

# Optimization of Polymer-Enhanced Sustainable Concrete: A Composite Approach with Bentonite and Crumb Rubber Aggregates

Yedlapalli Akhila<sup>1\*</sup>, M. Achyutha Kumar Reddy<sup>2</sup>, V. Sree Lakshmi<sup>3</sup>

## Abstract

*The disposal of rubber tyres has become challenging; on the other hand, the utilization of rubber tyres is also increasing daily in society. The successful use of crumb rubber as an alternative aggregate and bentonite as a partial cement replacement in concrete composites has been well established through prior research. These materials have individually demonstrated their potential to enhance sustainability, improve concrete properties, and reduce environmental impact, paving the way for innovative construction solutions. The present research evaluated the combined effect of concrete composites made from crumb rubber as fine and coarse aggregate, whereas cement was substituted with bentonite. The mix proportions were determined using the variables bentonite substitution (0% to 5%) and crumb rubber substitution in both fine (25%) and coarse aggregate (10%). The experimental investigations were carried out to determine compaction factor, fresh density, compressive strength, split tensile strength, resistance against magnesium sulphate (MgSO<sub>4</sub>), resistance against sodium sulphate (Na<sub>2</sub>SO<sub>4</sub>), and resistance against sodium chloride (NaCl). Samples were cured in water, then in MgSO<sub>4</sub>, Na<sub>2</sub>SO<sub>4</sub> and NaCl solutions. After cleaning and weighing, compressive tests were conducted. Furthermore, the interfacial transition zone (ITZ) was also evaluated for a set of specimens. The results show that decrement in the behaviour of concrete was observed upon the addition of CA-CR and FA-CR. The compressive strength ranges between 5.1MPa to 26MPa and tensile strength is also impacted by the increase of aggregate content. The addition of bentonite up to 5% enhances the performance of concrete. The possibility of concrete made out of bentonite and crumb rubber aggregate was confirmed through this investigation*

**Keywords:** ITZ, bentonite, crumb rubber, sustainable concrete, fresh properties, Magnesium sulphate (MgSO<sub>4</sub>)

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## INTRODUCTION

Society is struggling with rubber tyres; the amount of waste rubber tyres is significantly expanding. The rubber does not break down over time and is not biodegradable. They may take up valuable space in landfills. The underground dumps are causing issues for the environment and aesthetic appeal. Harmful gases can be released into the atmosphere when tyres are burned at significant temperatures; nitrogen oxide, sulfur dioxide and carbon dioxide are involved in these emissions. These contaminants significantly raise pollution in the atmosphere and harm human health. High temperatures are required for melting rubber tyres, which may produce dangerous liquid materials for soil and water [1]. By 2030, around five billion

tyres will need to be managed or disposed of as they reach the end of their life span. Disposing of used tyres harms the ecosystem because it causes environmental issues [2]. Rubber as a replacement material in concrete is limited to particular ratios for various applications. For structural use, the incorporation of rubber is 10%; for nonstructural use, the incorporation of rubber is 40%. Crumb rubber and water are the two main components influencing the compressive strength of concrete incorporating crumb rubber concrete [3], [4]. The paper states that the rubber particles' size influences the concrete's strength. The greater size of crumb rubber particles in concrete reduces its strength [5], [6]. Compared to acceptable aggregate, replacement strength is reduced when coarse aggregate is replaced with crumb rubber, but energy absorption capacity is increased [7], [8].

Compared to acceptable aggregate, replacement strength is reduced when coarse aggregate is replaced with crumb rubber, but energy absorption capacity is increased [7]. There are three categories of recycled rubber tyres: rubber granules, rubber powder, and rubber crumb. Rubber powder can act as a binding agent and replacement for cement in concrete [9]. Granulated rubber, or crumb rubber, is usually less than 6mm in size and replaces fine aggregate in concrete [10]. Rubber granules are utilized as a coarse aggregate [11]. The mechanical characteristics of crumb rubber concrete are degraded when the fine and coarse aggregate is replaced with 100% crumb rubber, reducing compressive strength by 87% [12]. Compared to conventional concrete, crumb rubber concrete exhibits reduced modulus of elasticity, tensile strength, and compressive strength [13] [14]. Crumb rubber concrete is more durable, impact-resistant, and capable of absorbing more energy than conventional concrete [15]. Adding a high quantity of crumb rubber increases water permeability and absorption capacity. Concrete incorporating crumb rubber is also more resistant to sulphate attack [16]. This shows that high-strength concrete with rubber, highly resistant to harsh situations, is beneficial in areas prone to acid attacks [17]. Using crumb rubber in concrete for traffic barriers could improve safety outcomes by reducing impact energy. Treated crumb rubber concrete with sodium hydroxide (NaOH) and potassium permanganate (KMnO<sub>4</sub>) absorbs less water compared to untreated crumb rubber concrete [18], [19]. Recent advances in concrete technology have raised concerns about CO<sub>2</sub> emissions from cement production, contributing to global warming and ozone layer depletion. To address these issues, researchers are exploring sustainable alternatives, including polymer-based composites, to reduce environmental impact. [20], [39]. These greenhouse gases, especially carbon dioxide, severely harm environmental and human health [21]. Using pozzolanic materials to minimize CO<sub>2</sub> emissions has become a pattern for forty years. Additionally, there are certain disadvantages to employing industrially produced pozzolanic materials, making it necessary to investigate natural pozzolanic materials within polymer composite formulations. [14], [38]. In 1898, Knight presented bentonite, a naturally occurring clay mineral derived from volcanic ash. The mineral montmorillonite, which forms a plate or leaflet, is the primary material of bentonite [22]. It shows a unique quality, especially the ability to swell [23][24]. Bentonite contains abundant calcium and sodium ions, exhibits high elasticity, and is effective as a binding agent. Typically, its particle diameters are less than 0.002mm [25].

