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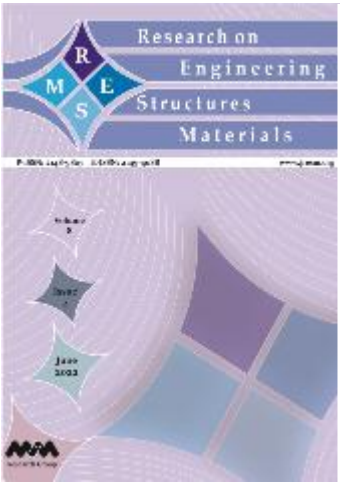

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Research Article

Performance studies on energy efficient paver block with treated recycled aggregate

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Abstract

Extensive research was performed to investigate the concrete properties (hardened and durability) with finer and coarser recycled aggregates. Fewer studies have discussed on the effect of bio-treatment to recycled aggregates in concrete to overcome its higher water absorption characteristics. However, the studies on the use of bio-treated recycled aggregates as alternative to natural aggregates in real time traffic applications needs to be increased. This paper investigates the feasibility of utilization of recycled coarse aggregate (RCA), recycled fine aggregate (RFA), bio-deposited recycled coarse aggregate (BRCA) and carbonated recycled fine aggregate (CRFA) in the production of sustainable paver blocks for various traffic volumes. The RCA was bio-treated with Bacillus sphaericus at 105cells/ml and RFA was carbonated at 0.2 bar to produce hexagonal paver blocks of 80 mm thickness. The research involves the determination of density, strength and water absorption of paver blocks at suitable ages. The strength of bio-deposited and carbonated paver blocks was reduced by only 6.13% and 8.9% and the water absorption bio-deposited and carbonated paver blocks was increased by only 2.86% and 1.24% compared to conventional paver block. The impact energy of bio-deposited and carbonated paver blocks was 18.6% and 17% lesser compared to conventional paver block. Microstructural investigations through scanning electron microscope (SEM) and X-ray diffraction (XRD) illustrates the $CaCO_3$ formation that seals the crevice on the recycled aggregate and improves the properties of paver block.

1. Introduction

The circular economy of a country aims at sustainable utilization of waste raw materials in the production of energy efficient products and ensuring cleaner energy. The waste management policies of 3R approach (Reduce, Recycle and Reuse) has diversified to 4R approach (Reduce, Recycle, Reuse and Recovery). Under such circumstances, the most prominent municipal solid waste generated out of construction activities namely Construction and Demolition (C&D) wastes takes its prime importance in 4R approach. C&D wastes, an outcome of demolition and rehabilitation activities in construction include concrete, bricks, steel, wood, plastics etc. in suitable proportions depending upon the structure. These wastes either dumped in landfill or used in temporary/unimportant works affecting the integrity of environment in the former and inefficient utilization strategy in the latter. On a whole, nearly 30% of wood, 45% of gravel, sand is being utilized by construction industries every year globally [1]. Nearly 10-15% of the materials end up as waste resulting in generation of municipal solid waste leading to disposal problems [2]. In India, every year around 150 MT of C&D wastes are generated which is nearly 40% of the those produced globally [3]. The Centre for Science and Environment (CSE) updates that only 1% of C&D wastes were being recycled out of 150 MT generated posing serious threat to the environment. Similarly, in other countries like USA, China etc. the generation

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of C&D wastes are increasing on a large scale alarming the effective recycling and reutilization. Meanwhile, it is well known that the construction activities depend prominently on natural resources as their source of raw materials resulting in the scarcity. This eventually necessitates the concept of recycling and reuse of construction wastes effectively again in the construction activities.

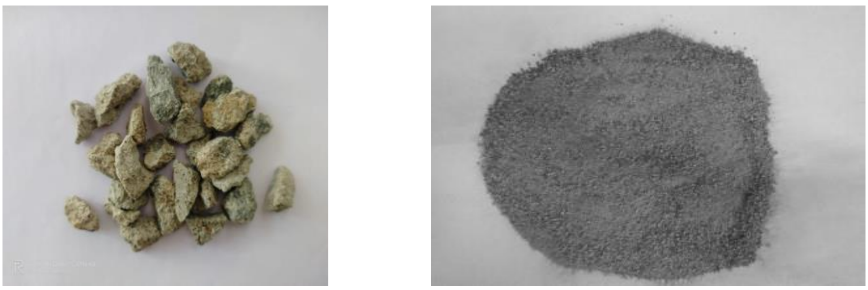
Extensive researches were carried out with the utilization of recycled construction wastes as fine aggregate (RFA) and coarse aggregate (RCA) in the concrete. Higher utilization of RFA and RCA in the concrete affects the concrete properties due to its inferior quality ensuing from higher porosity [4-7]. So, the researches focus on suitable treatments to RCA and RFA to enhance its quality by reducing its water absorption. Such treatments include acids, carbonation, bio-deposition, slurries, polymers etc. [8-13]. These treatments either involve in removal or coating of adhered mortar as it possesses micro-cracks that increases the porosity. However, the feasibility of utilization of RCA and RFA in the real time traffic/structural applications still needs to be investigated on a larger scale. Researcher [14] used recycled aggregates and crushed clay bricks in the paver block production and infer that higher utilization of recycled aggregates and crushed bricks increased the water absorption of paver block and that eventually reduces the performance of paver blocks and optimized utilization (50%) of both meet the least requirements as defined in AS/NZS 4455 (Grade B) of paver blocks. However, the author [15] reviewed the effective utilization of RCA and RFA in various construction applications and infer that progression of detailed specification on utilization of recycled aggregates reduced the risk factor of its utilization in real time applications that might reduce its environmental impact and scarcity problems. Meanwhile, [16] used dry, washed and pre-saturated RCA and RFA and found that paver-blocks with washed recycled aggregates exhibit required minimum standards with water absorption less than 5% of the control. The use of recycled asphalt pavement as aggregates in the manufacture of pervious paver blocks and found that higher grading resulted in 23.6% reduction in strength and finer grading resulted in 43% reduction in the strength compared to conventional blocks [17]. Researcher [18] produced 80 mm I shaped paver block with RCA and found the optimal replacement of 60% without a significant reduction in strength, density and impact energy. The replacement beyond 60% reduced the strength of the paver block by 13.7% and increased the water absorption by 72%.

