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Research Article

Experimental study on the utilization of construction and demolition waste of recycled aggregate with GGBS and I-Crete in pavement quality concrete

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Abstract

This study investigates the mechanical properties of M40 concrete in Pavement Quality Concrete (PQC) by incorporating Recycled Aggregates (RA) from construction, demolition waste and industrial wastes, such as GGBS and I-Crete, for sustainable pavement construction. The research explores varying proportions of RA (25% to 100% by weight in 25% intervals). Results show concrete mechanical strength decreases with higher RA proportions but all mixes still meet target strength criteria (compressive, flexural, split tensile) at 7, 28, and 90 days of curing. Further testing on 100% RA (MRCA-100) with GGBS admixture from 5% to 35% in 5% increments found strength improves significantly up to 10% GGBS replacement by cement weight, with subsequent decreases at higher percentages Initially. Then introducing the mineral additive, I-Crete at 2% by weight of cement in 15% to 35% GGBS range results in notable strength enhancement, peaking at 25% GGBS replacement. Ultrasonic pulse velocity (UPV) and water absorption tests showed similar trends in 28-day strength across all mixes. Increased strength from better bonding was observed, with Scanning Electron Microscopy (SEM) showing enhanced hydration and bonding due to mineral admixture and additive. These findings underscore the efficacy of such additives in enhancing the mechanical strength of sustainable PQC.

1. Introduction

In recent years, the construction industry has expanded significantly, focusing increasingly on sustainability and environmental accountability. This change has especially improved the attractiveness of using recycled materials in construction projects. Among these materials, Recycled aggregates (RA) have emerged as a viable and promising solution for promoting sustainable construction practices. RA encompasses crushed concrete, brick and other construction debris that have undergone a process of careful processing and preparation for reuse as a sustainable alternative. By repurposing these materials, the construction industry can substantially diminish the demand for virgin resources, mitigate waste generation, and lessen the environmental impact of construction activities.

The encapsulated mortar around the RAC (Recycled aggregate concrete) possesses a lower density than the virgin aggregate [1]. The specific gravity of the RAC was reported to be between 2.35 to 2.58, sometimes nearly equivalent to conventional aggregate [2,3]. The specific gravity of the collection material is 2.60, which is less than that of the virgin

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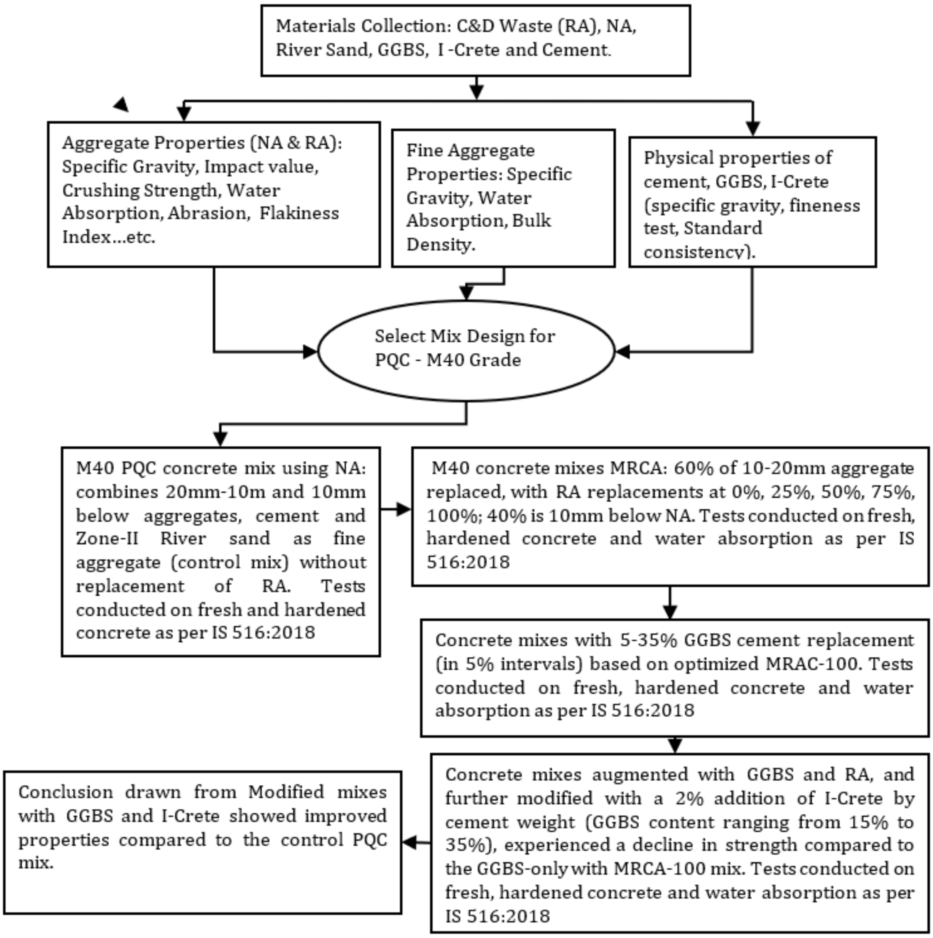
aggregate as shown in Table 1. The RAC has water absorption of1.80%, which is much higher than that of the virgin aggregate. The presence of adhered mortar in Recycled Aggregate Concrete (RAC) is primarily responsible for its porous nature, which results in higher levels of water absorption [3, 31]. Furthermore, another study [4] has reported even greater water absorption rates in RAC. The physical and mechanical properties of the RAC were judged to be less satisfactory than those of conventional aggregate due to the presence of residual mortar around the aggregate. This residual mortar is responsible for the weak structure observed in the RAC [5,6].

Due to the poor mechanical properties of the RAC, the compressive strength has been reduced by 15 to 20% compared to conventional concrete when using 100% replacements[6].The physical and mechanical properties of RA with different percentages of replacement RA as shown in Table 1 and its combined gradation with Natural aggregate (NA) of aggregate as shown in Table 3.It follows all permissible limits according to relevant codes and MORTH (Ministry of Road and Transportation Highways) specifications. Additionally, about a 20% to 25% reduction in strength was reported for replacements of 25%, 50%, 75%, and 100%.However, it has been suggested that recycled aggregate can be used in medium-strength concrete by incorporating 25% RAC with a uniform water-cement ratio [2]. The aggregate impact values increase as the replacement of RA increases [2, 7]. All the impact values are within the permissible limits asper code specifications IS:383-2016 [8, 9]and MORTH [10]. The compressive strength and flexural strength of the concrete with 25% replacement of RAC as coarse aggregate and 50% replacement as fine aggregate were observed to be in the range of 30% to 40% and 15% to 40%, respectively [11]. Replacing the virgin aggregate with RA leads to a decline in strength, despite achieving the target strength with its semi-porous structure. The increase in strength can be achieved through the incorporation of other supplementary materials such as Ground Granulated Blast Furnace Slag (GGBS).