Research on using bentonite as a pozzolanic in concrete was started by J Mirza in 2009, confirming that bentonite blending is possible [26]. Research has demonstrated that adding bentonite to cement typically increases the concrete setting time [27], [28]. By incorporating bentonite into the cement, the rheological qualities can be enhanced [29]. [30]. Adding bentonite to concrete can help prevent bleeding and segregation by absorbing excess water [31]. [32]. Additionally, it was discovered that using bentonite enhanced cement's strength characteristics [33]. Bentonite is a clay with exceptional swelling and sealing properties, making it highly valuable in environmental and geotechnical applications. Composed mainly of montmorillonite, bentonite can absorb significant amounts of water, causing it to expand and form a dense, gel-like layer. This swelling ability is crucial for creating low-permeability barriers, essential in applications like landfill liners, where preventing the leakage of contaminants is critical. When used in polymer composites for liners, bentonite's sealing properties ensure that harmful substances are contained, protecting soil and groundwater from pollution. Its effectiveness under varying environmental conditions makes it a reliable material for sustainable waste management solutions. [37]. It was also found that bentonite improved the cement's durability when added in small

amounts [31]. The utilisation of bentonite in the production of bricks shows behavioural improvement [34]. Adding up to 10% bentonite strengthened the concrete, but the strength started to decline after that point [35]. Additionally, after adding bentonite to the concrete at the appropriate dosage, there was a noticeable and significant improvement in its durability [36]. The behaviour was assessed on bentonite-made structural components, such as columns and beams, indicating its potential application [14].

This study aims to assess the interfacial transition zone (ITZ) in concrete, a critical area influencing durability and strength. In this paper, we replace traditional cement with bentonite and substitute fine and coarse aggregates with crumb rubber. This paper investigates how these substitutions affect concrete's ITZ. The main objective of this research is to assess how these material substitutions impact ITZ characteristics, such as bond strength and durability and interface interactions.

## **MATERIALS AND METHODS**

In this research, OPC 53-grade cement, meeting the IS: 12269-1987 specifications, was used alongside locally sourced aggregates, including fine aggregate (FA) passing through the sieve size of 4.75mm, coarse aggregate (CA) of two different sizes passing through the sieve sizes of 20mm, and 10mm were used. Bentonite clay is used as a partial replacement for cement. Crumb rubber was employed as acceptable (<4.75 mm) and coarse aggregate (<20 mm, <12.5mm), featuring specific gravities of 0.638 (FACR) and 1.09 (CACR), respectively. In comparison, water absorption rates ranged from 8.9% (FAN) to 0.79% (CACR). Fig.1 shows the bentonite used as a replacement for cement. Figure 1 and Figure 2 are the CACR and FACR used to replace aggregates. Fig 3 represents the bentonite.

### **Mix Proportioning**

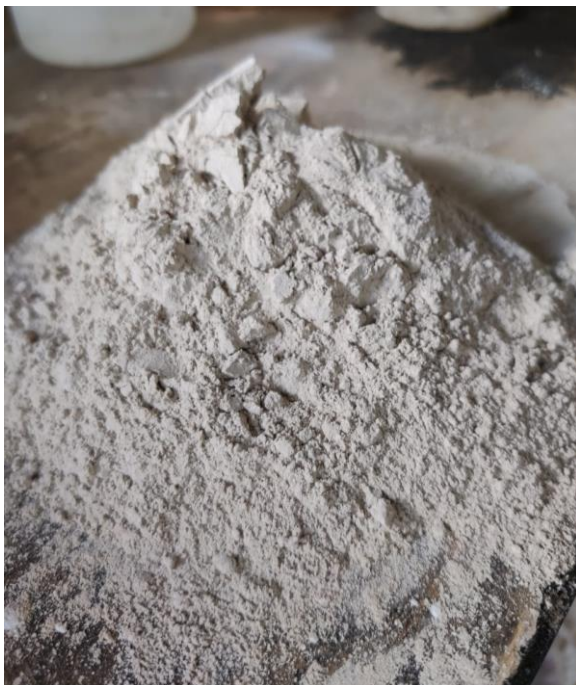
In this study, M30 grade concrete was developed following the guidelines of IS 10262:2009, with a water-cement ratio of 0.45. Fine aggregate and coarse aggregate were substituted with crumb rubber (FACR and CACR), and bentonite was also replaced in varying proportions. Numerous trials were conducted in the laboratory.



**Figure 1.** Crumb rubber as coarse aggregate.



**Figure 2.** Fine aggregate as crumb rubber.



**Figure 3.** Bentonite as a replacement for cement.

The combinations were made and examined for several qualities in the laboratory. Table 1 displays the many variable combinations found in these mixes, listed as MI-1, MI-2, MI-3 and MI-12. MI is the conventional concrete mix. Table 1 displays the proportions of the bentonite, CACR and FACR.

Table 2 presents the mix proportion information for cubic meters. In different proportions of 25%, 30%, 40%, 70%, 75% and 80% crumb rubber were used instead of fine aggregate. Different percentages of 10%, 15%, 35% and 40% crumb rubber were used in place of coarse aggregate.

Before pouring the concrete, a thin layer of grease was put on the inside of the moulds. The mould was demoulded a day after it was cast. After being cast, the specimens were removed from the moulds and allowed to cure in a water tank. After the process of curing, tests were conducted, including compaction factor, fresh density of concrete, compressive strength test, split tensile strength, resistance to sulphate and chloride attack, and water absorption were performed on the concrete specimens. Usually in the size of 150mm cubes and 300 mm height cylinders with a 150mm diameter.

**Table 1.** Mix matrix design.

S. N.	Bentonite (%)	CACR (%)	FACR (%)
1	5	15	25
2	15	35	75
3	5	15	30
4	15	35	70
5	5	15	40
6	15	35	80
7	5	10	25
8	15	40	75
9	5	10	30
10	15	40	70
11	5	10	40
12	15	40	80

**Table 2.** The mixed proportion data per cubic meter.

Run	Mix id	Cement(kg)	Bentonite(kg)	Natural coarse aggregate (kg)	CR Coarse aggregate (kg)	Natural fine aggregate (kg)	CR fine aggregate (kg)
1	MI-1	342	38	1050.70	71.67	525.10	42.85
2	MI-2	342	38	803.48	167.23	175.03	128.55
3	MI-3	380	0	1050.70	71.67	490.09	51.42
4	MI-4	380	0	803.48	167.23	210.04	119.98
5	MI-5	342	38	1050.70	71.67	420.08	68.56
6	MI-6	304	76	803.48	167.23	140.03	137.12
7	MI-7	380	0	1112.51	47.78	525.10	42.85
8	MI-8	304	76	741.67	191.12	175.03	128.55
9	MI-9	342	38	1112.51	47.78	490.09	51.42
10	MI-10	304	76	741.67	191.12	210.04	119.98
11	MI-11	380	0	1112.51	47.78	420.08	68.56
12	MI-12	342	38	741.67	191.12	140.03	137.12

## EXPERIMENTAL INVESTIGATION

### Compaction Factor Test

ASTM143 guidelines evaluated the compaction factor of samples. The readings of the compaction factor indicate how easily the concrete was compacted. The compaction factor test was performed on each combination in this experimental research. Pour concrete into the hopper to the proper level and fill it in. Allow the concrete to drop through the bottom hopper trapdoor by opening the top hopper. Using a rod, push the excess concrete and let the concrete fall into the cylinder by opening the trapdoor on the bottom of the hopper. Eliminate excess quantity—concrete with cylinder (w1). After the concrete has been fully compacted, level it and weigh it (w2). Weight an unfilled cylinder (w). Using the formula  $(w1-w) / (w2-w)$ , the fresh density of the compaction factor test was determined.