Similarly, use of both RCA and crusher dust infer that RCA can be replaced up to 45% for river gravel and crusher dust can be replaced up to 100% for river sand to produce strength equivalent to designated M40 grade for medium volume traffic volume applications [19]. Also, the study observed nearly 44% cost reduction in the production of 1 cu.m of paver blocks. Researcher [20] manufactured paver block and kerb stones with both RCA and RFA and observed optimal replacement of 25% of both RCA and RFA obtained the minimum requirements as per EN 1338. It is also suggested for its applicability in the pedestrian areas or light traffic volume conditions. The properties of bio-blocks with recycled aggregates infer that the unconfined strength of bio-blocks shows a minimum difference of 10% in strength and reduction in the water absorption by 58% [21]. The study also infers that the thermal resistance of bio bocks with natural coarse aggregate (NCA) and RCA was better at both high and low temperatures, but the strength of bio blocks with RCA was lesser compared to those with NCA but it eventually increases with increase in the CaCO3. It could be observed that relative application of RCA under various traffic volume conditions exhibit the minimum requirement for pedestrian walk (low volume) as specified in the standards. However, the effect of treated RCA and RFA on the behaviour of paver block under various traffic volume conditions has to be investigated. This study examines the effect of both treated RCA and RFA in the manufacture of energy efficient paver blocks wherein the RCA was treated with Bacillus sphaericus at 105cells/ml and RFA was carbonated at 0.2 bar.

2. Materials and Methods

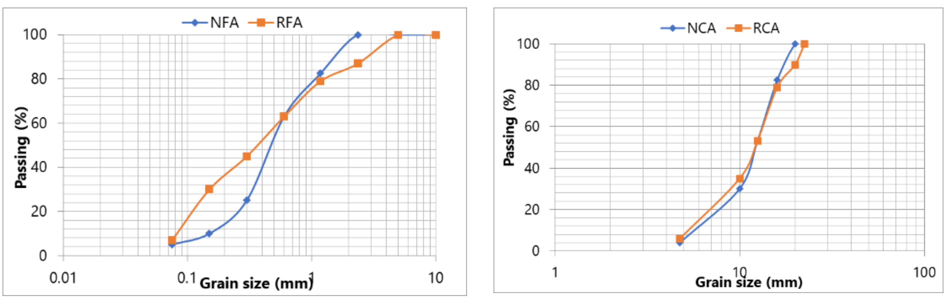
2.1. Concrete Materials

This study involves six different aggregates such as natural fine aggregate (NFA) with relative size of 2.36 mm~4.75 mm, natural coarse aggregate (NCA) with relative size of 10 mm~20 mm, RFA and RCA with size equivalent to NFA and NCA, bio-deposited recycled coarse aggregate (BRCA) with size equivalent to NCA and carbonated recycled fine aggregate (CRFA) with size equivalent to NFA. Fig. 1(a) shows the visual of RCA and Fig. 1(b) shows the visual of RFA used. Both the finer and coarser fractions were obtained by recycling the concrete wastes dumped as a result of casting works of students in the institution premises. The concrete wastes collected (the compressive strength and materials used in its manufacture) as boulders were sorted wherein the large boulders were broken with hammers and further recycled into required fractions, sieved and used as RCA and RFA. Fig. 2(a) depicts the gradation curves of RCA and Fig. 2(b) depicts the gradation curves of RFA. In this study, both RCA and RFA were thoroughly washed to remove the silt particles and pre-saturated to ensure SSD prior to its use in the experimentation. The pre-washing and pre-saturation of RCA and RFA will ensure the workability loss and resolve the delinquent of its higher porosity ensuing from the adhered mortar. Whilst, ordinary portland cement (OPC) with a characteristic strength of 43 N/mm2 was used in the concrete mix. Potable tap water with basic pH value was used in manufacture and curing operations.