GGBS is a widely used stabilized cementitious substitute material in the construction industry. It is obtained as a by-product of the iron and steel industry through the granulation of molten blast furnace slag. To enhance durability, a two-stage mixing process was employed, replacing 30% of the cement with GGBS and 50% with coal fly ash [12]. The strength can also be obtained with cement replacement made with 10% metakaolin and 15% GGBS. Alternatively, the desired strength can also be attained by replacing cement with 10% metakaolin and 15% GGBS [13]. The inclusion of GGBS could potentially lead to an increase in strength, but it may not match the strength of conventional materials. Therefore, ongoing studies are being conducted to enhance the strength by combining RAC and GGBS [14]. A decrease in the 28-day compressive strength of RA concrete mixtures containing only GGBS was observed initially, but these mixtures gained strength at a later stage [15]. The present study aims to improve the strength of RAC by using cement mineral admixture and mineral additive such as GGBS and I-Crete to make eco-friendly concrete that reduces the carbon footprint in PQC.

I-Crete complies with ASTM C1797 [16]: IS2645[17] and itis a mixture of additional cementitious ingredients and naturally existing minerals. It is a very reactive, high-quality addition for concrete applications because of its chemical makeup and well-regulated particle size retention on a 45-micronsieve of less than 10% [17, 18]. The physical properties for GGBS, Cement and I-Crete as shown in Table 2. The following flow chart depicts in detail the procedure to implement the methodology in Fig. 1.



1.1 Research Significance

Several studies have been conducted on the utility of recycled aggregate in concrete application, but limited research has been carried out on pavement application. Hence in this study, an attempt was made to use recycled aggregate as partial replacement of natural aggregate in PQC. In addition to replacing coarse aggregate, cement was replaced with GGBS and I-Crete to reduce carbon imprint in PQC. The optimal design mix is arrived at through laboratory investigations such as mechanical, water absorption and microscopic studies.

2. Experimental Program

This paper presents an experimental initiative conducted to investigate the performance of Pavement Quality Concrete (PQC) incorporating recycled aggregate and GGBS mineral admixture and I-Crete mineral additive. The study aims to assess the effects of these materials as partial replacements for cement in M40 grade PQC.

2.1. Material Used in The Study

RA was collected from the construction and demolition waste processing plant in Hyderabad, Telangana. It has a nominal size of 20-10 mm and exhibits high water absorption of 1.8% along with lower physical and mechanical properties and density compared to conventional aggregates. But they fall within the acceptable limits stated by IS 383-2016 [8] and the Ministry of Road and Transportation Highways (MORTH) [10]. In the present study, RA is used in the mix under Saturated Surface Dry (SSD) conditions. The properties of RA and conventional aggregates are presented in Table1. River sand confirming to Zone-II [8] is used as fine aggregate Table 4 and its properties such as specific gravity, water absorption and bulk density are presented in Table5.OPC 53 grade is used as the bonding material, which is collected from the local vendor in Visakhapatnam. The physical and mechanical properties of the cement are carried out in according to the IS 12269: 2013 [19]. The cement supplementary materials, such as GGBS and I-Crete used in this study, were acquired from Sri Vishnu Sai Saravana Enterprises in Visakhapatnam and Navodaya Sciences Pvt Ltd in Chennai, respectively. The properties of Cement, GGBS, and I-Crete are depicted in Table2. The chemical composition of GGBS, Cement, and I-Crete is shown in Table 6. The potable water was used following IS 456-2000 [20] for the design mix and curing. CONPLAST SP 430 was used as a chemical admixture with a specific gravity of 1.20 with no chloride content and less than 1.5% air. The materials selected for the study, as shown in the Fig. 2.

Table 1. Physical and mechanical properties of coarse aggregate

Properties	100% NA	50% NA + 50% RA	100% RA	Permissible limits as per standard specifications of MORTH and IS:383-2016
Bulk density (kg/m^3)	1800	1750	1600	1200-1800
Specific gravity	2.84	2.75	2.60	2.5 to 3
Fineness modulus	7.06	7.135	7.15	6-7.5
Water absorption (%)	0.30	0.90	1.80	2
Flakiness Index (%)	13	12	11	25
Elongation Index (%)	11	13	14	25
Aggregate impact value (%)	18.96	22.72	23.40	30
Aggregate crushing value (%)	18.01	22.41	25.47	30
Angularity number	2	2.7	3	10
Abrasion resistance (%)	20	24.4	25.26	30
Soundness test (mm)	0.5	0.9	1.2	10mm

Table 2. Description of physical properties of cement, GGBS, and I-Crete

Test/ Material	Specific gravity	Fineness (m^2/kg)	Initial setting time (min)	Final setting time (min)	Consistency
Cement	3.15	260	165	230	30
GGBS	2.90	340	190	322	32
I-Crete	2.43	-	125	205	22

Table 3. Combined aggregate gradation for pavement quality concrete: as per IRC-44-2017

Sieve size (mm)	A combined Natural aggregate of 20mm nominal size (% ge of finer)	Combined Recycled aggregate 20mm nominal size (% ge of finer)	IRC44-2017 (19mm nominal size) (% ge of finer)
37.5	100	100	100
31.50	100	100	100
26.50	100	100	100
19	97.84	100	90-100
9.50	56.14	61.64	48-78
4.75	32.47	35.5	30-58
0.6	19.24	21.34	8-35
0.15	2.57	1.34	0-12
0.075 (wet sieving)	0	0	0-5 0-2

Table 4. Fine aggregate gradation for pavement quality concrete

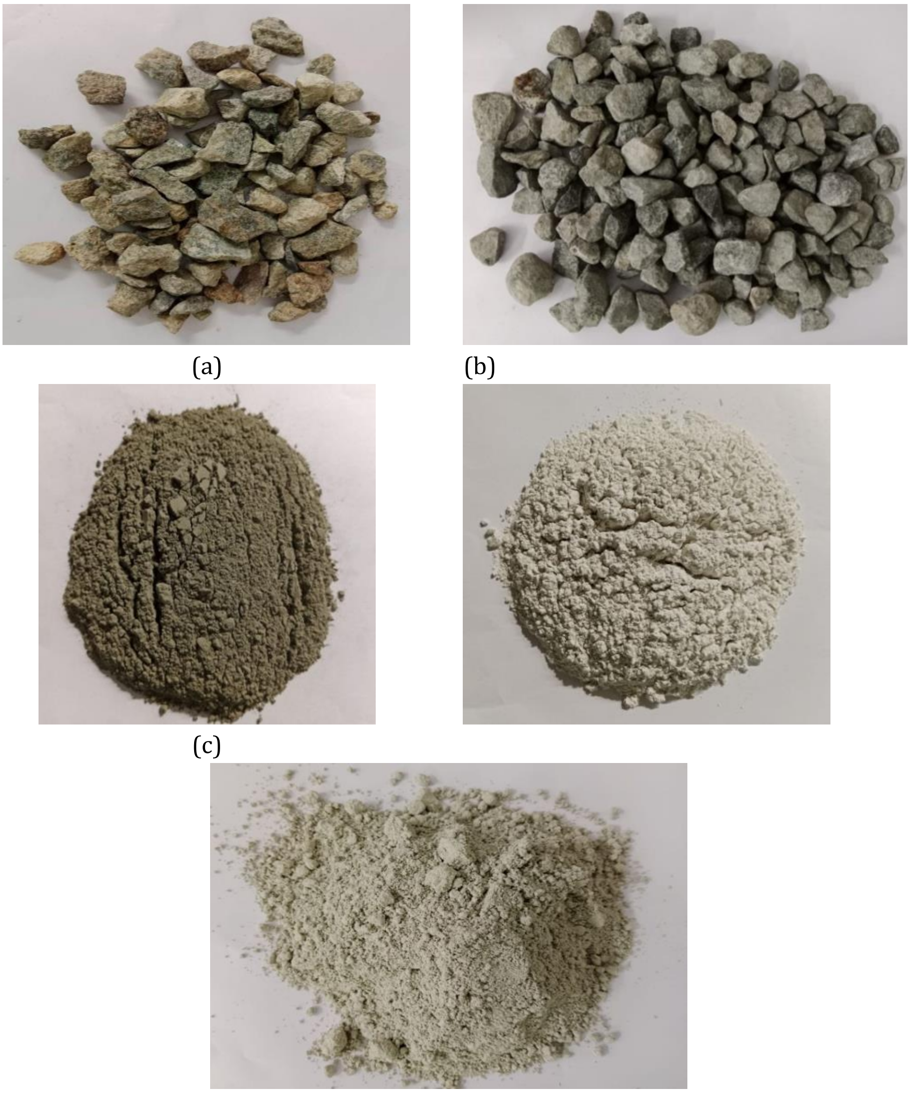
Sieve size (mm)	% Of finer	Zone-IIas per IRC -44-2017
10	100	100
4.75	98	90-100
2.36	85	75-100
1.18	65	55-90
0.600	60	35-59
0.300	25	8-30
0.150	2	0-10

