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Development of Green Paving Blocks Using Recycled Aggregates: An Approach towards Sustainability

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Abstract: *Present study deals with the laboratory investigations for fabrication of M-35 grade concrete paving blocks using recycled coarse and fine aggregates as a replacement of natural aggregates from 25 to 100 % level by weight and results were compared with control. It was observed that properties of recycled aggregates were inferior to natural aggregates. However, the properties of recycled aggregates enhanced after washing. The test results of blocks showed that the replacement of natural aggregates by recycled aggregates at the level of 25 % had little effect on the compressive strength and it decreased beyond these levels. As compare to natural aggregates, the flexural strength of paving blocks was higher using recycled aggregates. Durability performance of blocks like water absorption, density and abrasion resistance was also improved using washed recycled coarse aggregates. Petrographic image analysis showed improvement in the interface of washed recycled coarse aggregates and surrounding matrix.*
Keywords: *recycled coarse aggregates, paving blocks, compressive strength, flexural strength, C & D waste, natural aggregates*

I. Introduction

With the increase in population and urbanization, the demand of raw materials such as cement and aggregates has increased many folds in the construction industry all over the world. The high use of these raw materials has created a significant impact on environment and society [1]. The mission of sustainable development has led to a pressure demand for improving environmental performance in the construction process by reducing consumption of natural resources extracted. Further, it has been recognized that wastes from construction and demolition (C & D) sectors are of large volumes and this volume is increasing every year [2]. Dumping of C & D wastes for landfill causes shortage of dumping space and is an environmental hazard in cities. Utilization of demolished wastes offers not only the solution of disposal problems, but also help to conserve natural resources for meeting increased demand of aggregates and save energy. C & D wastes are normally composed of concrete rubble, bricks and tiles, sand and dust, timber, plastics, cardboard and paper and metals. Concrete rubble usually constitutes the largest proportion of C & D wastes which after separation, crushing and grading can be utilized for as a substitute for natural coarse aggregate in concrete or as a sub base layer in pavements. This type of recycled material is called recycled aggregates.

The interest in using recycled aggregates derived from construction and demolition wastes is growing all over the world [3-4]. According to 2010 European Aggregate Association Annual Review report [5], Germany is the greatest producer of recycled aggregate recycled aggregate, with a production of about 60 million tonnes followed by UK, Netherlands and France with about 49, 20 and 17 million tonnes respectively. Indeed, in some European countries, a large proportion of aggregates come from secondary sources and recommendations for the use of recycled aggregates has been set out by RILEM [6]. The recycled aggregate has been successfully utilized by various workers [7-13] for production of environmental friendly concrete for construction having similar mechanical and durability properties to those of conventional concrete.

In India, about 14.5 MT of solid wastes are generated annually from construction industries and about 25 % of it is recycled and utilized in building materials [14]. On the other hand, being a developing country, the

need of buildings, highways, bridges, power plants etc. are increasing in a big way. To meet this rapid infrastructural development, enormous amount of construction materials like natural coarse and fine aggregate is required. Legislation against quarrying of natural aggregates and restriction in land filling and deposition of C & D wastes, however, has increased interest in utilization of these wastes in construction sector.

The limited use of recycled aggregate in structural concrete is mainly due to old adhered mortar responsible for its low density, high porosity and higher values of water absorption in comparison to natural aggregates [15]. In recent years, advances in utilization of recycled aggregates to safeguard the environment has resulted in development of alternative value added construction materials like concrete masonry blocks and bricks [16-19]. An attempt has been made by Collins et al. [16] to fabricate blocks for a beam-and-block floor system using 25-75 % of recycled aggregates as replacement of natural aggregates. A compressive strength of 6.75 MPa and transverse strength of 1.23 MPa were observed for the blocks with 75 % of the recycled aggregates. Poon and Chan [17] investigated the use of fine crushed clay bricks in the production of concrete paving blocks using recycled aggregates. The results indicated that the incorporation of 25-75 % crushed clay brick reduced the density, compressive strength and tensile strength of the resulting paving blocks. Poon et al. [18] reported that small percentages of substitution of coarse and fine natural aggregates by recycled aggregates had smaller minor effect on the compressive strength of blocks produced but the same would decrease at high levels of replacement. The studies carried out by Poon et al. [19] show that the low grade recycled aggregates obtained from the construction waste sorting facility has potential to be used as aggregates for making non-structural precast concrete blocks. The 50 % was the optimal percentage observed for replacement of natural fine aggregates with recycled fine aggregates.