### Density of Fresh Concrete

Firstly, measure the cylindrical jar (w1). Fresh concrete is placed inside the cylinder. Until the jar is filled, compression is applied with the help of a tamping rod for at least 60 strokes for each 50mm layer. After the concrete's compression, the top surface should be level, and the fresh concrete should be weighed with the cylinder (w2). The formula used to get the fresh concrete density was  $(w2-w1) /$  volume of the cylindrical jar.

### Compressive Strength

After 28 days of curing, a 2000Kn universal machine (UTM) was used to assess the compressive strength. Three specimens were tested for every mix, and the average of those results was taken.

### Split Tensile Strength

The split tensile strength test for three cylinders was conducted by IS 5816 guidelines, allowing for a 28-day curing period. A split tensile strength test was conducted using a 2000kN UTM after 28 days of curing. Three different samples were tested for every mix, and the average of those results was taken.

### Sulphate Attack

Samples cured in water for 28 days were then cured for 56 days in solutions containing 2% magnesium sulphate (MgSO<sub>4</sub>) and 5% sodium sulphate (Na<sub>2</sub>SO<sub>4</sub>). Samples are tested for a period of 90 days. Samples are weighted after being cured in MgSO<sub>4</sub> and Na<sub>2</sub>SO<sub>4</sub> solutions. Before conducting the compressive test, the samples are cleaned with tap water after curing and weighed. Three samples are tested for every mix, and the results are averaged.

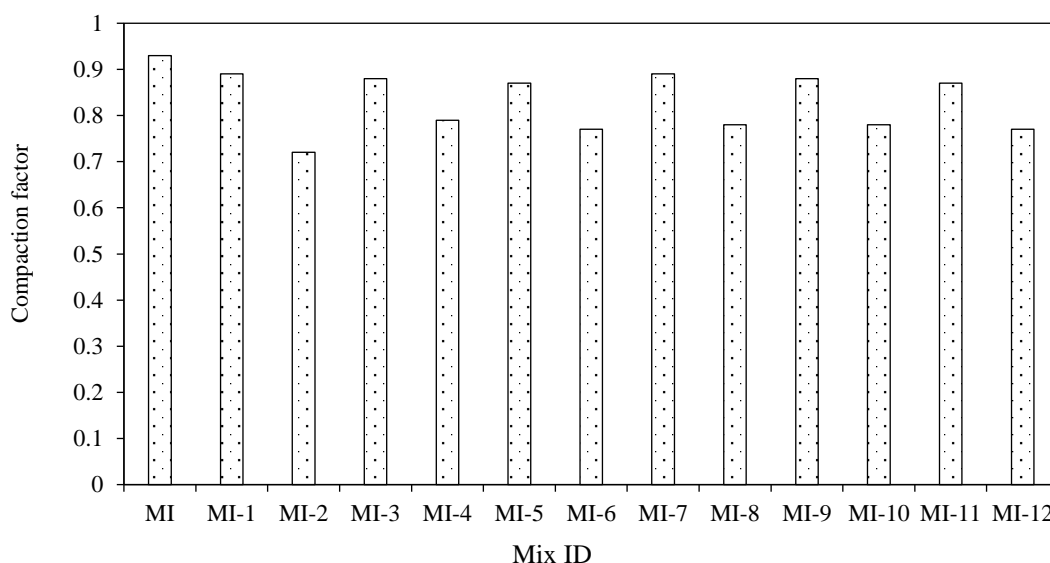
### Chloride Attack

Chloride concentration in the sea typically varies from 4% to 6%. A 3.5% sodium chloride (NaCl) solution is added to the water after the mixture has cured for 28 days. Samples are tested for 90 days. Before conducting the compressive test, the samples are cleaned with tap water after curing and weighed. Three samples are tested for every mix, and the results are averaged.

## RESULTS AND DISCUSSION

### Compaction Factor

Figure 4 shows the compaction factor of concrete for all mixes. Compaction factor values range from 0.72 to 0.93. The workability of the various mixes containing bentonite and crumb rubber substitutes varies, as seen by this range. MI-1, MI-3, MI-5, MI-7, MI-9, MI-11 mixes are highly workable because their flow table values are either at or above 0.87. These mixes will be similar in arrangement and compactness. The flow table value of the MI-2 mix is 0.72, which indicates poor workability. As a result, the mixture may become challenging to handle and prone to void or segregation. MI-4, MI-6, MI-8, MI-10, MI-12 mixes have values between 0.77 and 0.79, indicating moderate workability. Mix MI-2 has a higher content of bentonite (15%), FACR (75%), and CACR (35%), and it led to a decrease in workability. Lower bentonite content (5%) maintains higher workability. Higher substitution levels of crumb rubber reduce workability, making it an excellent aggregate crumb rubber. Mixes with a lower percentage of crumb rubber (fine and coarse aggregate crumb rubber) tend to maintain higher workability.



**Figure 4.** Compaction factor of concrete for all mixes.

### Fresh Density of Concrete

Fresh density indicates the concrete mix's overall mass and can influence the mix's workability, strength, and durability. Figure 5 shows the fresh density of concrete for each calculated combination. The lowest density value was found when 15% bentonite and 40% and 75% fine and coarse aggregate were replaced with crumb rubber. The maximum density was observed at the mix MI-7 when the lowest percentages were replaced. The lower specific gravity of crumb rubber compared to natural aggregate was the primary cause of the decrease. The fresh density of concrete is directly impacted by the percentage of crumb rubber in the concrete. Concrete with a more significant rubber percentage typically has a lower fresh density because the crumb rubber particles are lighter than natural aggregates.