Table 5. Physical and mechanical properties of fine aggregate (River Sand)

Properties	Test value	As per IS 383-2016
Specific gravity	**2.61**	**2.5 to 3.0**
Bulk density- compacted	1780	1680 to 1920 kg/m^3
Bulk density –Loose	1580	1440 to 1680 kg/m^3
Water absorption	1.06	1-2%

Table 6. Chemical composition of cement, GGBS, I-Crete

Material	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	Cao (%)	MgO (%)	Other (%)
Cement	22.5	0.3	6.5	62.5	3.2	5
GGBS	47.65	0.0	7.50	24.11	4.81	15.93
I-Crete	47.56	0.57	6.04	15.59	2.46	27.78



(a) (b)

(c)

(e)

Fig. 2. Images of the materials used in the current study (a) recycledaggregate, (b) natural aggregate, (c) cement, (d) ggbs and (e)I – crete

2.2 Mix Design

The complete mix design for M40 grade was carried out as per the specification provided inIRC-44-2017 [21] and IRC 15-2017 [22], incorporating the provisions of IS 10262-2019[23] for pavement quality concrete. The quantification for each design mix as shown in Table 7. The experimental procedure was performed in four stages, as follows:

- Stage 1: The PQC M-40 grade concrete mix uses natural aggregates, with no recycled aggregates or cementitious materials, serving as the control mix.

- Stage 2: The concrete mixture consisted of a 60% replacement of 10-20mm size aggregate in proportions of 0%, 25%, 50%, 75%, and 100% with RAC, while the remaining 40% was filled with a conventional aggregate size of 10mm.

- Stage 3: Concrete mixtures were prepared with GGBS as a cement replacement ranging from 5% to 35 % at 5% intervals, with 100% recycled aggregate.

- Stage 4: Concrete mixtures were prepared using GGBS 15%-35% at 5% intervals and with 100% RA, and with the addition of I-Crete at a 2% dosage by weight of cement.

2.3 Studies on Fresh Concrete

The workability of the freshly prepared concrete mixtures, composed of different proportions of Natural Aggregates (NA), Recycled Aggregate concrete (RAC), GGBS and I-Crete, was determined by using slump cone and compaction factor apparatus as per IS 1199(part-I):2018[24] and the experimental results are presented in Fig.3 and Fig.4 respectively.

2.4 Studies on Hardened Concrete

Destructive and Non-Destructive tests were performed on the hardened concrete to evaluate the quality and strength of the different concrete mixtures. The Non-Destructive tests (NDT), such as the UPV (Ultrasonic Pulse Velocity) test were performed after 28 days of curing as per IS 516 Part 5: Sec 1: 2018 [25]. Water absorption was determined after28 days of curing as per IS 516:Part 1:2018[25]. The compressive strength test was carried out following the standard procedure IS516:Part 1:2018[25]. Cube moulds of standard size of 150mm x 150mm x 150mm were cast to perform the compressive strength test. The maximum load corresponding to the failure of the specimen divided by the cross-sectional area of the specimen is recorded as the Compressive strength. Split tensile strength was carried out in compliance with IS 516 Part 1:2018[25]. Standard cylindrical specimens with a size of 150mm diameter x 300mm height were cast for each concrete mix. Prisms of the standard size 100mm x100mmx500mm were cast according to IS 516 Part 1:2018[25]. For each mix proportion, three replicates were cast, and the specimens were cured for 7, 28, and 90 days respectively.

Table 7. The quantification for each design mix

Notati-on	Mineral admixture and mineral additive (kg/m^3)				Recycled agg. (10mm-20mm) (60% of recycled agg.) replacement(kg/m^3)		40%0f 10mm size agg. (kg/m^3)	Total Coarse agg. (kg/m^3)	Cement (kg/m^3)	Water ltr/m^3	Fine agg. (River sand) (kg/m^3)
Type of Mix ID	GGBS		I-Crete								
	%	kg	%	kg	%	kg	Kg	kg	kg	ltr/m^3	kg/m^3
MNAC	0	0	0	0	0	0	509.20	1273	411	156	651
MRAC 25	0	0	0	0	25	176	504.80	1262	411	156	651
MRAC 50	0	0	0	0	50	352	498.40	1246	411	156	651
MRAC 75	0	0	0	0	75	528	492	1230	411	156	651

MRAC 100	0	0	0	0	100	728	485.20	1213	411	156	651
MRAC-100 +5% GGBS	5	20.55	0	0	100	728	485.20	1213	390.45	156	651
MRAC-100 +10% GGBS	10	40.10	0	0	100	728	485.20	1213	370.90	156	651
MRAC-100 +15% GGBS	15	61.65	0	0	100	728	485.20	1213	349.35	156	651
MRAC-100 +15% GGBS +2% I	15	61.65	2	8.22	100	728	485.20	1213	341.13	156	651
MRAC-100 +20% GGBS +2% I	20	82.20	2	8.22	100	728	485.20	1213	341.13	156	651
MRAC-100 +25% GGBS +2% I	25	102.75	2	8.22	100	728	485.20	1213	341.13	156	651
MRAC-100 +30% GGBS +2% I	30	123.30	2	8.22	100	728	485.20	1213	341.13	156	651

3. Results and Discussions:

3.1Studies on Fresh Concrete Mix

The slump values and compaction factors were observed to decrease with an increase in RA content as shown in Fig. 3 and Fig.4respectively. The slump values and compaction factors, with a uniform water-to-cement ratio (w/c) of 0.38 and 0.7% of super-plasticizer, ranging from 45mm to 38mm slump values and 0.89 to 0.79 compaction factor values respectively, as the RA replacement percentage increased from 0 to 100%. The decrease in slump can be attributed to the higher water absorption and porous structure of MRAC (Mix with Recycled Aggregate Concrete). Furthermore, with the inclusion of GGBS in addition to the 100% MRAC replacement, the slump value decreased to 30mm[9, 26, 27, 28,29].The compaction factor decreased to 0.73.As the proportion of the RAC rises, there is a corresponding decline in the compaction factor[30].This decrease can be attributed to the higher specific surface area of GGBS compared to cement which in turn requires more water to become workable [21, 28,].