The literature review reveals that most of the studies have been carried out using coarse recycled aggregates for development of concrete paving blocks. However, the very few studies have been performed for the utilization of fine recycled aggregates in fabrication of blocks. This is mainly due to the high porosity of the fine recycled materials which is responsible for the reduction in the performance of composites. [13]. Hence, there is a need to carry out systematic studies for utilization of recycled fine aggregates (RFA) in order to reduce their environmental impact and simultaneously reducing the extraction of sand form river beds. To fulfill the above objective, the present laboratory study has been undertaken for replacement of natural coarse and fine aggregates with recycled aggregates in the fabrication of concrete paving block (M-35 grade). The engineering and durability properties of concrete blocks prepared with natural aggregates have been compared with blocks using washed and unwashed recycled coarse aggregates. Petrographic image examination has been done to study the characteristics of inter-transition zone between recycled coarse aggregates and surrounding matrix.

II. Materials And Methods

2.1. Cement

Ordinary Portland Cement (OPC) of 43 Grade conforming to IS: 8112:1989 [20] was utilized as binder with surface area of 3220 cm^2/g and specific gravity of 3.14. Typical chemical composition of OPC analyzed by WDXRF (S8 Tiger, Brucker, Germany) has been shown in Table 1.

Table 1: Typical composition of ordinary Portland cement

Chemical Composition (%)											
CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	TiO_2	BaO	P_2O_5	Others
64.34	19.90	4.30	4.24	2.88	2.04	1.05	0.31	0.33	0.25	0.13	0.23

2.2. Coarse aggregates

The locally available natural crushed stone, generally of quartzite type has been used as natural coarse aggregate (NCA) of maximum 10 mm size satisfying the grading requirements of IS 383: 1970 [21]. Samples of demolition waste were collected from sorting facility of Municipal Corporation of Delhi, India which consists of concrete, bricks, stones, gravel, silt etc. After sorting, concrete waste was crushed in a jaw crusher to obtain a well graded recycled coarse aggregate (RCA) for maximum 10 mm to 4.75 mm nominal size as per IS 383: 1970. To obtain the washed aggregate, recycled aggregates were immersed in water for two hours and then washed two times manually in water for removal of adhered mortar, clay, girt, dust etc. The particle size distribution along with physical and mechanical properties of natural, washed and unwashed recycled aggregates determined as per IS 2386:1963 [22] are given in Table 2.

Table 2: Physical and mechanical properties of natural and recycled coarse aggregates.

Parameters	Natural aggregate	Recycled aggregate	
		Unwashed	Washed
Flakiness index (%)	9.11	13.51	11.46
Elongation index (%)	12.46	17.40	15.52
Water absorption (%)	0.40	4.72	3.50
Specific gravity	2.66	2.36	2.46
Bulk density (kg/l)	1.560	1.35	1.36
Crushing value (%)	13.21	21.74	18.45
Impact value (%)	9.54	16.34	12.12
Particle size distribution (%)			
12.5 mm	100	100	100
10 mm	85.56	88.55	90.75
4.75 mm	8.98	9.92	9.09
2.36 mm	2.21	3.58	2.86

2.3. Fine aggregates

Local river sand complying with the particle size requirements of IS 383: 1970 were used as natural fine aggregates (NFA) for fabrication of blocks. The fine fraction passing from 4.75 mm sieve obtained during crushing of waste concrete was used as recycled fine aggregates (RFA) for replacement of natural fine aggregates. The particle size distribution of natural and recycled fine aggregates have been shown in Fig. 1 along with minimum and maximum limits of grading specified in IS: 383: 1970. The physical properties of fine aggregates have been given in Table 3.

2.4. Mix proportions

A total of eight concrete mixtures were tried for fabrication of two layered interlocking paving blocks of 200 mm x 160 x 75 mm size using unwashed and washed recycled coarse aggregates in series I and II respectively. All the trial mixtures were expected to achieve target strength of 36.7 MPa (M-35 Grade) at the age of 28 days. The mix compositions and their designations used for control, unwashed and washed recycled coarse aggregates were given in Tables 4 and 5 respectively. Control (A0) specimens of blocks were prepared using 100 % natural coarse and fine aggregates and w/c ratio was kept 0.32 in both the layers (Table 4). The mix composition of control showed that top layer consisted of cement and fine aggregates in the proportion of 33.3: 66.6 % by weight, while in bottom layer, the proportion of cement: natural fine aggregates: natural coarse aggregates were 20: 20: 60 % by weight. In series I, the mixes containing unwashed recycled coarse aggregates were design as B-25, C-50, D-75 and E-100 for 25, 50, 75 and 100% replacement of natural aggregates respectively. In top layer, natural fine aggregate was replaced by recycled fine aggregate from 25 to 100 % by weight and in bottom layer only natural coarse aggregate was replaced by recycled coarse aggregates from 25 to 100 % by weight keeping the percentage of natural fine aggregates unchanged. In series II, using washed aggregates, similar mix proportions as in series I were used for both the layers and mixtures were designated as BW-25, CW-50, DW-75 and EW-100 for 25 to 100 % level of replacement. Zero slump concrete mixtures were prepared for fabrication of paving blocks to overcome the disadvantages of high water absorption. The free w/c ratio was varied 0.36 to 0.46 and 0.34 to 0.45 for series I and II for unwashed and washed coarse aggregates respectively.