(a) (b)

Fig. 1 (a) Visual of RCA, (b) Visual of RFA



(a) (b)

Fig. 2 (a) Gradation curves of RCA, (b) Gradation curves of RFA

2.2. Treatments to Recycled Aggregates

Extensive research on recycled aggregate concrete (RAC) infers that higher porosity in RCA and RFA affects the concrete properties [22-24]. To reduce the porosity, the RCA was treated with Bacillus Subtilis and the RFA was treated with CO_2. The strains of Bacillus subtilis were obtained and cultured in an Agar Medium consisting of 0.5% peptone, 0.3% beef extract and 0.5% NaCl. To prepare the agar medium, 30 g of agar concentrate was dissolved in 1000 ml of distilled water. The mixture is heated during stirring to allow the complete dissolution of the agar precipitate. It is then autoclaved at 120°C for 15 minutes and cooled. The cooled mixture is then transferred to Petri plates and kept undisturbed to congeal. The strains of Bacillus subtilis were added along agar medium, incubated at 37°C and shaken at 175 rpm for 48 hours. The grown culture is diluted and spread out on agar plates to calculate the cell count and obtained 7 x 105 cells/ml. Fig. 3 shows the culture solution of Bacillus Subtilis, which is used for bio-deposition treatment. The bio-deposition to RCA was performed under laboratory conditions, wherein the collected RCA was surface saturated and air-dried to reach SSD condition. It is then saturated in the cultured solution for 24 hours. The RCA was removed from the cultured solution and immersed in the bio-deposition medium for 72 hours. After 72 hours, the RCA was removed, surface washed and dried at room temperature to produce bio-deposited recycled coarse aggregate (BRCA).

(a) (b) (c)

Fig. 3 (a) Preparation of culture medium, (b) Centrifuging, (c) Cultured solution

In carbonation treatment, the RFA was treated with locally available CO2 (99.5% purity) in the fabricated carbonation set up at 20°C with an R.H. of 60%, as shown in Fig. 4. The carbonation chamber with RFA was subjected to 0.4 bar pressure for 24 hours. It is then allowed to cool at room temperature and used as carbonated recycled fine aggregate (CRFA).

2.3. Concrete Mix and Concrete Testing

The concrete mixtures were prepared with RCA, RFA, BRCA and CRFA as per IS 10262 (2019) [25] for M40 grade to manufacture paver -block for low and medium traffic applications. In this study, eleven concrete mixtures with different percentages of the RCA, RFA, BRCA and CRFA were manufactured to evaluate the suitability of manufactured hexagonal shaped paver blocks for the above said traffic conditions. The NCA and NFA was substituted with 25%, 50% and 100% of RCA and RFA by its weight. The raw material quantities for paver block preparation were given in the table 1 as per IS 10262 (2019). The concrete mixes with NCA were manufactured with normal mixing approach (NMA) and the concrete mixes with RCA and RFA were manufactured with two-stage mixing approach (TSMA) [26]. The RCA in the mixes tend to absorb water resulting in workability loss, so as to compensate the NMA was altered to TSMA, wherein 50% of water is added to compensate the absorption by RCA and rest 50% is added to overcome workability loss [27-29]. The concrete mixes prepared with NMA and TSMA were fabricated into hexagonal shaped paver block with 125 sq.mm side area and 80 mm thickness. The ingredients required for the paver-block manufacture were confirmed for its physical properties as per IS 383 (2016) [30]. The paver blocks manufactured with NMA and TSMA were tested for its density, compressive strength, tensile strength, flexural strength, impact strength and water absorption. To determine the density, the paver block is oven dried for 7 days and the density was calculated with the dry weight as per IS 15658 (2006) [31]. The compressive strength of the paver block was determined at 28 days as per IS 15658 (2006) [31]. The paver blocks are cured for 28 days at 20 ± 5°C, taken out, wet surfaces are wiped off and the specimens after drying were kept in such a way that the surfaces are properly aligned with the bearing plates in the compression testing machine (CTM). The specimens are loaded at a rate of 15 ± 3 N/mm2 per minute and the maximum load at failure is determined. The compressive strength of the paver block was determined at 28 days as per IS 15658 (2006) [31]. The paver block is placed in such a way that shortest length passes through the center of planar area. The specimens were loaded gradually corresponding to stress of 0.05 MPa and the tensile strength of the paver block is calculated using the equation (1).

Fig. 4 Carbonation treatment to RFA

$$\text{Tensile strength} = \frac{0.637 * P}{S} \quad (1)$$

Where, P is ultimate failure load; S size of the specimen

The flexural strength of the paver block was determined at 28 days as per IS 15658 (2006) [31]. The 28-days cured specimens were loaded in the universal testing machine at a rate of 6kN/min and with the maximum load at failure, the flexural strength is calculated using the equation (2)

$$\text{Flexural strength} = \frac{3Pl}{2bd^2} \quad (2)$$

Where, P is ultimate failure load; l – length of the specimen; b – breadth of the specimen; d – depth of the specimen

The water absorption of the paver block was determined at 28 days as per IS 15658 (2006) [31]. The paver block after 28 days of curing were wiped with dry cloth and oven dried at

107 ± 7°C and the difference in wet weight and dry weight were measured to determine the water absorption. To determine the impact energy, a 4.5 kg steel ball is allowed to fall freely from 3m height at the center of the specimen. The number of the blows at which the specimen fails were determined and the impact energy is calculated using the equation (3)

$$\text{Impact energy} = \frac{N*w*v^2}{2} \tag{3}$$

Where N is number of times of free fall of steel ball; w is the weight of the ball; v is the velocity of the steel ball

3. Results and Discussions

3.1. Material Properties

3.1.1 Chemical Constituents

The predominant compounds in the natural aggregates are its SiO_2 (quartz) constituting nearly 90% of weight, 1.5% of CaO, 4-5% of Al_2O_3 and 1-2% of Fe_2O_3 and MgO. In case of recycled aggregates, the constituents include SiO_2 (73-78%), Al_2O_3 (5-6%), CaO (5-6%), Fe_2O_3 (1-2%) and MgO (1-2%). The equivalence in the constituents with varying percentages defines the suitability of replacement of NCA and RCA. The ordinary portland cement (OPC) comprises of nearly 60% of CaO, 21% of SiO_2, 6% of Al_2O_3, 3% of Fe_2O_3, 2.5% of MgO and 7.5% of other minor constituents. Table 1 shows the chemical constituents of the materials used in the study.