### Compressive Strength

The results of the tested samples are shown in Fig. 6, and the compressive strength values after 28 days ranged from 5.1 to 26 MPa. The graph illustrates the different concrete mixes on the X-axis, while the Y-axis represents the compressive strength of these mixes tested at 28 days. Particular changes were observed based on the combinations of FACR and CACR. The control mix, which doesn't include substitutions of cement with bentonite or aggregates with crumb rubber, performed better in compressive strength than the other substituted mixes. Mix MI-12, replacing 40% OK and 80% coarse aggregate with 15% bentonite. It has led to a significant reduction in strength. The properties of the rubber used as a replacement, the interaction between the crumb rubber and cement mortar, and any changes in the microstructure or interfacial transition zone (ITZ) that contribute to the effect. These results show that increasing the amount of crumb rubber in the concrete mix significantly reduced its compressive strength. Higher crumb rubber content results in lower compressive strength due to crumb rubber's lightweight and deformability compared to regular aggregates. This behaviour also leads to overall density and compressive strength.

### Split Tensile Strength Test

Tension or splitting forces are determined by split tensile strength, indicating concrete resistance. Generally, concrete shows high compressive strength, but its ability to withstand tension is generally lower. At the control mix MI, the highest split tensile strength was observed. Concrete's optimal split tensile strength is achieved by incorporating 5% bentonite, 25% FACR, and 10% CACR as a substitution. The lowest results were obtained when combining 15% bentonite, 40% CACR, and 80% FACR. When bentonite and crumb rubber were partially substituted for cement and fine aggregate in concrete, split tensile strength increased. Fine aggregate crumb rubber can fill in the excess pores in the samples because of its small size and pore-filling abilities. Low strength in rubberized concrete may result from a weak ITZ zone between CACR particles and cement mortar. Split tensile strength decreased when a higher amount of CACR was substituted. It was also observed that adding bentonite clay improved the split tensile strength. Figure 7 shows the split tensile strength of samples in the MgSO<sub>4</sub> solution after curing each mix.

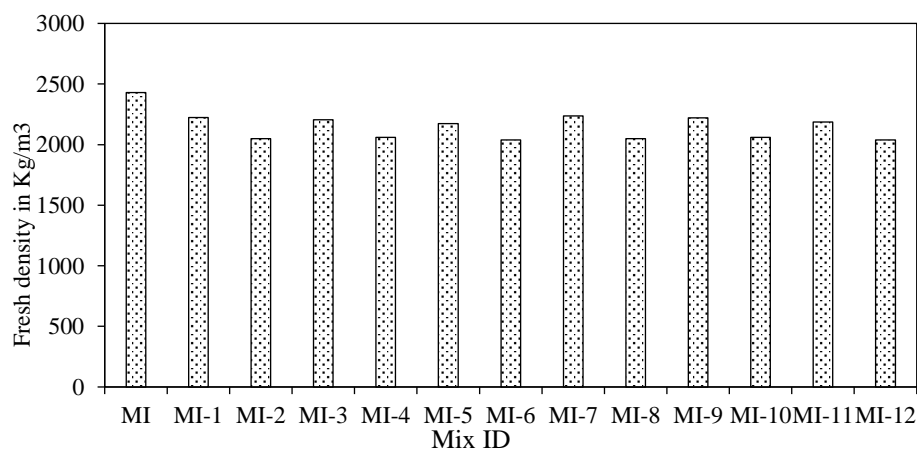
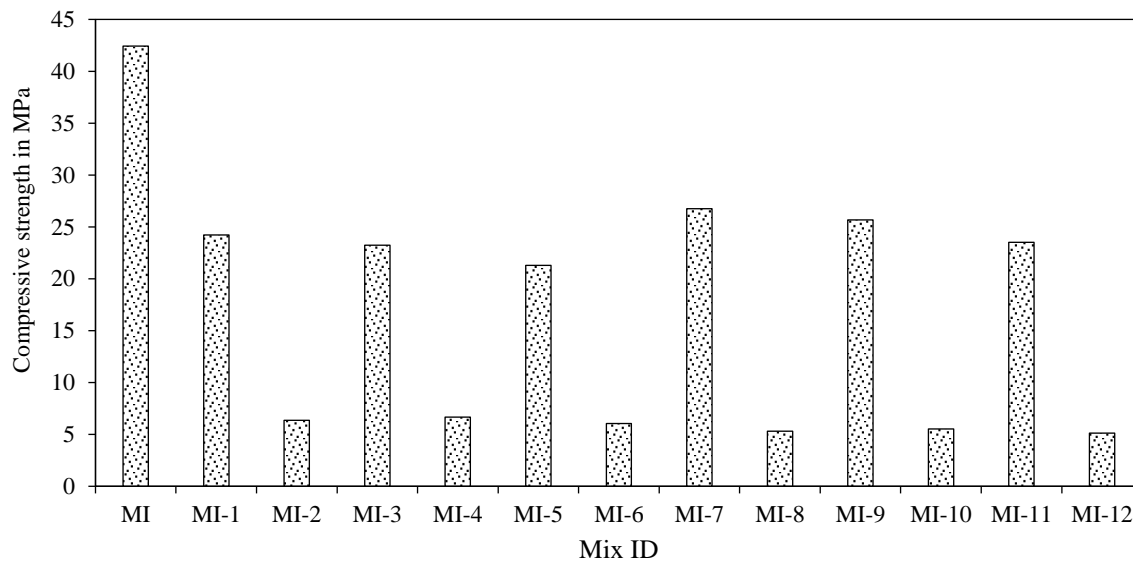
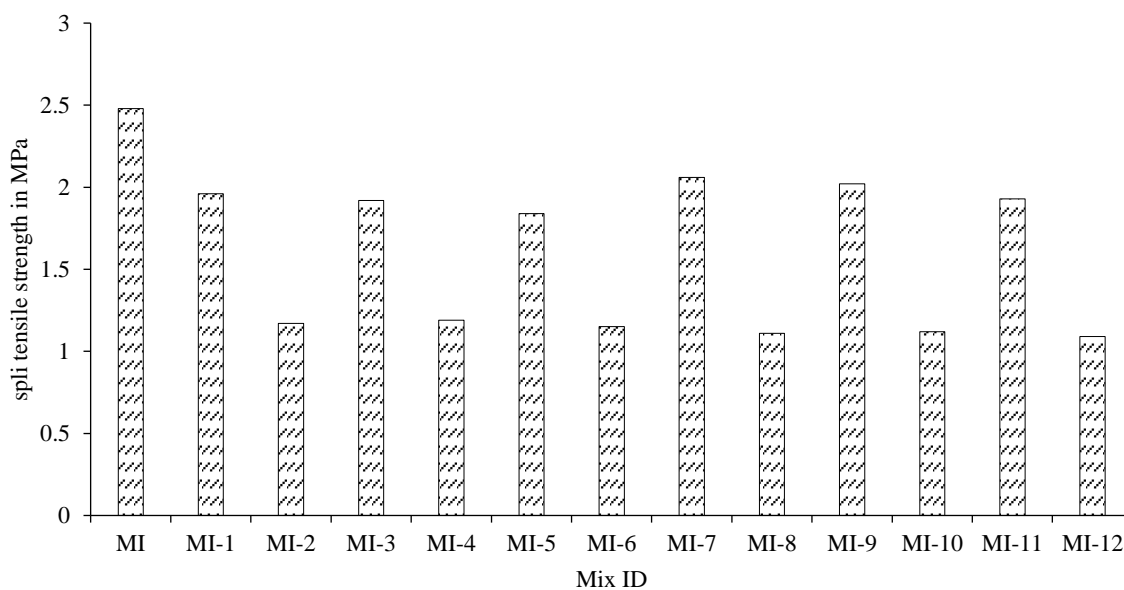


Figure 5. Fresh density of concrete for all mixes.