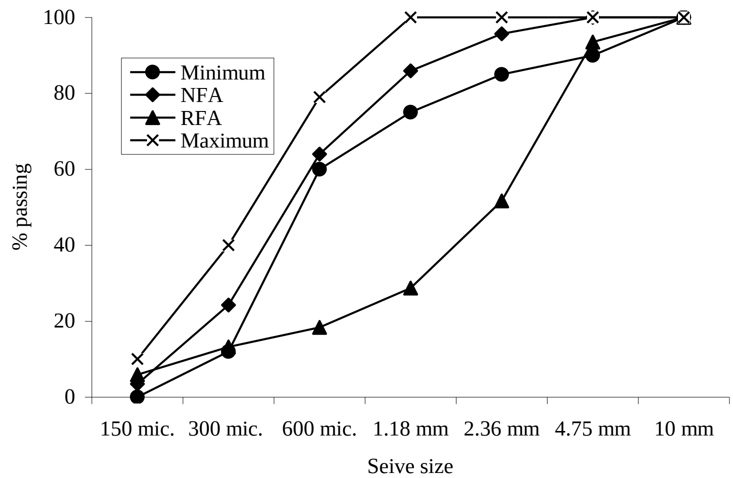

Fig.1: Particle size distribution curves of fine aggregate

Table 3: Physical and mechanical properties of natural and recycled fine aggregates

Parameters	Natural fine aggregate	Recycled fine aggregate
Fineness modulus	2.26	4.10
Specific gravity	2.68	2.49
Waterabsorption (%)	0.62	5.90
Density (kg/m^3)	2250	2090

2.5. Mixing, casting and curing

The fabrication of paving blocks was carried out using compaction method following the procedure and specifications described in IS: 15658: 2006 [23]. For preparation of top layer of the block, cement, fine aggregates and water were mixed in a pan as per proportions shown in Tables 4 and 5. The mixing for bottom layer was performed in a drum mixer using conventional method. The weighed quantities of cement and aggregates were poured in the drum and allowed to dry mix for two minutes. Subsequently water was added to the bulk materials as per mix design and the mixture was further mixed for two more minutes before casting. About 1880 g mixture for top layer was poured into the steel block and spread on the surface followed by about

3000 g material for bottom layer filled in the steel block. A hydraulic pressure of 50 tonnes was applied for 30 seconds on the mixture for compaction. After releasing the pressure, the paving block was removed from the mould, placed at room temperature for 24 h and then cured at a RH of over 90 % at room temperature (25±2^{o}C) for 28 days. The cured blocks were tested for physical and mechanical properties.

Table 4: Mix proportion of paving blocks using unwashed recycled coarse recycled aggregates (series I).

Mix designation	Proportion (%) by weight				
Cement	NFA	RFA	NCA	RCA	w/c ratio
A-0 (control)					
Top layer	33.3	66.7	---	---	0.32
Bottom layer	20.0	20.0	---	60.0	0.32
B-25					
Top layer	33.3	50.0	16.7	---	0.36
Bottom layer	20.0	20.0	45.0	15.0	0.36
C-50					
Top layer	33.3	33.3	33.3		0.39
Bottom layer	20.0	20.0	30.0	30.0	0.39
D-75					
Top layer	33.3	16.7	50.0	---	0.43
Bottom layer	20.0	20.0	15.0	45.0	0.43
E-100					
Top layer	33.3	---	66.7	---	0.46
Bottom layer	20.0	20.0	60. 0		0.46

* NFA: natural fine aggregates; RFA: recycled fine aggregates; NCA: natural course aggregates; RCA: recycled coarse aggregates

2.6. Physical properties

The physical properties of paving blocks like density, water absorption and abrasion resistance were determined after 28 days curing period. The density of paving blocks was determined using water displacement method in accordance with BS 1881-114: 1983 [24] for hardened concrete.

Water absorption is the measure of permeability and porous nature of hardened concrete and is determined after 28 day of curing as per method described in IS: 15658:2006 [23]. The blocks of all mixes were completely immersed in water at room temperature for 24 h. After removal from water, blocks were allowed to drain for 1 min by placing them on a 10 mm wire mesh, and visible water was removed with a damp cloth and immediately weighed. Subsequent to saturation, the blocks were dried in ventilated oven at 105±2^{o}C for 24 h. The blocks were weighed after cooling at room temperature to calculate the water absorption and the average of three specimens was reported.