Table 1. Chemical constituents

S.No	Constituents	Percentage (%)		References	
		Natural Aggregate	Cement	Natural Aggregate	Cement
1	SiO_2	90	21	[16, 20]	[14, 17]
2	CaO	1.5	60		
3	Al_2O_3	4-5	6		
4	Fe_2O_3	1-2	3		
5	MgO	1-2	2.5		

3.1.2 Physical and Micro-Structural Properties

Table 2 depicts the variation in the physical properties of NFA, RFA, NCA, RCA, BRCA and CRFA. The density and specific gravity of RCA and RFA were found to be lower than those of NCA and NFA. The specific gravity of RCA and RFA was 13.5% and 6.2% lower compared to NCA and NFA and similarly, the bulk density of RCA and RFA was 9.5% and 10.54% lesser compared to NCA and NFA. Concerning to water absorption, the water absorption of RFA and RCA was 88.57% and 85.80% more compared to NFA and NCA. Similarly, the crushing index, impact value and abrasion value of RCA was 19.10%, 34.73% and 38.2% more compared to NCA. Except for water absorption, all of the physical properties of recycled aggregates were inferior to natural aggregates but within the limitations of IS 383 (1970). The inferior quality of RCA and RFA was attributed to the incidence of smeared mortar on its surface [5, 6]. The crushing of concrete fractions of recycled aggregates results in the formation of micro-cracks on the adhered mortar surface and that eventually increases the porosity and affects its quality. However, the water absorption of RFA was higher than RCA as the more crushing stages is involved in the reducing the particle size resulting in the increases micro-cracks and silt content [6, 15]. This could be eventually observed with 45.7% increase in the silt content in RFA compared to NFA resulting in higher water absorption. Such inferior properties of RCA and RFA could reduce it utilization in real time applications and thus both RCA and RFA was treated to improve its properties. The specific gravity of CRFA and BRCA was 2.41% and 5.57% more compared to RFA and RCA and the bulk density of CRFA and BRCA was 9.7% and 4.15% more compared to RFA and RCA. The water absorption of CRFA and BRCA was 85.3% and 79.44% lower compared to RFA and RCA, but 21.8% and 30.95% more compared to NFA and NCA. Similarly other properties of CRFA and BRCA was better compared to RFA and RCA owing to the treatments. In carbonation treatment, the CO2 reacts with the Ca(OH)2 on the smeared mortar to form CaCO3 that deposits on the RFA and seals the micro-cracks and improves its properties [12]. The bio-deposition of RCA precipitates CaCO3 due to the urea hydrolysis that increases the nucleation sites for CaCO3 [5, 11]. The precipitated CaCO3 bonds on the RCA, either seals on the surface or impregnates into the micro-pores of the RCA and improves its properties.

Table 2. Physical properties of aggregates

S. No	Description	NFA	RFA	CRFA	NCA	RCA	BRCA
1	Specific gravity	2.58	2.42	2.48	2.74	2.37	2.51
2	Bulk Density (kg/m^3)	1602	1433	1587	1631	1476	1540
3	Water absorption (%)	0.93	8.14	1.19	0.87	6.13	1.26
4	Crushing index (%)	-	-	-	20.41	25.23	21.67
5	Impact value (%)	-	-	-	17.23	26.4	24.51
6	Abrasion value (%)	-	-	-	21.38	34.6	31.76
7	Fineness modulus	3.07	3.52	-	6.87	7.32	-
8	Silt content	2.5	4.61	-	-	-	-

The XRD patterns of NCA, RCA, BRCA, CRFA is shown in the Fig. 5. Fig. 5(a) shows the XRD pattern of NCA, Fig. 5(b) shows the XRD pattern of RCA, Fig. 5(c) shows the XRD pattern of BRCA and Fig. 5(d) shows the XRD pattern of CRFA. The maximum 2θ (Diffraction angle from incident ray) was observed at 30 with NCA, between 60 to 70 with RCA, 20 to 30 with BRCA and 20 to 30 with CRFA. The peak in NCA pattern specify the incidence of SiO_2, $NaAlSiO_3O_8$, and $CaCO_3$, with the highest being SiO_2. This might be advantageous in the development of a C-S-H that endorses the concrete strength. In RCA, the peak signifies the calcite compound ensuing from the cement mortar and traces of SiO_2. In BRCA, higher peaks are observed with calcite similar to RCA but the intensity is more compared to RCA. This could be the $CaCO_3$ precipitated as a result of microbial activity in addition to the traces of $Ca(OH)_2$ from the smeared mortar. In CRFA, similar to BRCA, the evidence of $Ca(OH)_2$ and $CaCO_3$ was observed, wherein the former was due to the cement mortar and latter due to the interaction of $Ca(OH)_2$ with CO_2 to form $CaCO_3$.