There was no appreciable change in slump observed with the incorporation of I-Crete. It can be noted that adding 2% of I-Crete, which is a marginal amount, hardly influenced the slump and compaction factor. However, the observed slump values are within the permissible limits (30±15 mm) stipulated by the IRC 15-2017[22], and for achieving the necessary workability control in pavement quality concrete, compaction is more appropriate than slump values. As per IS 456-2000[20], suggested IS 1199(part-I):2018

[24]for PQC is 0.75 to 0.80. In most cases, the compaction factor values of the above mix follow the recommended range.

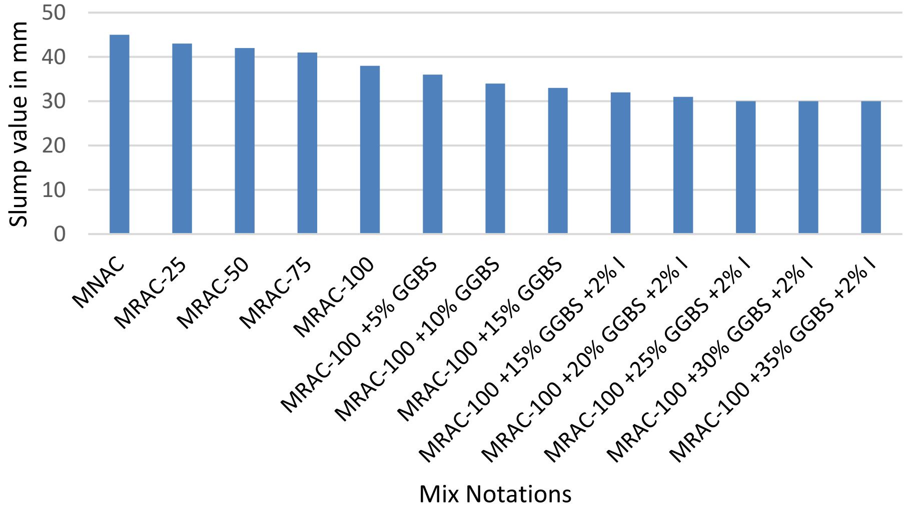


Fig. 3. Variations of slump values for different mixes

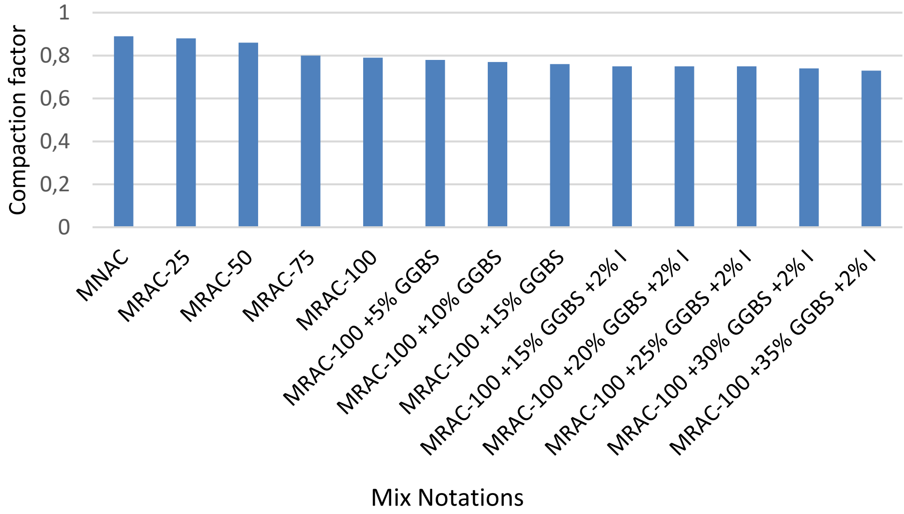


Fig. 4: Variation of compaction factor for different mixes

3.2 Studies on Hardened Concrete

3.2.1 Compressive Strength

Compressive strength of the concrete mixtures was carried out in the laboratory as perIS516:2018[25]. When replaced with RAC up to 100% with 25% intervals, The 7 days compressive strength of (MNAC, MRAC-25, MRAC-50, MRAC-75, MRAC-100) decreases from 38.32 MPa to 35.35 MPa, the percentage of reduction compressive strength is when compared MNAC mix to MRCA-100 is 7.75%. The exhibited a decrease from 51.10 MPa to 48.43 MPa at 28 days curing and 53.01 MPa to 50.05 MPa at 90 days curing, as indicated in Table 8. The reduction in compressive strength can be attributed to the fact that the available free surface on the RAC for cement adhesion has been diminished. This reduction is a result of the pre-attached mortar on the RAC, which creates a weakened Interfacial Transition Zone (ITZ), thus leading to a compromised bonding mechanism [9, 27]. Additionally, the texture of the RAC is porous, resulting in higher water absorption and lower mechanical strength in comparison to conventional aggregates [31]. Despite these factors, the total observed percentage decrease in strength was 5.58% at 100% RAC when compared to conventional concrete. Nevertheless, the achieved strength still satisfied the required target strength specified by the IRC58:2017[32] code provisions. Subsequent investigations involved the incorporation of GGBS as a cement replacement in conjunction with 100% RAC replacement.

GGBS was introduced in varying proportions, ranging from 5% to 35% with a 5% increment. The decision to employ 100% RAC replacement was made based on its ability to attain the target strength, thus maximizing the effective utilization of RAC for sustainable concrete construction. A maximum increase in compressive strength of 0.97% was noted in the case of 10% GGBS inclusion (MRAC100+10% GGBS) when compared to 100% RAC (MRAC-100) alone. However, as the GGBS content was further increased, a subsequent decrease in strength was observed. The Same trend follow in 7 days of curing. The observed strength enhancement resulting from the inclusion of GGBS can be attributed to its higher specific surface area, which facilitates the formation of efficient reactive hydration products in conjunction with the cement [20]. However, surpassing the 10% GGBS leads to an increase in voids within the mixture, consequently causing a decline in strength. Despite identifying the optimized GGBS content at 10% through analysis, the aim to minimize carbon footprint prompted the utilization of the maximum GGBS proportion, some research findings indicate that the optimal results in terms of compressive strength for rigid pavement were achieved when GGBS was used as a partial replacement for cement, specifically up to 15%. Notably, at a 10% replacement level, a substantial 12% increase in compressive strength was observed [33].Efforts were undertaken to balance the strength with that of conventional aggregate.