The abrasion resistance of dried blocks was determined as per procedure described in IS: 1237:2012 [25] using an abrasion machine. Square shaped specimens measuring 71±0.5 mm were cut from the block specimens and oven dried at a temperature of 105^{o}C. The weight of the specimens was determined both prior and after completion of four cycles. The grinding path of the disc of the abrasion testing machine was evenly strewn with 20 g of standard abrasive powder and the specimens were the holding device such that the testing surface faces the grinding disc. The specimens were centrally loaded with 294±3N. The grinding speed of the disc was kept at 30 rpm and stopped after one cycle of 22 revolutions. After cleaning the disc and contact face for abrasive, the specimens were turned at 90^{o} in clock wise direction and 20 g of abrasive powder was evenly strewn on the testing track before starting the next cycle. Loss in the abrasive wear of the specimen after 16 test cycles was calculated and reported.

2.7. Mechanical properties of concrete

Mechanical properties like compressive strength and flexural strength was determined according to the procedure described in IS: 15658: 2006 [23] after 28 days curing and the average values of three specimens tested for each mix were reported in the results. Before determination of compressive strength, all the specimens were stored for 24 h in water at room temperature of 25±2^{o}C, air dried and tested. A compression testing machine equipped with two steel bearing blocks for holding the specimens was used for determination of compressive strength. The upper face of the blocks was capped by 4 mm thick plywood sheet of size larger than the blocks by a margin of 5 mm from all the edges. The specimens were kept aligned with those of bearing plates and a compression load of 15 N/mm^{2}/min was applied to the face with a area of 200 mm x 160 mm until no greater load sustained by the specimen. The maximum load applied was recorded and the apparent

Table 5: Mix proportion of paving blocks using washed recycled coarse recycled aggregates (series II)

Mix designation	Proportion (%) by weight				
Cement	NFA	RFA	NCA	RCA	w/c ratio
A-0 (control)					
Top layer	33.3	66.7	---	---	0.32
Bottom layer	20.0	20.0	---	60.0	0.32
BW-25					
Top layer	33.3	50.0	16.7	---	0.34
Bottom layer	20.0	20.0	45.0	15.0	0.34
CW-50					
Top layer	33.3	33.3	33.3	---	0.37
Bottom layer	20.0	20.0	30.0	30.0	0.37
DW-75					
Top layer	33.3	16.7	50.0	---	0.41
Bottom layer	20.0	20.0	15.0	45.0	0.41
EW-100					
Top layer	33.3	66.7	---	---	0.45
Bottom layer	20.0	20.0	---	60.0	0.45

compressive strength was calculated by dividing the maximum by plain area of the block. The corrected compressive strength has been calculated by multiplying the apparent strength with correction factor for thickness and arris/chamfer of paving block according to IS: 15658.

Flexural strength was determined using a UTM of maximum 30 kN load capacity as per the procedure of IS: 516: 1959 [26] and the specimens were prepared as in case compressive strength [23]. The supporting rollers having a diameter of 30 mm were used with a supporting span of 150 mm. The load was applied from top of the specimen in the form of a simple beam loading through a roller placed midway between the supporting rollers. The applied load was increased at a rate of 6 kN/min until the specimens failed and the maximum load applied was recorded to calculate flexural strength of blocks.

2.8. Petrographic Image Analysis

The petrographic studies were performed to evaluate the micro cracking and characteristics of the aggregate-cement mortar interface using optical microscope (ZEISS, AxioCam ERc 5s, German). For this study, thin section (0.03 mm) of the blocks were prepared using a diamond cutter of fractured surfaces at the point of failure during determination of compressive strength.

III. Results And Discussion

3.1. Properties of coarse aggregates

Particle size distribution of coarse aggregates (Table 2) shows that all the aggregates have been properly graded and satisfy the IS: 383 requirements. The results clearly indicate low density, low specific gravity and high water absorption of recycled coarse aggregates as compared to natural aggregates as well as the mechanical properties like crushing and impact values of unwashed recycled aggregates are also higher. The deterioration in physical and mechanical properties is due to presence of adhered mortar which is light and porous in nature. Therefore the recycled aggregate may be characterized as inferior quality aggregate by being weaker than the normal aggregate [27-28]. However, it has been observed that after washing, recycled coarse aggregates shows significant improvement in all the properties due to the removal of old adhered mortar.

3.2. Properties of fine aggregates

Grading curves (Fig. 1) show that particle size distribution of natural sand is complying with the limits of IS: 383: 1979 and conform to Zone III being relatively finer. While, the values of particle size distribution for recycled fine aggregates are not within the range of IS: 383 being coarser than the natural sand and the same is also justified by high value of fineness modulus shown in Table 3. The recycled fine aggregate shows low specific gravity, density and high water absorption as compared to natural fine aggregates (Table 3).

