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CHARACTERIZATION OF CRUSHED BRICKS AGGREGATE AS A REPLACEMENT OF NATURAL COARSE AGGREGATE IN CONSTRUCTION OF ROLLER–COMPACTED CONCRETE PAVEMENT

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Abstract: This study presents the results of a laboratory work carried out at to evaluate the properties of roller compacted concrete made with crushed bricks for pavement application. The bricks materials were crushed in order to obtain useable coarse aggregate sizes as specified in relevant standard specifications. The properties investigated were the aggregate impact value, aggregate crushing value, Los Angeles abrasion value, specific gravity and water absorption. The coarse aggregate (crushed granite) was replaced with crushed bricks at 0%, 20%, 40%, 60% and 80% by weight. The concrete mixtures were batched at 1: 3.5: 3 mix ratio of cement, fine aggregate and coarse aggregate. Workability and the density of fresh concrete, and the compressive strength, splitting tensile strength, and flexural strength of hardened concrete were investigated. Compressive strength was measured at 3rd, 7th, 14th, 28th, 56th, and 91st days. The results of the laboratory tests carried out on concrete produced with crushed bricks aggregates were compared with the results of laboratory tests on non–crushed brick concrete specifications and with the specifications of relevant standards and manuals. The results indicate that crushed bricks aggregates can be used as partial replacement of natural coarse aggregates in roller–compacted concrete pavement construction and maintenance.

Keywords: Concrete Pavement, Compressive Strength, Flexural strength, Crushed Bricks Aggregate, Natural coarse aggregate, Roller Compacted

1. INTRODUCTION

Use of roller compacted concrete (RCC) for pavement applications is growing. This material offers great technical and economic benefits. Roller–compacted concrete (RCC) is a special mixture of controlled, dense–graded aggregates, Portland cement and possibly pozzolans (fly ash), mixed with just enough quantity of water so that it could self–stand when paved using either a slip–form paver (without needle vibrators) or asphalt paver. It is usually compacted using vibratory roller. Once compacted to the required density, RCC is cured using conventional methods. It has constituent materials similar to routine concrete, but is handled more like granular materials or soils. Due to dense packing, RCC renders itself as a high strength material that can be utilized in different pavement applications. Typical applications include low–maintenance roads, parking lots, industrial roads, intersections, city streets, heavy duty pavements, airport pavements, pavement bases, and pavement shoulders. RCC applications have been expanding across the globe (PCA EB215.02. 2002, and PCA IS009 2004).

When compared to conventional pavement and other types of concretes, RCC typically has a higher volume of aggregate with and lower binder and water contents, and hence, reduced paste volume. For a given binder content, RCC will typically offer higher strength than the corresponding conventionally compacted pavement concrete (CCPC). Aggregates used in CCPC can be used in RCC as long as there are sufficient fines in the mixture. It also needs to be noted that most of the CCPC's will be dosed with chemical admixtures like plasticizers, water reducers, retarders and air entrains.

Apart from this, RCC pavement construction requires no jointing, reinforcement for load transfer (dowel bar), no formwork and can be easily rolled and finished. Thus, there is a potential for significant economic savings in materials and construction. Moreover, due to cement savings, RCC offers itself as a more sustainable material (PCA IS328. 2005, and ACI 325. 2004). RCC pavements are strong, dense, and durable. These characteristics, combined with construction speed and economy, make RCC pavements an excellent alternative for parking and storage areas; port, intermodal, and military facilities; highway shoulders; streets; and highways. RCC can also be used in composite systems as base material.

To achieve a successful roller compacted concrete pavement project, it is important that the specification writer or engineer distinguish roller compacted concrete from conventional concrete, and apply the specifications that are most appropriate for roller compacted concrete pavement. RCC is essentially Portland cement concrete. However, it is engineered and constructed differently than conventional concrete and requires different placement and design considerations even though it is made of the same constituent materials: aggregate, portland cement, supplementary cementitious materials, chemical admixtures and water. Although made of similar materials, RCC pavements are unlike conventional concrete pavements in many ways, especially during production and placement. Therefore, it is important for the specification writer or engineer to be keenly aware of these differences while designing, specifying and constructing roller compacted concrete pavement (PCA EB215.02. 2002, PCA IS009. 2004, PCA IS328. 2005, and ACI 325. 2004).

Rashid *et al*, (2009) investigated the properties of higher strength concrete made with crushed brick as coarse aggregate and found that higher strength concrete (fcu = 31.0 to 45.5 N/mm^2) with brick aggregate is achievable whose strength is much higher than the parent uncrushed brick implying that the compressive strength of brick aggregate concrete can be increased by decreasing its water–cement ratio. Bricks are a versatile and durable building and construction material, with good load–bearing properties. Various researches have been carried out on porosity, permeability and absorption of bricks. Rashid *et al*, (2009) reported the properties of concrete which use crushed bricks as natural coarse aggregate partial substitute. Experimental investigation has also been done to achieve higher strength concrete using crushed brick aggregate. It has been found that even recycled brick can also be used as coarse aggregate in concrete. Kesegic, *et al*, (2008) have showed that concrete can be successfully produced by using recycled aggregates that have been produced from demolition and construction waste.

