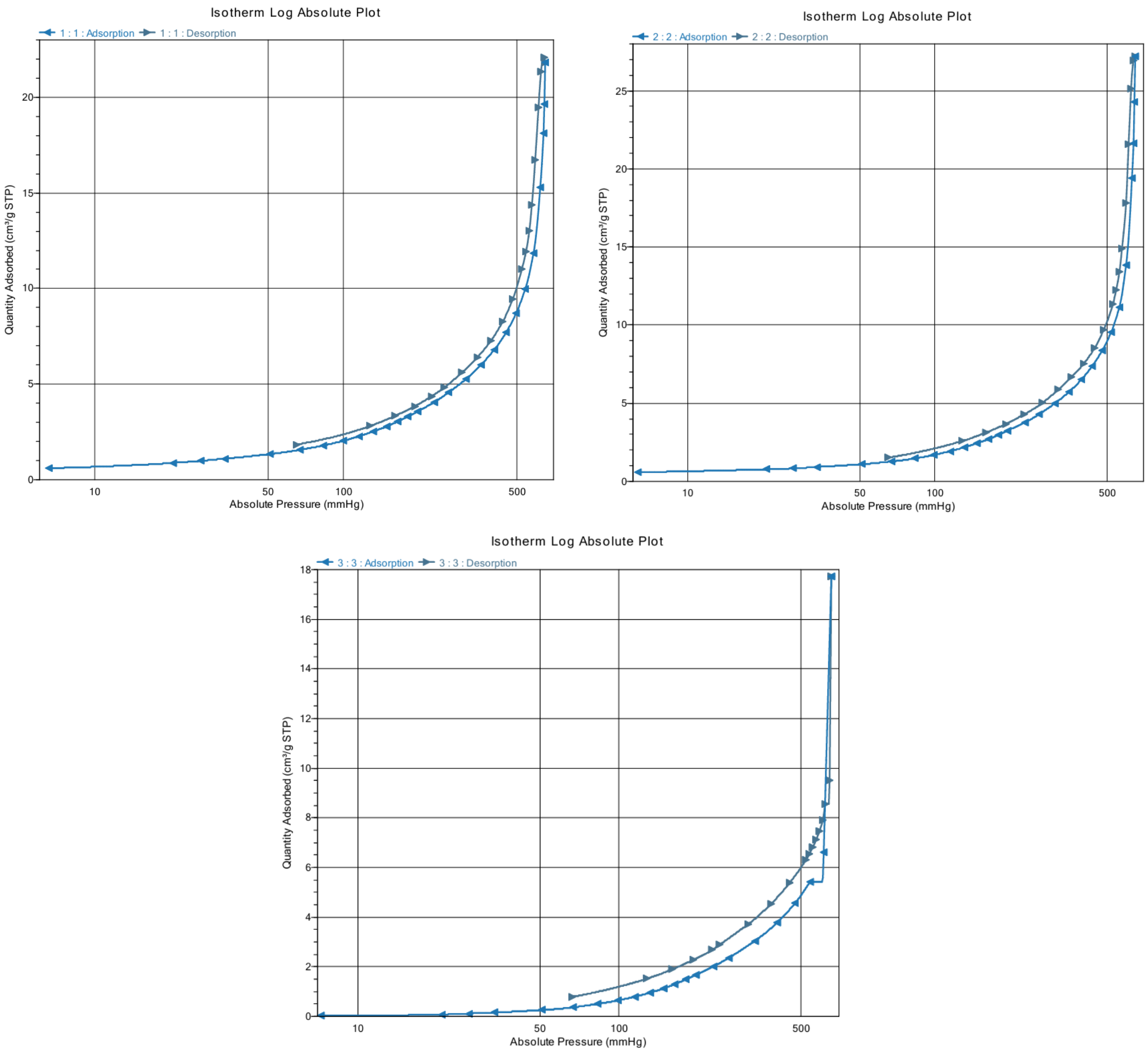

Figure 16. *IUPAC Hysteresis Loop Tables*

5. CONCLUSION

The compaction method employed for RCC road concrete is distinct from that of traditional vibrated concretes, a distinction that arises from the former's comparatively low water content. In this context, the present study has demonstrated that nanomaterial and fibre additives have a decisive role in determining the mechanical and durability properties of RCC. The utilisation of nanomaterials resulted in the formation of a more compact structure, whilst the incorporation of basalt fibres led to an augmentation in flexural strength due to the retardation of crack formation. This combination provides a significant advantage for increasing the resistance of RCC to traffic loads. The dense microstructure of the concrete surface resulted in reduced deformation under abrasive loads. This is of particular significance in the context of heavy road-bearing roads. The results of BET analyses demonstrate that nanomaterials reduce voids and increase impermeability. This feature is a critical parameter for longevity in road concretes. Furthermore, the finding that the slump value measured in the study was close to zero indicates that the appropriate consistency for RCC has been achieved and that the compressibility of the concrete is at an optimum level. This outcome aligns with the recommended consistency values for RCC as outlined in the extant literature (Öztürk, 2018).

The present study investigates the effects of nanomaterials and basalt fibres on RCC road concretes. The findings of the study have led to the formulation of the following recommendations:

• Further Elaboration of Microstructural Analysis: The effects of nano-additives on hydration processes can be examined in more detail by using additional analysis methods such as XRD (X-ray Diffraction) and MIP (Mercury Porosimetry).

• Long-Term Performance Tests: To evaluate the effects of nanomaterial additives on performance over time, freeze-thaw, sulfate resistance and abrasion tests should be performed.

• Different Nanomaterial Combinations: The microstructure optimisations of diverse nanomaterials can be investigated by examining the combination of other nanomaterials, including nano SiO2, nano Al2O3 with Fe_2O_3 and TiO_2.

• Field Applications: To verify the laboratory-scale results, field tests should be carried out to evaluate performance under different traffic and climate conditions.

In conclusion, this study provides significant data on the microstructural enhancement of nano-additive RCC road concretes. The extant literature contains only a limited number of studies on the use of RCC using nano Fe_2O_3, nano TiO_2 and basalt fibre together, and these are supported by both SEM and BET analyses. Consequently, the findings of this study offer significant contributions to both the academic field and practical applications in road engineering.

AUTHOR CONTRIBUTIONS

Conceptualization, Ş.S. and A.T.; methodology, A.T.; fieldwork, Ş.S.; software, Ş.S.; title, A.T. and Ş.S.; validation, Ş.S.; laboratory work, Ş.S.; formal analysis, Ş.S.; research, A.T. and Ş.S.; sources, A.T. and Ş.S.; data curation, A.T. and Ş.S.; manuscript-original draft, Ş.S.; manuscript-review and editing, A.T.; visualization, Ş.S.; supervision, A.T.; project management, A.T.; funding, A.T. All authors have read and legally accepted the final version of the article published in the journal.

ACKNOWLEDGEMENT

This work is supported by Atatürk University BAP office with the research project numbers 11012.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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