3.3. Visual inspection

After 28 days of curing period, visual inspection of blocks was carried out in natural day light prior to the tests for other properties. Visual inspection revealed that all paving blocks were sound and free of cracks. No other visual defects were observed which may interfere with proper paving of the unit or impair the strength or performance of pavement constructed with the paving blocks. The bottom layer was showing proper bonding with top layer in all the paving blocks. The photograph of fabricated paving blocks has been shown in Fig. 2.

Fig. 2: Photograph of fabricated paving blocks at the age of 28 days

3.4 Density of blocks

The test results for density of blocks have been shown in Table 6 which indicates that the density decreases up to 7 % with an increase in recycled aggregates content from 25 to 100 % as compared to control specimens. The reason for lower density of recycled aggregates may be attributed to the presence of porous adhered mortar on the surface of recycled aggregate [27]. This mortar lowers the specific gravity of the aggregates as compared to natural aggregates. However, paving blocks prepared with washed recycled aggregates (series II) show improvement in density and it is about 2 to 4 % higher than those prepared with unwashed recycled aggregates (series I).

Table 6: Test results of physical properties of paving blocks at the age of 28 days

Mix designations	Density (kg/m^3)	Water absorption (%)	Δ_1 (±0.2 mm)	Δ (%)
Control	2210	1.5	2.2	----
Series I				
B-25	2153	3.0	2.7	22.72
C-50	2115	3.5	3.1	40.90
D-75	2092	3.8	3.3	50.00
E-100	2045	4.2	3.5	59.00
Series II				
BW-25	2191	2.0	2.4	09.09
CW-50	2165	2.8	2.6	18.18
DW-75	2152	3.2	2.9	31.18
EW-100	2128	3.6	3.2	45.45

3.5. Water absorption of blocks

Table 6 depicts that water absorption of series I and II mix specimens is higher than the control specimens. Data reveals that the water absorption of series II specimens varies from 2 to 3.6 % with increase in recycled aggregates content from 25 to 100 % and is significantly lower (15-34 %) than blocks prepared under series I. However, it has been observed that all mix compositions are satisfying the requirements of IS: 15658 (<6 %) for water absorption.

3.6 Abrasion resistance of blocks

The results of the abrasion resistance test of blocks have been presented in Table 6 (Δ_1 and Δ being respectively the absolute and relative thickness loss of wearing layer in comparison to the control) A perusal of the Table 6 shows that paving blocks prepared with recycled aggregates show higher abrasion value (2.7 to 3.5 ± 0.2 mm) than control specimens (2.2 ± 0.2 mm) and it is a function of recycled aggregate content. However, the blocks prepared using washed coarse aggregates (series II) show reduced abrasion (13-18 %) as compared to blocks prepared with unwashed aggregates due to removal of porous adhered mortar. For mixes using recycled coarse aggregates, the increase in effective water/cement ratio with the increase in replacement level of natural c oarse aggregates increase the porosity of the paste, causing a reduction in the abrasion resistance. Similar findings have also been reported by Alves et al. [12] using recycled sanitary ware aggregates. However, results obtained by de Brito et al. [29] are in disagreement with the results of this study with the results of this study with the results of this study when replacing the natural coarse aggregates with recycled aggregates of ceramic origin. A possible explanation is the fact that the authors kept constant the apparent w/c ratio for all the compositions produced, which due to the high water absorption of the recycled aggregates, decreased the effective w/c ratio, reducing the porosity of the mortar.

3.7. Compressive strength

The compressive strength of concrete paving blocks determined after 28 days of curing has been shown in Fig. 3. In general it depicts that the compressive strength is lower for blocks using recycled aggregates content as compared to control specimens and it decreases with increase the replacement percentage from 25 to 100 % by weight of recycled aggregates content. This may be due to the extra amount of water added in mixtures containing recycled aggregates in addition to their inferior quality. Although, the results show that a 25 % of replacement of natural aggregates by recycled aggregates had little effect on the compressive strength of paving blocks, but beyond this level, a systematic decrease in strength has been observed and similar observations has also been reported by earlier workers [30] for development of bricks and blocks using recycled aggregates. However, the blocks using washed recycled aggregates (series II) shows about 7-10 % higher strength than unwashed recycled aggregates (series I) and this may be due to the removal of old and weak mortar after washing. Further, it has also been observed that the compressive strength of all the blocks prepared using recycled aggregates meet the 28-day target strength of 36.7 MPa required for light traffic purpose as per IS: 15658. The 28 days strength of mixes BW-25 (45.2 MPa) using washed recycled aggregates is comparable to that of control mix (46.5 MPa). The strength of blocks prepared with unwashed recycled aggregates is about 9-21 % less as compared to control specimens. The mixtures B-25, BW-25, CW-50, DW-75 and EW-100 can also be recommended for medium traffic purpose as these are satisfying the minimum strength requirements of M-40 grade as per IS:15658.