In a study, Fadia (2009) concluded that crushed bricks can be used satisfactory as coarse aggregate for making concrete of acceptable strength characteristics. Apebo, *et al*, (2014) concluded that crushed over burnt bricks can also be used to produce concrete with higher compressive strength with reduced weights if the bricks are properly burnt. They also suggested that reducing the water–cement ratio in crushed bricks concrete increases the compressive strength.

The aim of this work is to investigate the effect of the partial replacement of natural coarse aggregate with crushed bricks coarse aggregate in roller compacted concrete pavement. Environmental constrains of quarrying natural aggregates, such as noise, dust, vibrations, considerable impact on the countryside, besides the consumption of a non–renewable material tend to considerably limit their exploitation. Consequently, alternative materials such as construction and demolition waste (CDW) as well as other industries by–products are increasingly being tested and used as environmental sustainable natural aggregates substitutes. Crushed bricks coarse aggregate is one of the alternative materials and the need to study the characteristics of roller compacted concrete pavement incorporating crushed bricks coarse aggregate is motivated by the above challenges.

2. MATERIALS AND METHODS

— Materials:

» Hydraulic cement:

According to ACI 325 (2004), PCA IS009 (2004) and PCA IS328 (2005) the cementitious materials to be used in roller compacted concrete pavement must satisfy the required design strength and durability requirements. Roller compacted concrete mixtures can be made with any of the basic types of hydraulic cement, blended cements, or a combination of hydraulic cement and pozzolan. A detailed discussion of the selection and use of hydraulic cements and supplementary cementitious materials for roller compacted concrete can be found in ACI 225R (2016), Guide to the Selection and Use of Hydraulic Cements, and Integrated Materials and Construction Practices for Concrete

Pavement: A State–of–the–Practice Manual (FHWA HIF – 07 – 004 2007). Hydraulic cement used in this study is an ordinary Portland cement satisfying the specifications of ACI 225R (2016), FHWA–07–004 (2007) and ASTM C150/C150M (2017).

» **Natural fine aggregate:**

Natural sand was used as a fine aggregate. The sand (fine aggregate) used for this study is locally available well graded river sand passing through sieve 4.75mm but retained in sieve 2.36mm, 1.18mm, 600 micron, 300 micron and 150 micron. The fine aggregate conformed to the specifications of ASTM C33/C33M–16e1 (2016), and ASTM D448– 12 (2012).

» **Natural coarse aggregate (crushed granites) and brick coarse aggregate:**

The natural coarse aggregate (NCA) and the crushed bricks coarse aggregate (CBA) were pre–wetted and selected in accordance with the specifications of ASTM C127–15 (2015), and ASTM D 448 – 12 (2012). Crushed granites and bricks passing through sieve 25mm but retained in sieves 18.75mm, 12.5mm, 10mm, 6.25mm and 4.75mm was used as coarse aggregate. The natural coarse aggregate and the brick coarse aggregate were pre–wetted and saturated surface dried before batching.

— **Methods:**

» **Aggregate properties:**

Aggregates used in conventional concrete with a good proven record should also perform well in RCC. As with conventional concrete, the aggregate source should be inspected and tested for quality and consistency throughout the construction period. Testing can be performed to confirm the consistency of the aggregate gradation as well as properties such as absorption, specific gravity, plasticity index, abrasion resistance, alkali–silica reactivity (ASR), and durability.

The sieve analysis, specific gravity, water absorption of the fine and coarse aggregate were conducted in accordance with FHWA HIF–07–004 (2007), ASTM C33/C33M–16EI (2016), and ASTM D448– 12 (2012). The aggregate crushing value, aggregate impact value and the abrasion value tests were conducted for the natural coarse aggregate (crushed granites) and the crushed bricks coarse aggregates in accordance with ACI 327R–14 (2014), ASTM C33/C33M – 16el (2016), ASTM C131/C131M (2014), and PCA EB215.02. (2002).

» **Concrete mix ratio:**

Concrete mix was design in accordance with USDOT–FHWA FP 14 (2014), WSDOT M41–10 (2016), and WSDOT M46–01 (2016). All concrete specimens were prepared by keeping the water cement ratio constant and at a mix ratio of 1:3.5:3 of cement, fine aggregate and coarse aggregate. The crushed bricks coarse aggregate replacement percentage is defined as the weight ratio of crushed bricks coarse aggregate to the total coarse aggregates in the concrete mixture and depending upon the selected replacement percentage, direct substitution of natural coarse aggregate (crushed granites) with an equal weight of crushed bricks coarse aggregate particles was carried out in this study.