Fig. 5. Compressive strength test

To counteract the diminishing strength, the introduction of I-Crete commenced at the 15% GGBS inclusion level. This development could potentially represent a significant stride towards reducing carbon emissions and establishing sustainable methods for the effective utilization of waste materials [31]. Maintaining a constant 2% I-Crete content, the assessment of strength was conducted by progressively increasing the GGBS content up to 35%. Notably, commendable compressive strengths of the 7 days of early-stage strength are at MRCA-100+20%GGBS+2I gained early strength 38 MPa and it is nearly equal to the MNAC mix. The reason for developing early strength is that I-Create is a composite pozzolanic material that develops good bonding strength in the early stages. The 51.11 MPa and 52.88 MPa were observed at 28 and 90 days of curing with a GGBS content of 25% and an I-Crete content of 2%. These values align with the compressive strength of the conventional concrete mixtures (MNAC) as shown in Fig. 6. Compressive strength test setup with specimen shown in Fig. 5.

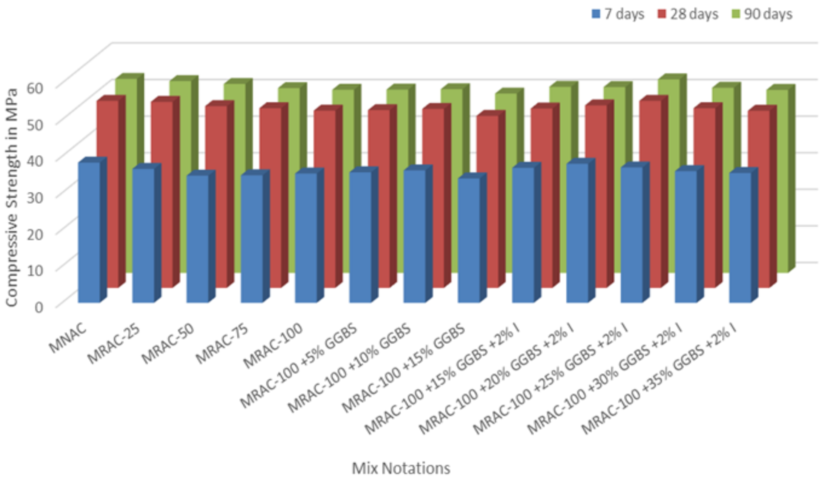


Fig. 6. Variation of compressive strength with different curing periods for different mixes

3.2.2 Split Tensile Strength

The trend observed in split tensile strength followed as that of the compressive strength. The 7 days split tensile strength of (MNAC, MRAC-25, MRAC-50, MRAC-75, MRAC-100) decreases from 3.78 MPa to 2.69 MPa, the percentage of reduction is when compared MNAC mix to MRCA-100 is 28.83% decreased. The most notable reduction in tensile strength was seen at 100% RAC, amounting to a decline of 28.83%, as indicated in Table 8. The split tensile strength exhibits a decreasing trend as the replacement ratio of RAC increases [34,35]. Subsequently, the introduction of GGBS to the 100% (MRAC-100) mixture increased in tensile strength. This increase can be attributed to the inter-particle bonding between cement and GGBS, which leads to reduced porosity and enhanced tensile strength. The most significant increase, amounting to 20.64%, was observed with a 10% GGBS replacement of cement at the 90-day mark. The incorporation of slag cement has been noted to elevate the tensile strength of RAC by a significant 25% compared to RAC without these mineral admixtures [36], followed by a subsequent decrease with higher GGBS content. To counter the decline in strength [33]. I-Crete was incorporated into the concrete mixtures starting from 15% GGBS, Strength enhancement was observed with increasing I-Crete content, up to 25% GGBS, paralleling the trends seen in the compressive strength observations. The 7 days of early stage split tensile strength is at MRCA-100+20%GGBS+2I gained early strength 3.90MPa and it is more than to the MNAC mix. The reason for developing early strength is that I-Create is a composite pozzolanic material that develops good bonding strength in the early stages.

The 4.20 MPa and 5.10 MPa were observed at 28 and 90 days of curing with a GGBS content of 25% and an I-Crete content of 2%. These values align with the split tensile strength of the conventional concrete mixtures (MNAC) as the trend is shown in Fig. 8. Split tensile strength test setup with specimen shown in Fig. 7.

Fig. 7. Split tensile strength test

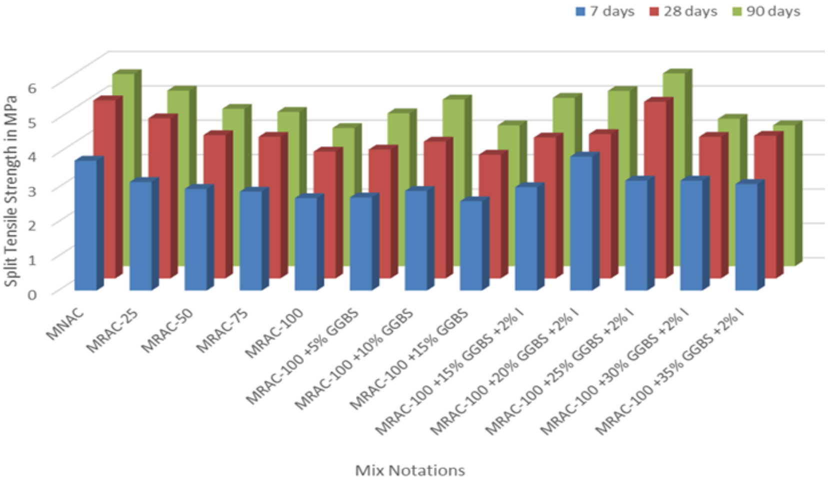


Fig. 8. Variation of split tensile strength with different curing periods for different mixes

3.2.3 Flexural Strength

Flexural strength plays a vital role in the design of rigid pavement, especially when subjected to the effects of multi-axle repetitions. These repetitions can lead to phenomena such as bottom-up and top-down cracking, which are further influenced by concurrent diurnal and seasonal temperature variations. The primary application of concrete's flexural strength lies in the calculation of the stress ratio. This ratio serves as a determinant for the number of repetitions required to induce cracking. For design purposes, the 90-day flexural strength is typically chosen, as concrete continues to gain strength during this period. IRC 58-2015 [32] recommends a flexural strength of 4.5 MPa at 28 days, and at 90 days, the flexural strength should be 1.1 times that of the 28-day strength. The 7 days flexural strength of (MNAC, MRAC-25, MRAC-50, MRAC-75, MRAC-100) decreases from 4.33MPa to 3.64MPa, the percentage of reduction is when compared MNAC mix to MRCA-100 is 15.93%. All the mixtures achieved a flexural strength of more than 4.5 MPa at 28 days, thereby satisfying the design criteria as per IRC58-2015[32]. In the current analysis, the flexural strength after a 90-day curing period ranged from 1.02 to 1.10 times the flexural strength at 28 days for mixtures containing RAC replacement.