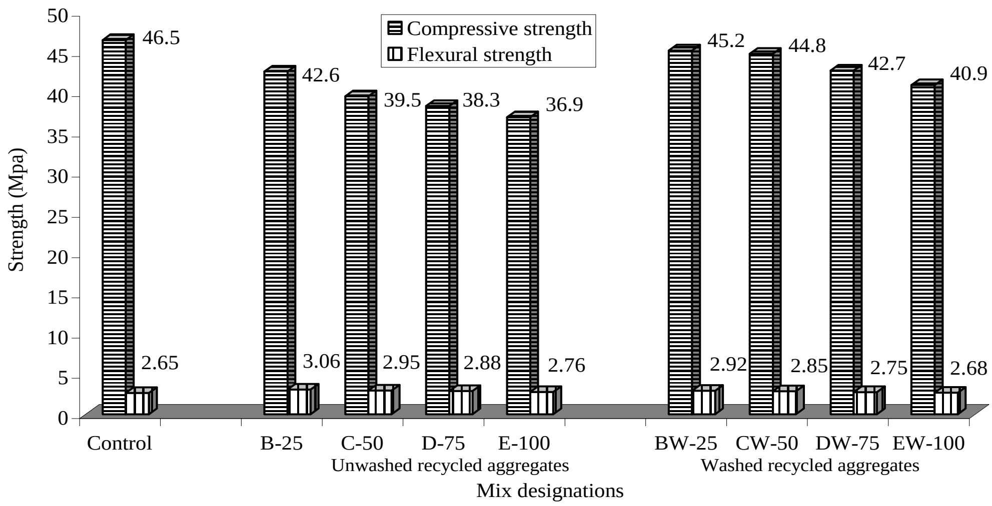

Fig. 3: Mechanical strength of pavers block at the age of 28 days.

3.8. Flexural strength

The 28-day flexural strength of paving blocks (Fig. 3) using recycled aggregates in series I and II are higher than control specimens. Further, it is observed that flexural strength decreases with increase in recycled aggregate content. High flexural strength with recycled aggregates may be accompanied with the angular shape and rough surface of the recycled aggregates which is generally beneficial for good bond between the crushed aggregates and the cement paste as is reported by Dedieb and Kenai [2].

3.9. Petrographic Study

Thin sections of the concrete specimens have been examined and evaluated to study the micro textural composition and performance of concrete along with characteristics of inter-transition zone between the coarse aggregates and the surrounding matrix (cement mortar) in concrete paving blocks. The petrographic images for natural, unwashed and washed recycled coarse aggregates mixes are shown in Figs. 4-6. Fig. 4 shows that natural coarse aggregates mix consist of angular fragments petrographically belonging to mainly quartz (Qr)

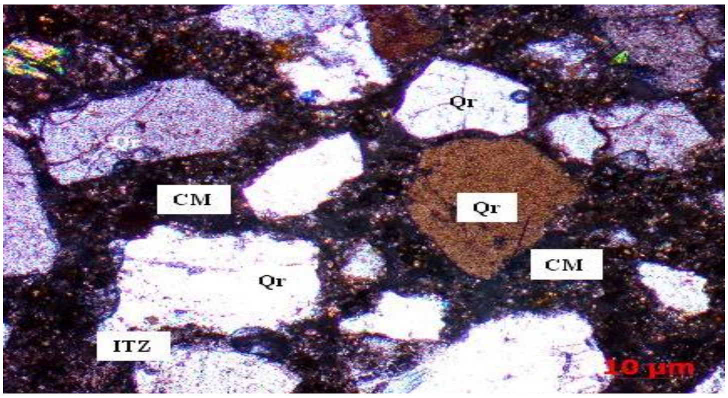

Fig.4: Petrographic image of concrete containing natural aggregates
(CM-cement mortar; Qr-quartz; ITZ-inter transition zone)

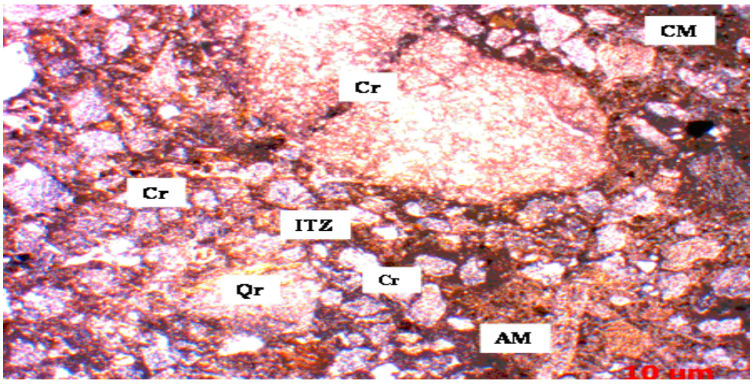

Fig.5: Petrographic image of concrete containing unwashed recycled coarse aggregates
(CM-cement mortar; Qr-quartz; ITZ-inter transition zone; AM-adhered mortar; Cr-cracks)