The SEM images of NCA, RCA, BRCA, CRFA is shown in the Fig. 6. Fig. 6(a) shows the SEM image of NCA, Fig. 6(b) shows the SEM image of RCA, Fig. 6(c) shows the SEM image of BRCA and Fig. 6(d) shows the SEM image of CRFA. In NCA, high angular dense particles were observed due to the its grading whereas in RCA, few traces of adhered mortar were observed on the angular particles owing the crushing of RCA to required particle size. In BRCA and CRFA, CaCO3 deposition were observed on the surface of RCA and RFA resulting in the improvement in their properties. The former is due to the urea lytic activity of bacteria whereas the latter is due to the carbonation.

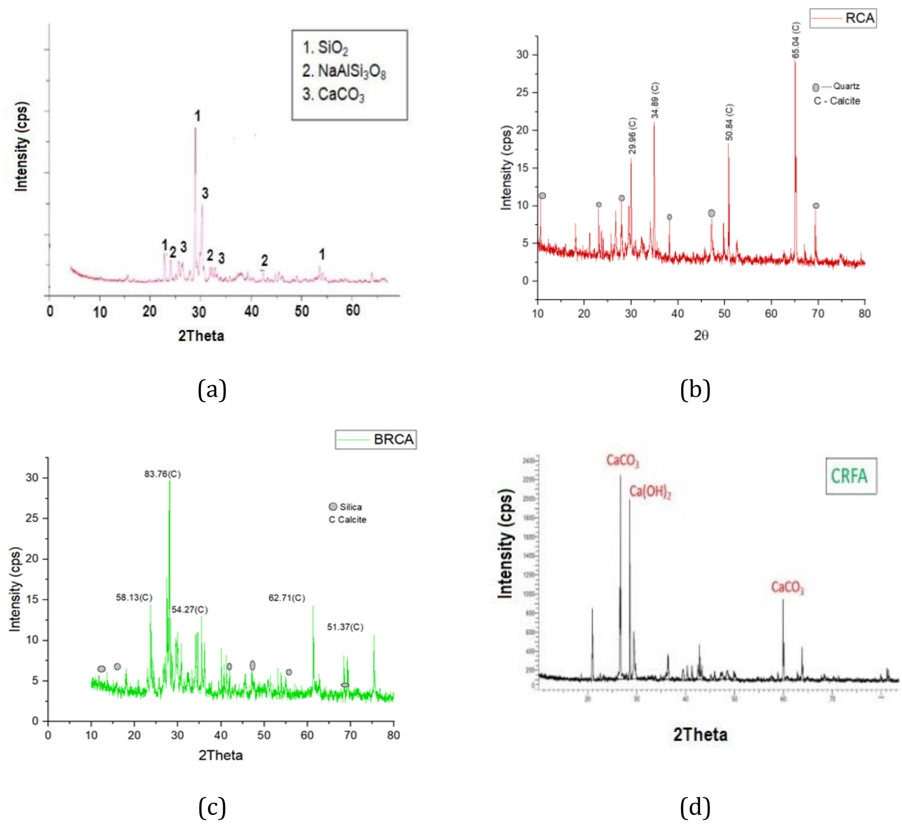
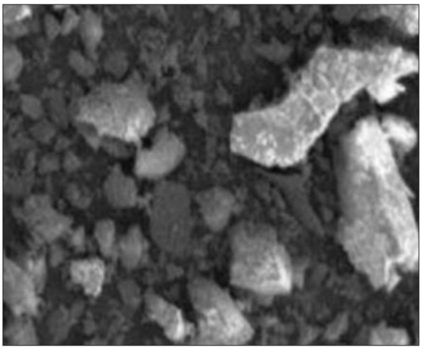


Fig. 5 (a) XRD of NCA, (b) XRD of RCA, (c) XRD of BRCA, (d) XRD of CRFA

3.1.3 Concrete Properties

The compressive strength of the paver block with different mix combinations at 28 days is given in the Fig. 7. The compressive strength of RC-25-RF-0 was 1.47% more compared to the conventional block. Nevertheless, the compressive strength of RC-50-RF-0 and RC-100-RF-0 was 12.01% and 17.64% lesser compared to the conventional paver block. The compressive strength of RC-0-RF-25, RC-0-RF-50 and RC-0-RF-100 was 9.35%, 14.61% and 22.70% lesser compared to conventional paver block. The reduction in the strength is ascribed to the higher porousness of recycled aggregates owing to the micro-cracks on the smeared mortar from the recycling process [10, 22]. It could be observed that with the use of RFA, the decline in the strength is more compared to RCA owing to the increase in the recycling stages to reduce its particle size. The increase in the recycling stages intensifies the micro-cracks resulting in higher porousness compared to RCA and thus higher reduction in the strength of RAC. However, with 100% of RCA and RFA, the strength of paver block was reduced by nearly 30% compared to conventional paver block. In RAC, apart from the higher porosity, the weak interfacial transition zone (ITZ) in RAC was another predominant factor. NAC comprises NCA, matrix, and an ITZ between matrix and NCA, whereas RAC comprises RCA (RFA), matrix, and two ITZ. The first ITZ is between old and original mortar, and the second is between original mortar and RCA (RFA). The former ITZ in the RAC is the weakest zone ensuing from the micro-cracks on RCA (RFA) that weaken its adherence with the new cement mortar.