The introduction of 2% I-Crete resulted in a range of approximately 1.03 to 1.19 times the strength at 28 days. The flexural strengths of all the mixtures exhibited similar trends to those observed in compressive strength. The flexural strengths of all the mixes followed similar trends as that of the compressive strength. The highest reduction in strength occurred in MRAC100, amounting to 17.90% in RCA mixtures alone. The flexural strength of RAC exhibits a diminishing trend as the replacement ratio of RA increases. [28, 37, 38]. Conversely, an increase in strength of 7.38% was noted when comparing MRCA100 to the mix with 10% GGBS inclusion (MRAC100+10%GGBS) [39]. The strength equivalent to MNAC was achieved in the MRAC100+25%GGBS+2%I mixture, measuring 5.98 MPa at 28 days and 6.65 MPa at 90 days, the trend as shown in Fig. 10. Flexural strength test setup with specimen shown in Fig. 9.

Fig. 9. Flexural strength test

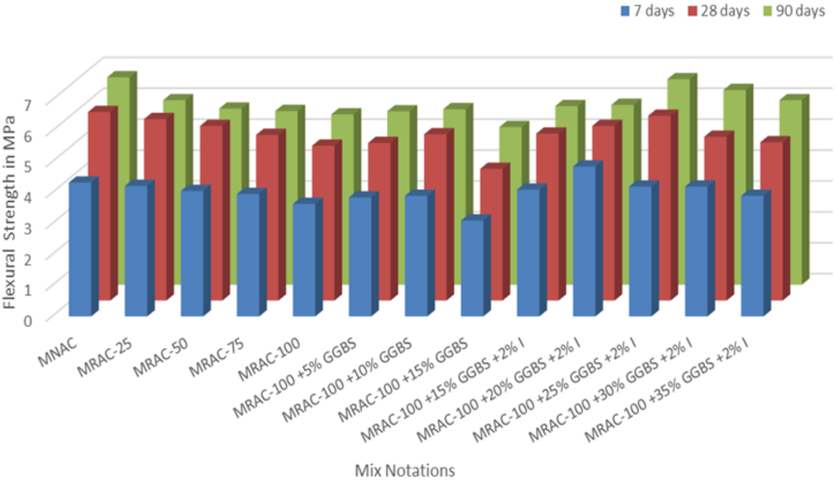


Fig. 10**.** Variation of flexural strength with different curing periods for different mixes

3.2.4 Correlation Between Compressive Strength and Flexural Strength

A correlation, with a coefficient of 0.9481, has been obtained between compressive strength and flexural strength for all concrete mixtures, as shown in Fig. 11. It has also been observed that there is a power function relationship between compressive strength and flexural strength in one of the studies, characterized by a correlation coefficient of 0.89[40]. With the correlation established in this study, it is possible to estimate the compressive strength of all mixtures based on their flexural strength.

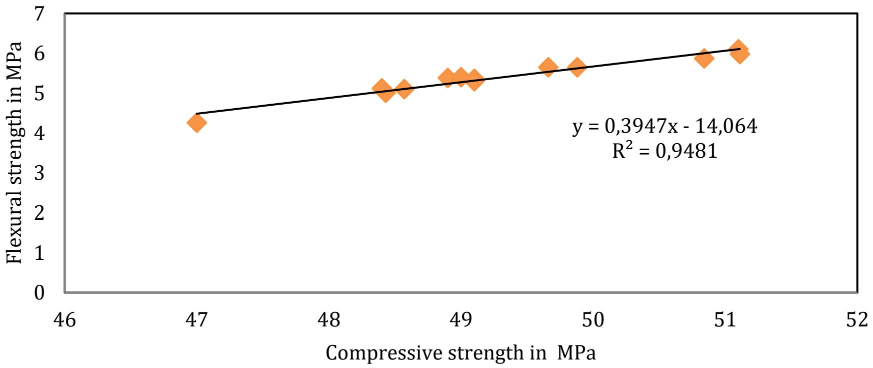


Fig. 11**.** Correlation graph between compressive strength and flexural strength for all mixes

3.2.5 Correlation Between Compressive Strength and Split Tensile Strength

For all concrete combinations, a high association between compressive strength and split tensile strength has been found, with a coefficient of 0.8413, as indicated in Figure 12. Additionally, it has been noted that one of the researches shows a power function relationship with a correlation coefficient of 0.89 [40] between compressive strength and split tensile strength. It is now feasible to determine the compressive strength of any mixes based on their split tensile strength owing to the correlation discovered in this research.

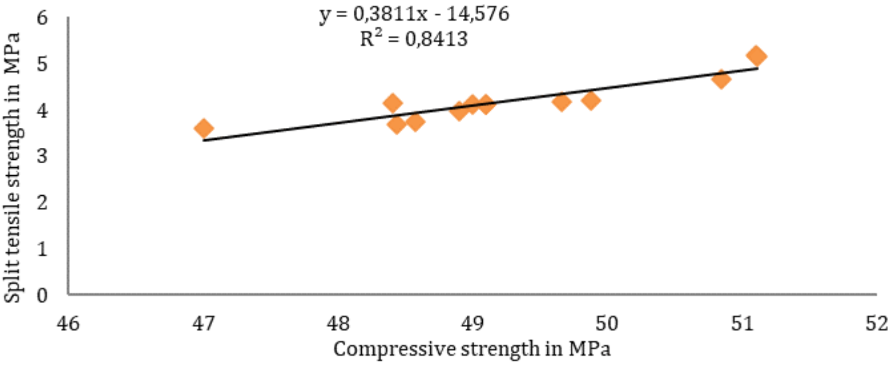


Fig. 12.Correlation graph between compressive strength and split tensile strength for all mixes

Table 8. Mechanical properties of concrete mixes under study

Mix designation	**Compressive strength (MPa)**			**Flexural strength (MPa)**			**Split tensile strength(MPa)**			**Water absorption (%) 28 days**	**UPV for 28 days in (m/s)**
	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days		
MNAC	38.32	51.10	53.01	4.33	6.10	6.71	3.78	5.18	5.59	0.94	5043
MRAC-25	36.60	50.84	52.41	4.22	5.87	5.97	3.16	4.66	5.11	1.12	4958
MRAC-50	34.76	49.66	51.63	4.06	5.65	5.70	2.96	4.17	4.58	1.60	4881
MRAC-75	34.86	49.10	50.50	3.96	5.36	5.62	2.88	4.12	4.49	1.80	4820
MRAC-100	35.35	48.43	49.00	3.64	5.01	5.51	2.69	3.69	4.02	1.20	4617
MRAC-100 +5% GGBS	35.67	48.57	50.10	3.85	5.10	5.61	2.71	3.75	4.45	1.90	4663
MRAC-100 +10% GGBS	36.2	48.90	51.20	3.90	5.38	5.68	2.90	3.98	4.85	1.15	4748
MRAC-100 +15% GGBS	34.00	47.00	49.00	3.10	4.26	5.10	2.60	3.60	4.10	1.10	4636
MRAC-100 +15% GGBS +2% I	36.90	49.00	50.85	4.10	5.40	5.78	3.01	4.10	4.90	1.05	4776
MRAC-100 +20% GGBS +2% I	38.00	49.88	50.78	4.85	5.65	5.82	3.90	4.20	5.10	1.01	4900
MRAC-100 +25% GGBS +2% I	37.00	51.11	52.88	4.20	5.98	6.65	3.20	5.14	5.61	0.90	5002
MRAC-100 +30% GGBS +2% I	36.00	49.10	50.60	4.20	5.30	6.30	3.20	4.12	4.29	1.01	4950
MRAC-100 +35% GGBS +2% I	35.50	48.40	50.01	3.90	5.12	5.97	3.10	4.15	4.10	1.00	4750