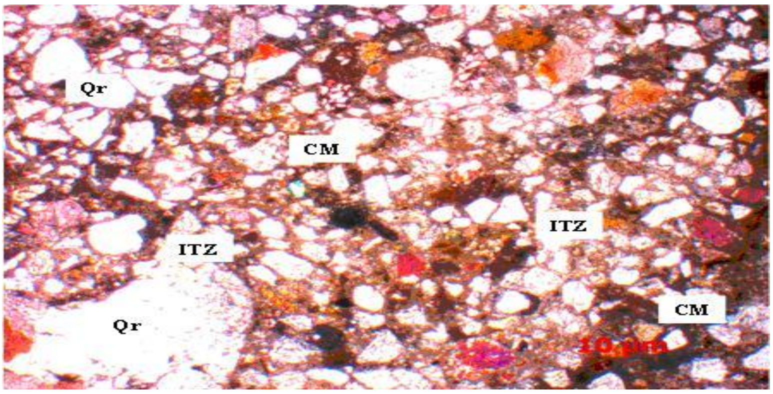

Fig.6: Petrographic image of concrete containing washed recycled coarse aggregates
(CM-cement mortar; Qr-quartz; ITZ-inter transition zones)

Rocks containing microcrystalline quartz with mortar textures and undulatory extinction. It is observed that in case of natural aggregates containing mix, the interface of coarse aggregates and surrounding matrix is quiet strong and no signs of cracking (Cr) of aggregates at the interface are visible. The various hydration phases formed at the surface of aggregate is intact and providing strength to the concrete. The image analysis of unwashed recycled coarse aggregate (series I) specimen (Fig. 5) shows that recycled aggregates are covered with porous old adhered mortar (AM) and interfacial bond is not much strong due to presence of adhered mortar forming weak linkage with the aggregates. Cracks (Cr) are clearly visible at the inter-transition zone (ITZ) of old mortar and recycled aggregates responsible for lower strength. Fine aggregates adhered to recycled coarse aggregates consist of predominantly mono-mineral quartz that forms 80–95% of the fine-grained fraction. Image analysis (Fig. 6) of washed recycled coarse aggregates mix (series II) depicts that after washing, recycled aggregate is free of old adhered mortar and angularity is comparable to that of natural coarse aggregates. The interfacial bond of washed recycled aggregates with surrounding matrix is stronger and crack free as compared to unwashed coarse aggregates mix.

IV. Conclusions

Laboratory trials were carried out for fabrication of paving blocks from recycled coarse aggregates as a replacement of natural aggregates at levels of up to 100 % by weight and tested for mechanical and durability properties for application purpose. Based on the results, the following conclusions can be drawn:

1. The characterization of recycled coarse aggregates showed that it was of inferior quality as compared to natural coarse aggregate and the properties get improved after washing due to removal of weak and porous adhered mortar.
2. Density of the blocks in series I and II were 7 and 4 % lower respectively than the control specimens due to the reduction in density of recycled aggregates.
3. Water absorption of blocks prepared in series II was significantly lower (15-34 %) than blocks prepared in series I. However, all mix compositions were satisfying the requirements of Indian Standards for water absorption.
4. Abrasion resistance was negatively affected by the incorporation of recycled coarse aggregates and linearly decreased with increase in replacement ratio.
5. The compressive strength of the blocks decreased with an increase in recycled aggregates content and was lower than control using natural aggregates. However, the blocks using washed recycled aggregates showed about 7-10 % higher strength than unwashed recycled aggregates. The compressive strength of all the blocks prepared using recycled aggregates meet the 28-day target strength of 36.7 MPa (M-35 Grade) required for light traffic purpose. The mixtures containing washed recycled aggregates can also be recommended for medium traffic purpose as these are satisfying the minimum requirements of M-40 Grade as per Indian Standard.
6. The flexural strength of paving blocks using recycled aggregates were higher than control specimens and it decreased with increase in recycled aggregate content.
7. Sharp cracks visible in petrographic image analysis showed that old and weak mortar adhered on the surface of the unwashed recycled aggregate was responsible for weak interfacial zone of aggregate and surrounding matrix.
8. Improvement in the over all performance of the paving blocks using washed recycled coarse aggregates was due to the removal of weak and porous mortar. The results showed that the recycled aggregates have the potential to be used for fabrication of non structural precast paving blocks.