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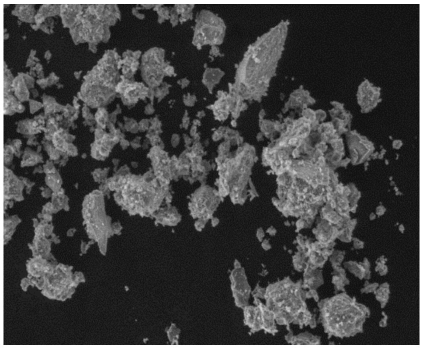

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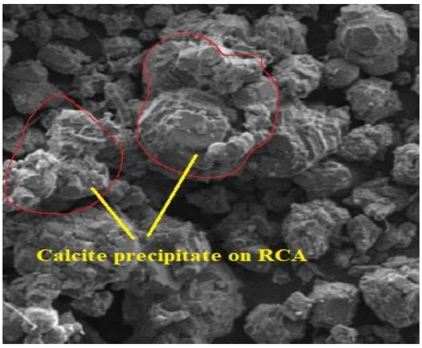

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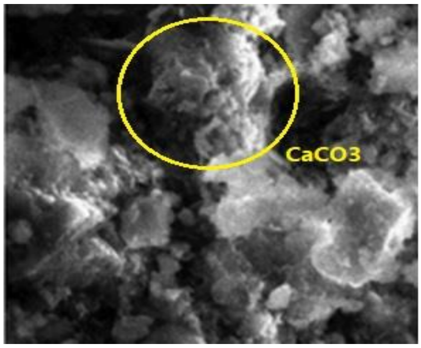

(d)

Fig. 6 (a) SEM image of NCA, (b) SEM image of RCA, (c) SEM image of BRCA, (d) SEM image of CRFA

The carbonation to RFA and bio-deposition to RCA tend to improve the strength of the RAC. The strength of BRC-100-RF-0 was only 6.13% lesser compared to RC-0-RF-0, but 12.26% more compared to RC-100-RF-0 and 25.36% more compared to RC-100-RF-100. The deposition of $CaCO_3$ on the micro-cracks of the RCA reduces the water absorption and improves its strength. The strength of RC-0-CRF-100 was only 8.9% lesser compared to RC-0-RF-0, but 15.07% more compared to RC-0-RF-100 and 23.02% more compared to RC-100-RF-100. The interaction of CO_2 with $Ca(OH)_2$ forms $CaCO_3$ that lessens the water absorption of paver block and improves its strength. It could also be observed that higher efficiency was observed with carbonation treatment rather than bio-deposition treatment. This is because owing to finer particle size with increased crack width on adhered mortar surface of RFA, the rate of impregnation of $CaCO_3$ into the micro-cracks was higher whereas with bio-deposition the crack width is less resulting in $CaCO_3$ deposition on the surface rather than impregnation into the cracks [13, 21].

The tensile strength of the paver block with different mix combinations at 28 days is shown in the Fig. 8. The tensile strength of RC-25-RF-0, RC-50-RF-0 and RC-100-RF-0 was 1.47%, 7.83% and 20.54% lesser compared to the conventional paver block. The compressive strength of the paver block with RC-0-RF-25, RC-0-RF-50 and RC-0-RF-100 was 0.81%, 10.27% and 25.67% lesser compared to conventional paver block. Similar to compressive strength, higher reduction in tensile strength was observed with RFA than RCA. However, the tensile strength of RC-100-RF-100 was reduced by nearly 28% compared to conventional paver block. Similar to compressive strength, the carbonation treatment to

RFA and bio-deposition treatment to RCA tend to improve the tensile strength of the RAC. The tensile strength of BRC-100-RF-0 was only 11.08% lesser compared to RC-0-RF-0, but 10.63% more compared to RC-100-RF-0 and 18.84% more compared to RC-100-RF-100. The strength of RC-0-CRF-100 was only 14.6% lesser compared to RC-0-RF-0, but 13% more compared to RC-0-RF-100 and 15.50% more compared to RC-100-RF-100. The justification of variation in tensile strength is equivalent to that of mechanism behind the improvement in the compressive strength of the paver block.