**Figure 6.** Compressive strength of samples in the MgSO4 solutions after curing each mix.



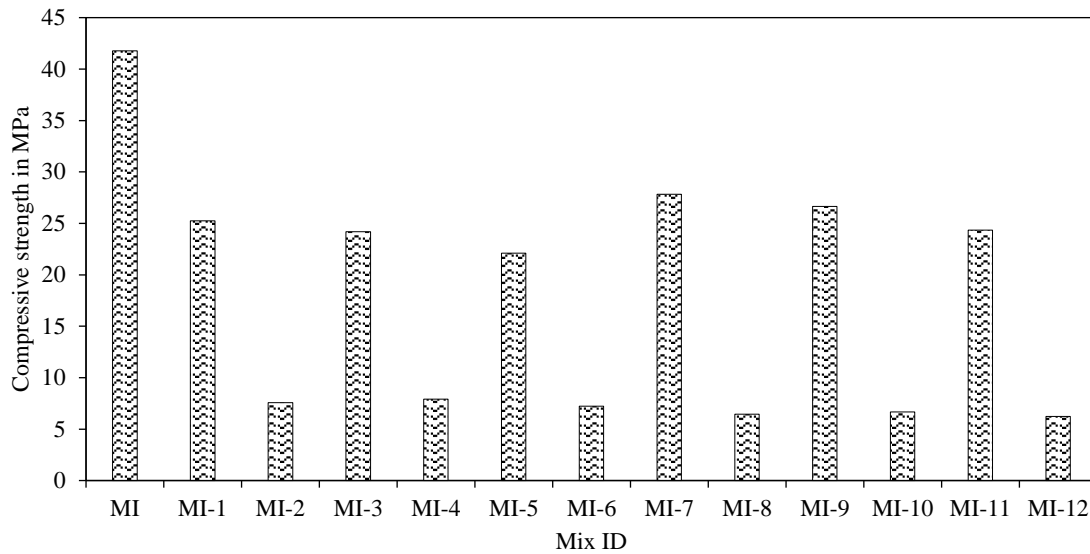
**Figure 7.** Split tensile strength of samples in the MgSO4 solution after curing of each mix.

**Resistance To Sulphate Attack**

A chemical process known as a sulphate attack occurs when concrete is exposed to sulphates in the soil and underground water. The concrete may deteriorate due to this reaction, compromising its stability and reducing its lifespan and durability.

**Magnesium Sulphate (Mgso4)**

The compressive strength of the cube after 56 days of curing in MgSO4 solution is displayed in Figure 8. The graph’s X-axis displays mix id, while the Y-axis displays the specimen’s compressive strength. Among all the mixes, regular concrete achieved the highest compressive strength after 90 days at 41.6M. For mix MI-2, the highest compressive strength observed in the replacement concrete was 27MPa. When the percentage of CACR and FACR increased, the compressive strength of the mixes MI-8 and MI-12 decreased significantly. Figure 7 illustrates the water absorption of concrete specimens exposed to a MgSO4 solution after 90 days.



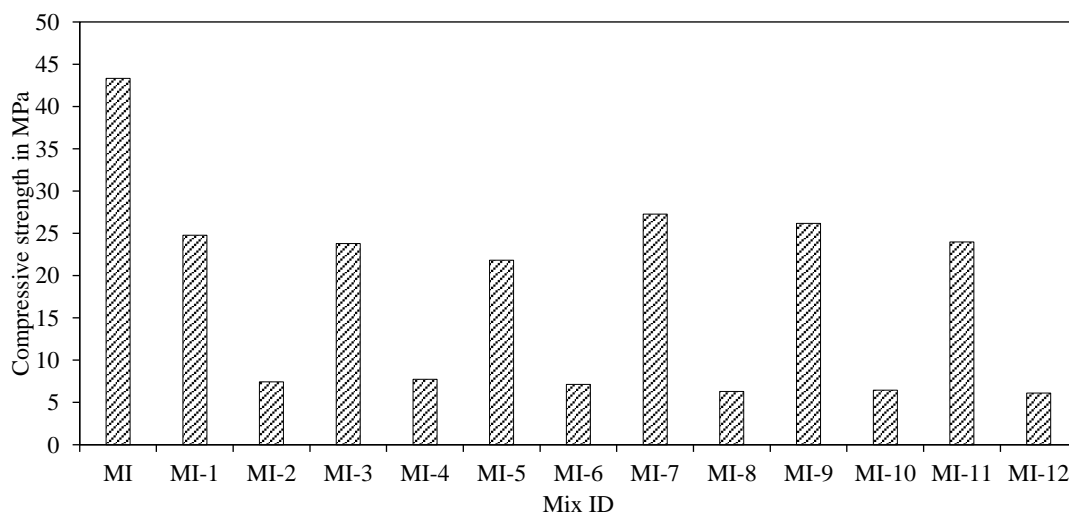
**Figure 8.** Compressive strength of samples in the MgSO<sub>4</sub> solution after curing each mix.