3.2.6Water Absorption

In the conventional concrete mix design, the MNAC water absorption percentage after28 days of curing is found to be 0.94%. However, as the percentage of recycled aggregate in the mix increases, the water absorption also increases [9, 27]. For MRAC-100, the water absorption rate is 1.2%, which is higher than the conventional mix. This represents a 32.5%increase in water absorption compared to the conventional concrete mix. This higher water absorption adversely affects the concrete, leading to poor workability, significant slump loss, and the potential for concrete pumping blockages. It has been observed that incorporating different mineral admixtures tends to reduce the water absorption percentage, and the degree of reduction varies depending on the properties of the included mineral admixture and mineral additive. In the case of concrete mixes with GGBS, the observed water absorption value for MRAC-100+25% GGBS+2I is only 0.9%, and it is lower than that of MNAC mix, while for mixes with GGBS, this value is approximately 1.9% and 1.15% for MRCA-100+5% GGBS and MRCA-100+ 10% GGBS, respectively. This improvement in water absorption parameters can be attributed to the presence of ultrafine particles in the mineral admixture and mineral additive, which refines the pore structure of the concrete, making it less permeable. This, in turn, leads to better strength development in concrete, as discussed in the results for compressive, flexural, and split tensile strength as shown in Fig. 12.

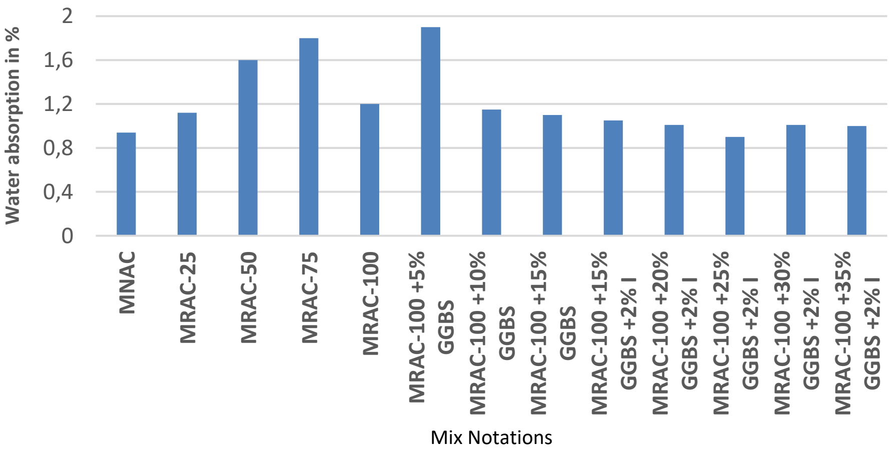


Fig: 12. Variation of water absorption with different curing periods for different mixes

3.2.8 Ultrasonic Pulse Velocity

Indian Road Congress (IRC) provides guidelines for quality control of pavement materials and construction, including the use of Ultrasonic Pulse Velocity (UPV) for assessing the quality of PQC as shown in Fig. 14. These guidelines help ensure that the concrete used in road construction meets the required standards and specifications IS 516 part5-2018[25]. The test setup for cube as shown in Fig. 13.

Fig. 13. Ultrasonic pulse velocity test

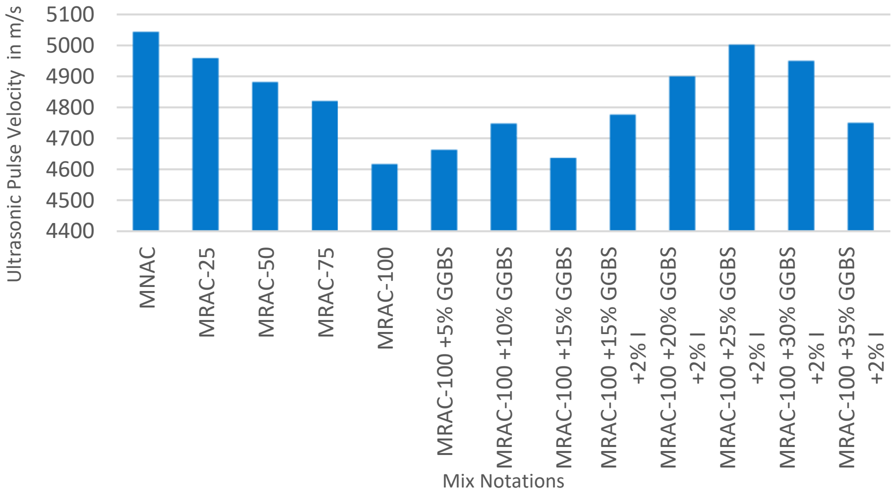
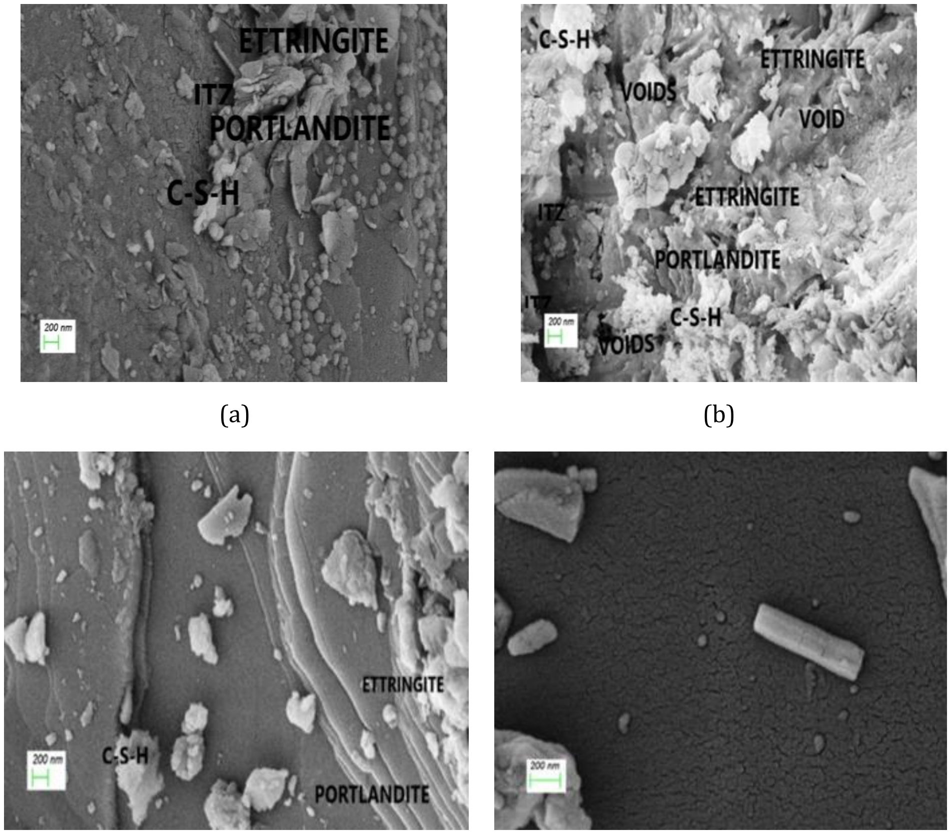