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References

[1]. T.C. Hansen, and S.E. Hedegard, . Properties of recycled aggregate concretes, ACI Journal, 81(1), 1984, 21-26.
[2]. F. Debieb, S. Kenai, The use of coarse and fine crushed bricks as aggregates in concrete, Constr Build Mat 22(5), 2008, 886-893.
[3]. T.C.Hansen, RILEM Report. Recycling of demolished concrete and masonry. E&FN Spoon, UK, 1996.
[4]. RILEM Report 22, Sustainable raw materials-construction and demolition wastes. Edited by Ch F Hendriks, HS Pietersen, The publishing Company of RILEM, 2000.
[5]. European Aggregates Association, Annual review 2011-2012. Brussels, Belgium; 2012.
[6]. RILEM 121-GRG, Specification for concrete with recycled aggregates, Mater Struct, 27(173) 1994, 557-559.
[7]. I. Abdul Rahman, H. Hamdam, and A.M.Ahmad Zaidi, Assessment of Recycled Aggregate Concrete, Modern Applied Science, 3(10), 2009, 47-54.
[8]. A. Rao A, K.N. Jha, and S. Misra, Use of aggregates from recycled construction and demolition waste in concrete, Resour Conserv Recycl, 50(1), 2007, 71-81.
[9]. S. Marinkovic, V. Radonjanin, M. Malesev, and I. Ignjatovic. Comparative environmental assessment of natural and recycled aggregate concrete, Waste Management, 30(11), 2010, 2255-2264.
[10]. K.K. Sagoe-Crentsil, T. Brown, and A.H. Taylor, Performance of concrete made with commercially produced coarse recycled concrete aggregate, Cem Concr Res, 31(5), 2001, 707-12.
[11]. M.B. Leite, Evaluation of the mechanical properties of concrete made with aggregates recycled from construction and demoliotion waste, Porto Alegre, 2001, 390 [in Portugese].
[12]. A.V. Alves, T.F. Vieira, J. de Brito, and J.R., Correria, Mechanical properties of structural concrete with fine recycled ceramic aggregates, Constr Build Mat 64 (August), 2014, 103-113.
[13]. L. Evangelista, J. de Brito, and J.R. Correria, Durability performance of concrete made with fine recycled concrete aggregates, Cem Concr Comp, 32(1), 2010, 9-14.
[14]. A. Pappu, M. Saxena M, and S.R. Asolekar, Solid waste generation in India and their recycling potential in building materials, Build and Environ, 42(6), 2007, 2311-2320.
[15]. Application of recycled aggregate concrete for structural concrete, part-1: experimental study on the quality of recycled aggregate and recycled aggregate concrete. In: Dhir DK, Handerson NA, Limbachiya MC, editors. Proceedings of the International Conference on the Use of Recycled Concrete Aggregates. UK:Thomas Telford, 1998. P.55-68.
[16]. R.J.Collins, D.J.Harris, and W. Sparkes, Blocks with recycled aggregates: Lbeam-and-block floors, BRE report, UK: Building Research Establishment, 1998.

[17]. C.S. Poon, and Dixon Chan, Paving blocks made with recycled concrete aggregate and crushed clay brick, Constr Build Mat, 20(8), 2006, 569-77.
[18]. C.S. Poon, D. and Dixon Chan, The cause and influence of self cementing properties of fine recycled concrete aggregates on the properties of unbound sub-base, Waste Management, 26(10), 2006, 1166-1172.
[19]. C.S. Poon, Sc. Kou, H.W. Wan, and M. Etxeberria. Properties of concrete blocks prepared with low grade recycled aggregates, 29(9), 2009, 2369-2377.
[20]. IS 8112: Specification for 43 grade ordinary Portland cement. India; Bureau of Indian Standards; 1989.
[21]. IS 383: Specification for coarse and fine aggregates from natural sources for concrete. India; Bureau of Indian Standards; 1970.
[22]. IS 2386: Methods of test for aggregates for concrete Part I-IV. India; Bureau of Indian Standards; 1963.

[23]. IS 15658: Precast concrete blocks paving-specification. India; Bureau of Indian Standards; 2006.
[24]. BS1881-114: Testing concrete. Methods for determination of density of hardened concrete. British Standards Institution, 1983.
[25]. IS 1237: Cement Concrete Flooring Tiles –Specification. India; Bureau of Indian Standards, 2012.
[26]. IS 516: Method of Tests for Strength of Concrete. India; Bureau of Indian Standards, 1959.
[27]. S. Ismail, and M. Ramli, Engineering properties of treated recycled concrete aggregate (RCA) for structural applications, Constr Build Mater, 44(7), 2013, 464-76.
[28]. M. Chakradhara Rao, S. Bhattacharyya, and S. Barai, Influence of field recycled coarse aggregate on properties of concrete, Mater Struct , 44(1), 2011, 205-220.
[29]. J. de Brito J, Pereira AS, and J.R. Correia, Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates. Cem Concr Comp 2005;27:429-33.
[30]. C.S. Poon, S.C. Kou SC, and L. Lam, Use of recycled aggregates in molded concrete bricks and blocks. Constr Build Mat, 16(5), 2002, 281-289.