### Sodium Sulphate (Na<sub>2</sub>SO<sub>4</sub>)

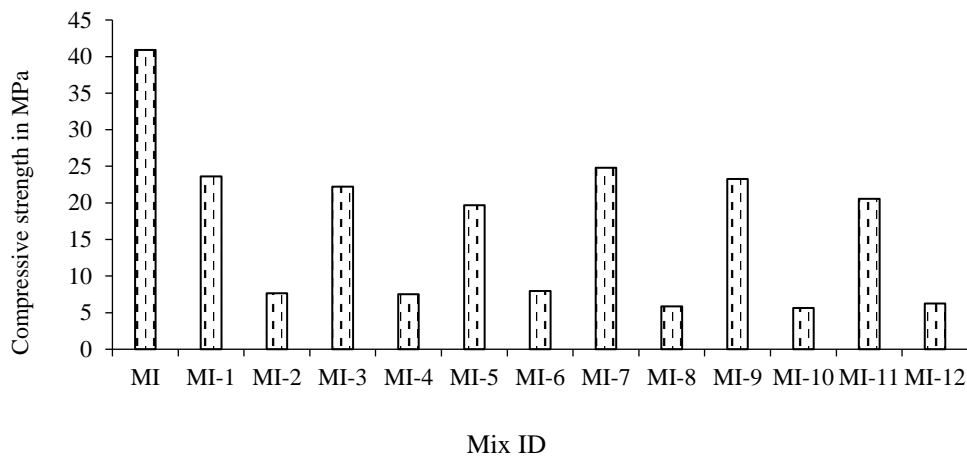
The compressive strength of the cubes exposed to Na<sub>2</sub>SO<sub>4</sub> solution after 90 days is displayed in Figure 9. The graph represents the Y-axis compressive strength and the X-axis mix ID. After 90 days of exposure to this solution, the compressive strength of regular concrete is highest (43.3MPa). The second height's compressive strength was achieved by mix MI-7, which measured 27MPa. The compressive strength decreases with the highest rubber replacement, as shown in Figure 9.

### Sodium Chloride (NaCl)

Figure 10 shows the performance of different concrete mixes under salt exposure, providing insights into their durability in a corrosive environment. After 90 days of exposure to NaCl solution, Figure 9 presents the compressive strength of cube specimens. Mix id is plotted along the X-axis, while the Y-axis depicts the corresponding compressive strength values. Regular concrete exhibited a high compressive strength of 40MPa after 90 days of exposure to this solution. Concrete replaced with 5% bentonite, 10% CACR, and 25% FACR demonstrated a high compressive strength at 24MPa under similar conditions. The figure shows a decrease in compressive strength with the highest replacement of crumb rubber.



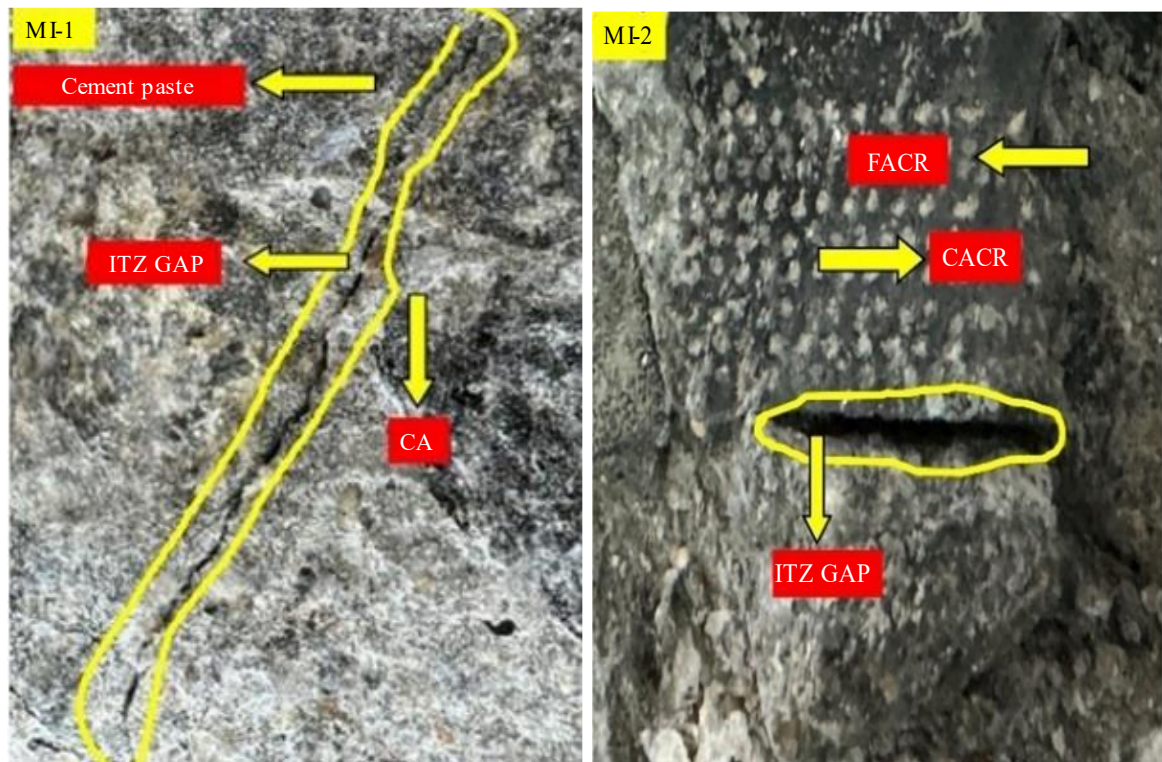
**Figure 9.** Compressive strength of samples in the Na<sub>2</sub>SO<sub>4</sub> solution after curing each mix.