Fig. 14. Ultrasonic pulse velocity for various mixes

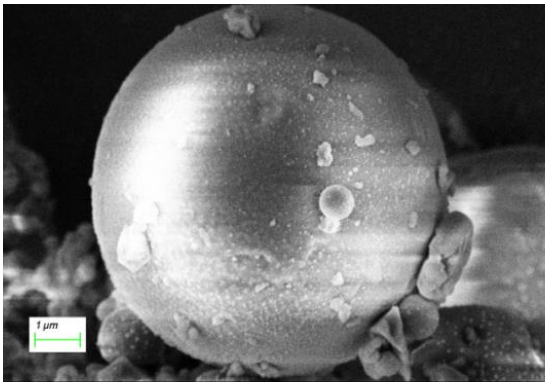
4. Scanning Electron Microscopic (SEM) Analysis

Scanning Electron Microscopy (SEM) is one of the most adaptable technologies available for observing and analyzing the micro structural characteristics of solid materials. SEM is used to provide high-resolution photographs of an object's form and to detect spatial differences in chemical composition. SEM investigations of the fracture surfaces of concrete constructed from RAC with varying mineral contents were performed [41]. These composites were included in a study at a curing age of 28 days. In Fig. 15 (a), the SEM imaging of the MNAC mix show the microstructure at the virgin aggregate-concrete-cement interface, revealing the formation of Calcium-Silicate-Hydrate (C-S-H) gel and other hydrated compounds. The existence of hexagonal and fine bundle-type structures implies that hydroxide compounds and C-S-H gels are abundant. In Fig. 15(b) the microstructure of MRAC-100 diverges from that of normal concrete due to the presence of adhered mortar from the old cement matrix. This results in the formation of two Interfacial Transition Zones (ITZ): one between natural aggregates (NA) and the old cement matrix, and another between the new cement matrix [42, 43]. The MRAC-100 mix's SEM picture displays an abundance of needle-like ettringite and hexagonal calcium hydroxide particles. Incomplete hydration is responsible for the occurrence of an excess of calcium hydroxide particles, voids, and the ITZ. This loss of strength is attributed to a weaker ITZ caused by weakly adhered mortar surrounding the recycled aggregate particles, which interferes with aggregate bonding and reduces the overall strength. Utilizing SSD aggregates has been observed to notably diminish the micro pores in concrete. This is attributed to the fact that SSD aggregates, having no absorbed water during the casting process, do not release entrapped air during the concrete setting [44]. Prior research has efficiently summarized the analysis of Recycled Aggregate Concrete (RAC) with pozzolanic materials; Chemical admixtures boost ITZ density. Pozzolanic reactions with unhydrated $Ca(OH)_2$ generate secondary C-S-H gel, improving MRAC structural weaknesses [27, 44-47]. Indications show that the mean and median particle sizes of GGBS and I-Crete particles are spherical in shape. SEM images were obtained for GGBS Fig. 15(d) and I-Crete Fig. 15(e). Spherical particles increase ITZ in concrete by increasing packing efficiency, reducing voids, and more uniformly dispersing stresses. Their smooth surface and greater workability aid in bonding, resulting in a stronger ITZ. SEM image Fig. 15(c) of MRCA-100+25% GGBS+2I reveals an increase in C-S-H and Calcium Hydroxide (CH) content in the mix. GGBS and I-Crete have pozzolanic qualities that, when added to concrete, accelerate the hydration process and increase the amount of hydration products.



(a) (b)

(c) (d)



(e)

Fig. 15. SEM Images(a) MNAC mix, (b) MRCA – 100 mix, (c) MRCA – 100+25% GGBS + 2I, (d) GGBS and (e) I – Crete

The enhanced strength metrics, particularly in compressive and flexural strength, clearly demonstrate the strength of the ITZ. This improvement in flexural strength (as shown in Table 8) is especially desired because the concrete mix has been specifically formulated for stiff pavement applications. Increased durability is also a result of the decrease of voids.

5. Conclusion

The laboratory study yields the following conclusions.

- Studies conducted on fresh concrete with increasing amounts of RA have shown a decrease in the compaction factor from 0.89 to 0.79 and the slump also followed a similar trend, decreasing from 45 mm to 38 mm. further replacement of cement up to 10%GGBS, also showed a decrease in compaction factor from 0.79 to 0.73 and slump reduction from 38mm to 30mm. However, the inclusion of I-Crete had no appreciable effect on the properties of fresh concrete.

- The replacement of NA with RA decreased the performance of RAC. Compressive strength decreased by 5.22% to 7.84% across all curing durations, while flexural strength and split tensile strength decreased by 15.93% to 17.88% and 28.08% to 28.83%, respectively. However, the required target strength was met.

- GGBS replacement levels increased from 5% to 35% in 5% intervals, with MRCA-100 being the most efficient. MRCA-100 with GGBS demonstrated up to a 10% improvement in compressive strength, with results ranging from 0.96% to 4.29% for all phases of curing when compared to the MRCA-100 mix. Flexural strength and split tensile strength increased by 2.99% to 6.87%, and 7.24% to 7.28%, respectively, throughout all curing times This increase can be attributed to the inter-particle bonding between cement and GGBS, which leads to reduced porosity and enhanced compressive strength, tensile strength and flexural strength. However, strength began to decline after GGBS replacement levels were above 15%.

- Adding 2% I-Crete to MRCA-100 with 15% to 35% GGBS in 5% intervals showed increases in compressive, split tensile, and flexural strength by 5.24% to 7.33%, 28.34% to 31.02% and 16.22% to 24.94% respectively increased in the MRCA-100+25%GGBS+2I mix exhibited these improvements over MRCA-100 across 7, 28 and 90-day curing periods. The reason for developing strength is that I-Create is a composite pozzolanic material that develops good bonding strength in the early and later stages. The optimal replacement of 25% GGBS and 2% I-Crete in RAC mixes not only improves strength but also drops prices and adverse environmental impacts, as GGBS is an industrial by-product.

- In conventional concrete, 28-day cured MNAC specimens had a water absorption rate of 0.94%. But MRCA-100 exhibits a 32.5% rise to 1.2%, due to increased RA concentration. Adding mineral admixtures such as GGBS and I-Crete helps to limit water absorption. The UPV test target result is exceptional in all I-Crete and virgin mixtures, and good in others, indicating that they fulfill IS:516 specifications.

- The SEM image of the 28-day-cured MNAC mix reveals a complex microstructure at the interface of virgin aggregate, concrete, and cement, including gels made up of C-S-H and hydrated compounds with hexagonal and fine bundle-type structures. In MRAC-100, the inclusion of needle-like ettringite and hexagonal calcium hydroxide particles indicates insufficient hydration and a weak ITZ, resulting in decreasing strength. SEM pictures of GGBS and I-Crete reveal spherical particles and, when mixed in MRCA-100+25% GGBS+2I, an increase in C-S-H and CH. Their pozzolanic capabilities increase hydration while also improving pavement bonding as well as structure quality.

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