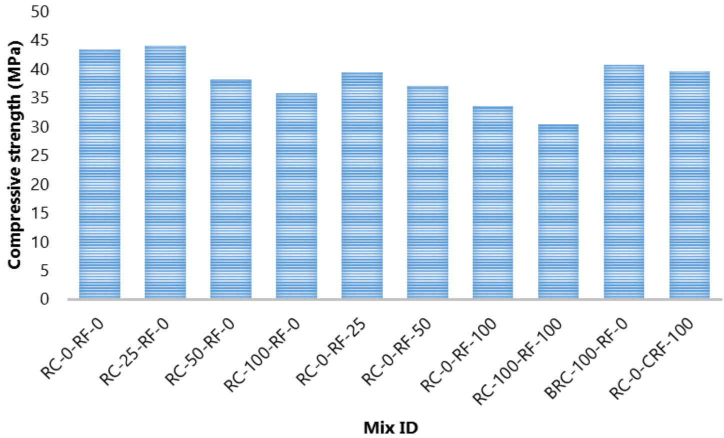

Fig. 7 Compressive strength of the paver block

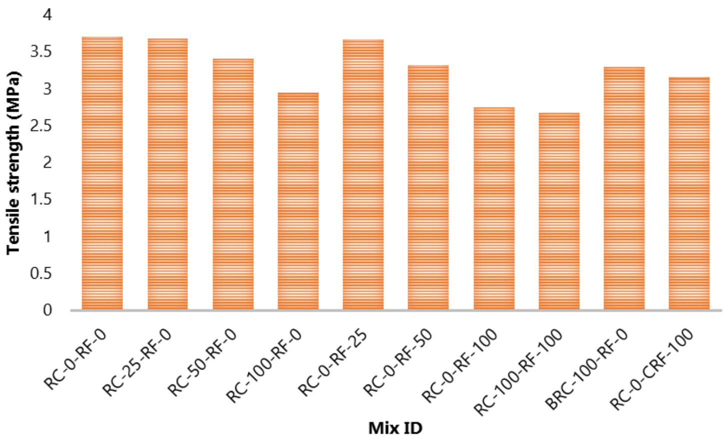

Fig. 8 Tensile strength of the paver block

The flexural strength of the paver block with different mix combinations at 28 days is shown in the Fig. 9. The flexural strength of RC-25-RF-0 was 0.65% more compared to conventional paver block, however the flexural strength of RC-50-RF-0 and RC-100-RF-0 was 6.27% and 9.3% lesser compared to the conventional paver block. The flexural strength of RC-0-RF-25, RC-0-RF-50 and RC-0-RF-100 was 4.76%, 7.57% and 12.12% lesser compared to conventional paver block. Similar to compressive strength and tensile strength, higher reduction in flexural strength was observed with RFA than RCA. However, with 100% of RCA and RFA, the flexural strength of paver block was reduced by nearly 16.23% compared to conventional paver block. Similar to compressive strength, the carbonation treatment to RFA and bio-deposition treatment to RCA tend to improve the flexural strength of the RAC. The flexural strength of BRC-100-RF-0 was only 3.24% lesser compared to RC-0-RF-0, but 6.26% more compared to RC-100-RF-0 and 13.42% more compared to RC-100-RF-100. The strength of RC-0-CRF-100 was only 4.54% lesser compared to RC-0-RF-0, but 7.93% more compared to RC-0-RF-100 and 12.24% more compared to RC-100-RF-100. The justification of variation in flexural strength is equivalent to that of compressive strength and tensile strength of the paver block.

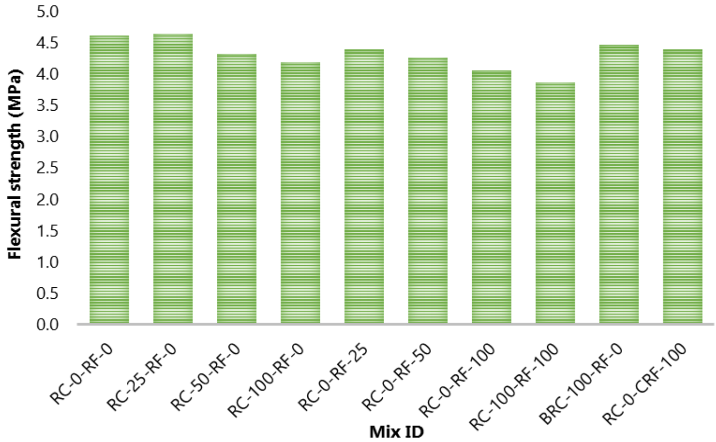

Fig. 9 Flexural strength of the paver block

The water absorption of the paver block with different mix combinations at 28 days is shown in the Fig. 10. The water absorption of RAC paver block with 25%, 50% and 100% of RCA was 4.01%, 9% and 15.17% more compared to conventional paver block. The increase in the water absorption is due to the higher porousness of the RCA and that eventually increases the water absorption of the paver block. The water absorption of RAC paver block with 25%, 50% and 100% of RFA was 5.75%, 18.24% and 22.51% more compared to conventional paver block. The porosity of RFA was higher compared to RCA resulting in higher water absorption. The recycling of concrete fractions of C&D wastes to finer particles increases the crack width ensuing in higher water absorption than RCA [14, 23]. The water absorption of RC-100-RF-100 was 25.19% more compared to conventional paver block. However, after treatments to RFA and RCA, the water absorption of paver block tends to reduce. The water absorption of BRC-100-RF-0 was only 2.86% more compared to RC-0-RF-0 and the water absorption of RC-0-CRF-100 was only 1.24% more compared to RC-0-RF-0. The bio-deposition of RCA precipitates CaCO3 that bonds on the surface of RCA [13, 21] whereas carbonation treatment to RFA produces CaCO3 that impregnates into the micro-cracks of the RFA resulting in the reduced water absorption compared to the paver block with untreated RCA and RFA [2, 4, 12].

The impact energy of the paver block with different mix combinations at 28 days is shown in the Fig. 11. The impact energy of RC-0-RF-0 is 11000 kN.mm and the impact energy of the paver block with 25%, 50% and 100% of RCA was 1.36%, 29.15% and 67% lesser compared to conventional paver block. The reduction in the impact energy of paver block is directly related to the increase in the impact value of the RCA. The impact value of RCA was 34.73% more compared to NCA eventually causing lesser resistance of paver blocks to impact load. The impact energy of paver block with 25%, 50% and 100% of RFA was 2.91%, 30.45% and 69% lesser compared to conventional paver block. The impact energy of RC-100-RF-100 was 70% lesser compared to RC-0-RF-0. The impact energy of paver block with RFA is further reduced compared to those with RCA owing to the reduced impact resistance of RFA compared to RCA [18, 19]. The impact energy of BRC-100-RF-0 and RC-0-CRF-100 was only 18.6% and 17% lesser compared to RC-0-RF-0 and 59.44% and 62.65% more compared RC-100-RF-0 and RC-0-RF-100. The improvement in the impact value of RCA and RFA due to treatments eventually improves the impact energy of the paver blocks for its suitable application.