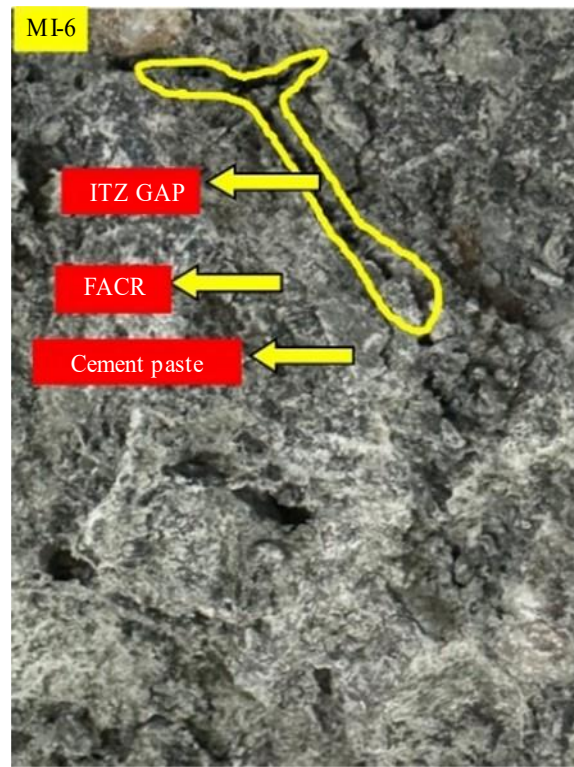
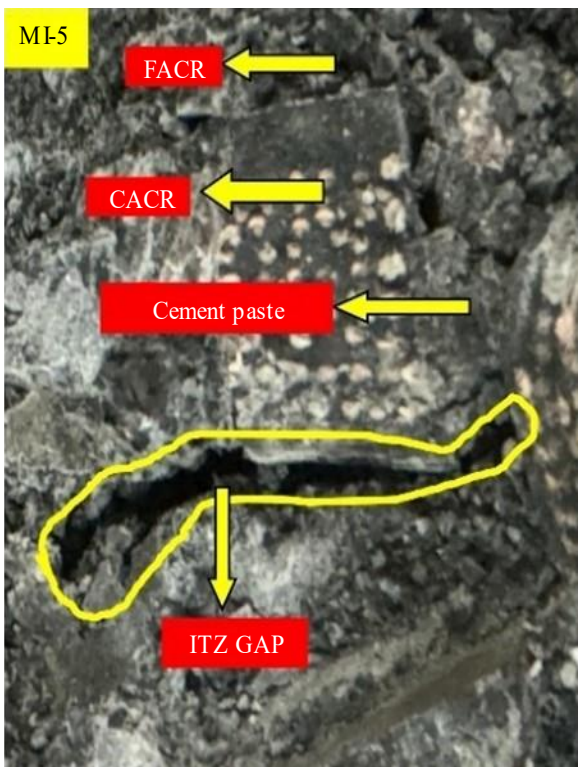
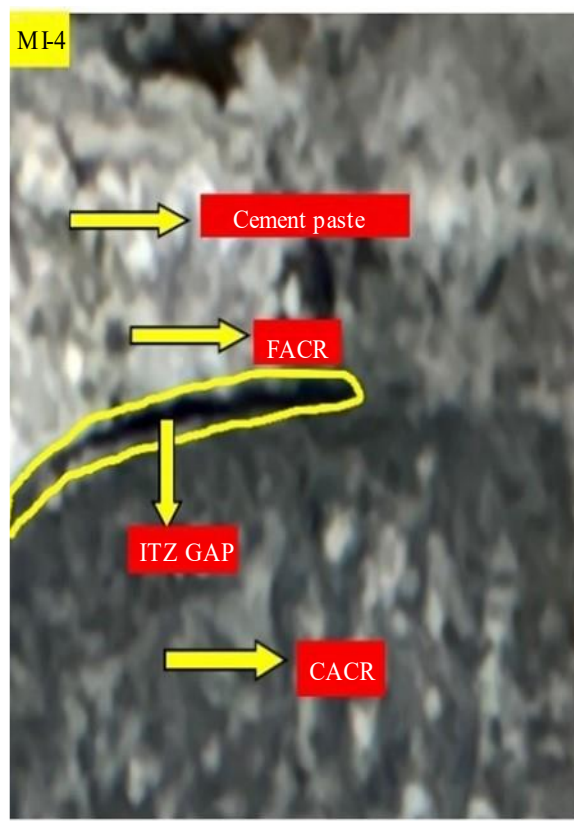
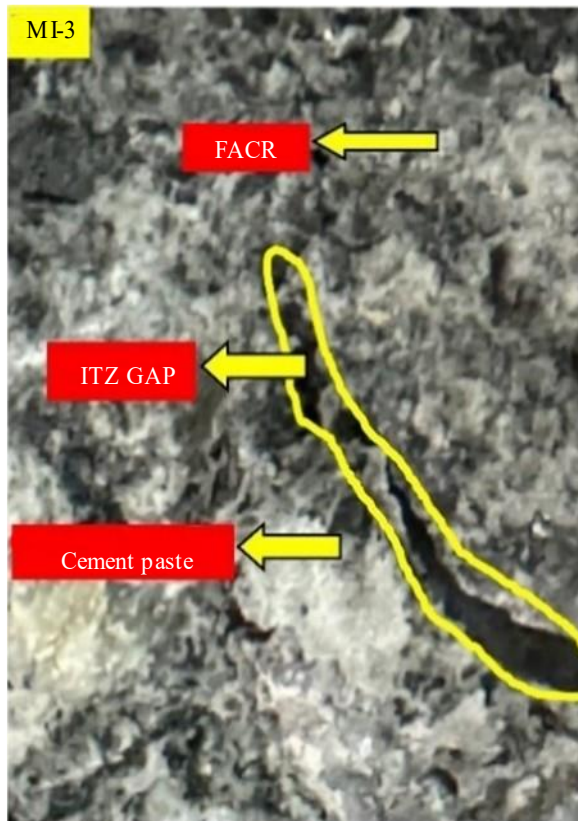