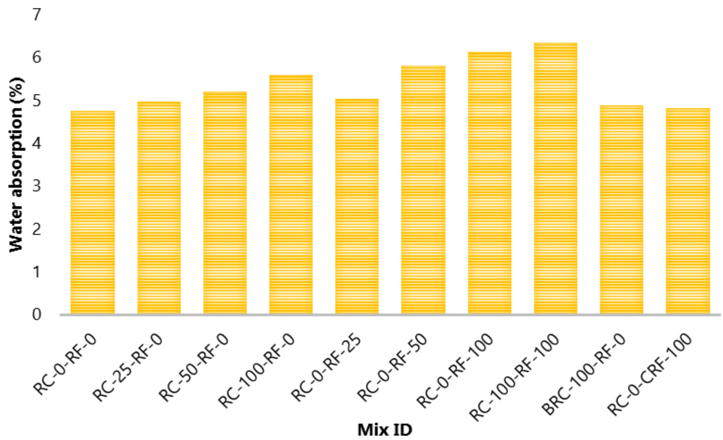

Fig. 10 Water absorption of the paver block

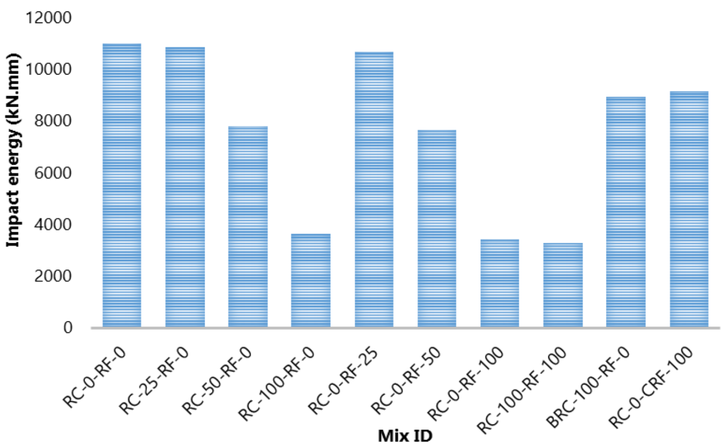

Fig. 11 Impact energy of the paver block

4. Conclusions

In this research, use of NCA, NFA, RCA, RFA, BRCA and CRFA in the production of energy efficient paver blocks were studied and the following inferences were made as follows:

- The specific gravity of RFA and RCA was 6.2% and 13.5% lesser compared to NFA and NCA, however the specific gravity of CRFA and BRCA was 2.41% and 5.57% more compared to RFA and RCA. The bulk density of RCA and RFA was 9.5% and 10.54% lesser compared to NCA and NFA but the bulk density of CRFA and BRCA was 9.7% and 4.15% more compared to RFA and RCA. The water absorption of RFA and RCA was 88.57% and 85.80% more compared to NFA and NCA while the water absorption of CRFA and BRCA was 85.3% and 79.44% lower compared to RFA and RCA, but 21.8% and 30.95% more compared to NFA and NCA. The carbonation treatment to RFA and bio-deposition of RCA seals the micro-cracks on the adhered mortar and improves its properties.

- The compressive strength of paver block with 100% of RCA and RFA was 17.64% and 22.70% lesser compared to the conventional paver block. However, the compressive strength of paver block with 100% of BRCA and CRFA was 12.26% and 15.07% more compared to those with 100% of RCA and RFA. Similar variations in trend were observed with tensile strength and flexural strength.
- The water absorption of paver block with 100% of RCA and RFA was 15.17% and 22.51% more compared to conventional paver block, The water absorption of paver block with 100% of BRCA and CRFA was only 2.86% and 1.24% more compared to conventional paver block.
- The impact energy of paver block with 100% of RCA and RFA was 67% and 69% more compared to conventional paver block, however the impact energy of paver block with 100% of BRCA and CRFA was 59.44% and 62.65% more compared to those with 100% of RCA and RFA.

From the study, it could be inferred that paver block manufacture with 25% of RCA tend to withstand the required 40 MPa strength for medium traffic conditions. However, upon treatments, the paver block prepared with 100% of BRCA and 100% of CRFA exhibit 40.85 MPa and 39.61 MPa which is ample for M40 grade ensuing its suitability in medium volume traffic applications.

Nomenclature

NCA	: Natural coarse aggregate	RCA	: Recycled coarse aggregate
NFA	: Natural Fine aggregate	RFA	: Recycled fine aggregate
BRCA	: Bio-deposited recycled coarse aggregate	CRFA	: Carbonated recycled fine aggregate
XRD	: X-ray diffraction	SEM	: Scanning electron microscope
RAC	: Recycled aggregate concrete	C&D	: Construction & Demolition
TSMA	: Two-stage mixing approach	NMA	Normal mixing approach

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