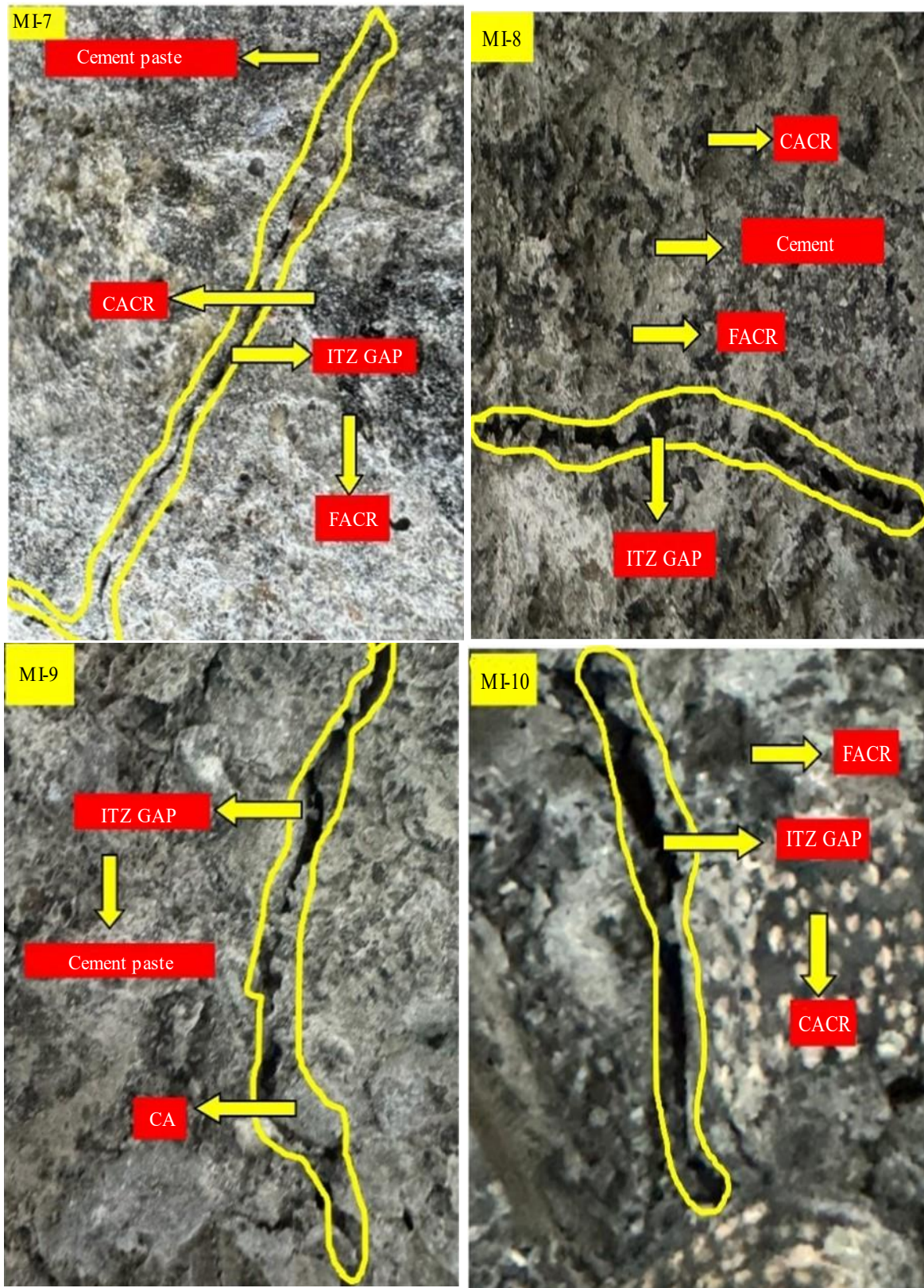
**Figure 10.** Compressive strength of samples in the Na<sub>2</sub>SO<sub>4</sub> solution after curing each mix.

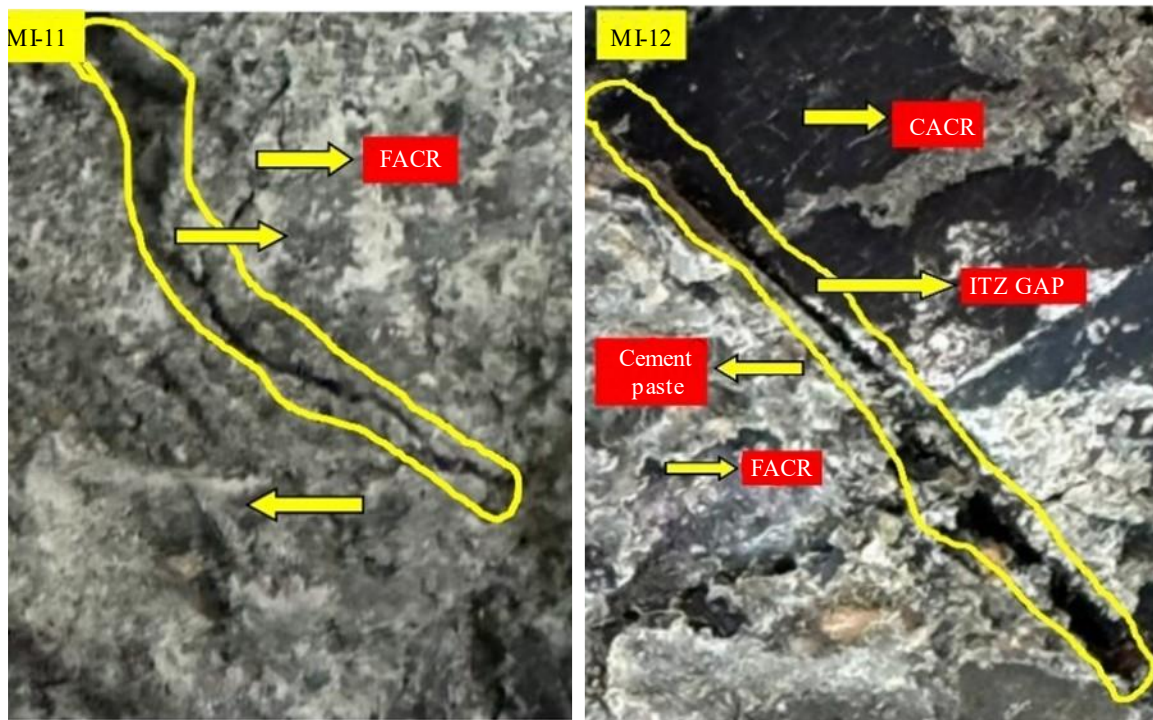
**Interfacial Transition Zone (ITZ)**

The mechanical properties and durability of concrete are significantly influenced by the interfacial transition zone (ITZ). The ITZ surrounds aggregate particles, typically exhibiting higher porosity and a weak structure than the surrounding cement paste. In traditional concrete, addressing the weakness of the interfacial transition zone (ITZ) is critical as it can significantly affect the concrete’s overall performance and durability. Substituting cement with bentonite in concrete improvement led to a less dense and less porous microstructure within the ITZ. If the bentonite proportion increases, it increases shrinkage and micro-cracking in the concrete. Rubber is hydrophobic, which means it doesn’t mix well with water. This causes a problem at the ITZ in concrete, where the rubber particles don’t bond effectively with the surrounding cement paste. This weak bond creates space and weak spots in the concrete. The size and quantity of crumb rubber affect the strength of the concrete. Figure 10 shows that using a high amount of crumb rubber caused cracks in the concrete. CACR exhibits strong resistance to water. In crumb rubber concrete, the mechanical performance heavily depends on the ITZ. Figure 11 shows the interfacial transition zone for all the mixes.









**Figure 11.** Interfacial transition zone for all mixes.

## CONCLUSIONS

The following conclusions were drawn upon analysis of the results.

- Incorporating bentonite and crumb rubber into concrete led to a lower compaction factor than standard concrete.
- This is mainly due to the higher crumb rubber content, creating a denser mixture. However, the bond between cement and rubber is weakened, which negatively impacts workability and may also reduce compressive strength.
- Concrete that uses crumb rubber and bentonite as material substitutions shows higher water absorption, a lower compaction factor and fresh density than conventional concrete.
- Split tensile strength decreases when a higher proportion of the CACR and FACR is utilized.
- < UNK > Using bentonite and crumb rubber in concrete development was initially verified.

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