» **Slump test:**

Fresh concrete is a transitory phase of the ultimate material, but is fundamental in affecting the strength and long–term performance of the final concrete. The key properties of fresh concrete include ease of mixing, handling, transporting, laying, compacting to desired density, finishing to render a typically void–free, homogeneous and consistently dense mass. This mass upon hardening offers the desired performance.

According to USDOT–FHWA FP 14 (2014) and WSDOT M46–01.25 (2016) the slump test is a measure of the consistency of the concrete and a change in the slump test indicates that something in the manufacturing of the concrete has changed. In this study, slump test was conducted on the fresh concrete in accordance with USDOT–FHWA FP 14 (2014) WSDOT M41– 10 (2016), WSDOT M46–01 (2016), and ASTM C143/C143M – 15a (2015).

» **Compressive strength test:**

The ‘concrete cylindrical test’ is the most familiar test and is used as the standard method of measuring compressive strength for quality control purposes of concrete. Compressive strength test was performed on the hardened concrete in accordance with USDOT–FHWA FP–14 (2014) WSDOT M41–10 (2016), WSDOT M46–01 (2016), and ASTM C39/C39M–16b (2016). The test specimens were of the size 150 mm diameter x 300 mm long and were cast as soon as practicable after mixing using standard moulds and compacted. The filling of the moulds was in three layers of 100mm each and each layer was compacted. The samples were marked and cured in clean fresh water and were maintained at a room temperature of 25 ± 2°C. Six cylindrical specimens from each of the five different mixes were crushed at 3rd, 7th , 14th , 28th, 56th and 91st days age respectively and the average compressive strength were recorded.

» **Splitting tensile strength and flexural strength tests:**

Split tensile strength and flexural strength for each mix were carried out in accordance with USDOT–FHWA FP 14 (2014), WSDOT M41–10 (2016), NRMCA CIP–16 (2000), ASTM C78/C78M–16 (20016), and WSDOT M46–01 (2016), at the 14th, and 28th day. The 150mm diameter by 300mm long cylindrical concrete specimens was used for the splitting tensile strength and the 150mm wide by 150mm depth by 700mm long beams were used for flexural test. Four specimens each were tested for slitting tensile strength and flexural strength. The average results were recorded as the splitting tensile strength and flexural strength values respectively.

» **Water absorption and Voids in hardened concrete:**

The density, percentage absorption, and percentage voids in hardened concrete for different percentage replacement of NCA with CBA was determined in accordance with the procedure specified in ASTM C642 (2013) at the 28th, and 91st day of curing. The specimens used were 100mm diameter and 50mm thick cylindrical concrete of volume 393cm^3 and oven dry mass of 943g. Each portion of the specimens were free from observable cracks, fissures, or shattered edges.

3. RESULTS AND DISCUSSIONS

— Aggregate properties:

Well graded fine aggregate, crushed bricks coarse aggregate and natural coarse aggregate (crushed granites) were used in this study as shown in Tables 2, 3 and 4 and in Figures 1 and 2. From Tables 1, 2, 3 and 4 and Figures 1 and 2 it can be observed that the aggregate are of good quality and satisfied the specifications of ACI 327R–14 (2014), ASTM C33/C33M –16e1 (2016), FHWA HIF – 07 – 004 (2007), PCA IS328. (2005), USDOTFHWA FP–14 (2014), and WSDOT M41–10 (2016).

Table 1: Properties of the aggregates used

Aggregate	Specific gravity	Water absorption (%)	Aggregate crushing value (%)	Aggregate impact value (%)	Los Angeles abrasion value (%)
Fine	2.633	1.434	–	–	–
Crushed bricks	2.403	2.73	24.84	29.91	37.11
Natural Coarse (crushed granite)	2.731	1.23	19.63	22.54	24.71

Table 2: Sieve Analysis of Fine Aggregates (initial weight=1000g)

S/N	Sieve Size (mm)	Weight Retained (g)	Percentage Retained (%)	Cumulative Percentage Retained (%)	Percentage Passing (%)
1	6.25	0.00	0.00	0.00	100.00
2	4.75	17.70	1.77	1.77	98.23
3	2.36	58.80	5.88	7.65	92.35
4	1.18	182.50	18.25	25.90	74.10
5	0.60	148.50	14.85	40.75	59.25
6	0.30	254.50	25.45	66.20	33.80
7	0.15	308.00	30.80	97.00	3.00
8	0.075	13.00	1.30	98.30	1.7
Total		983g	98.30%		

Table 3: Gradation of Crushed Bricks Coarse Aggregate (initial weight=1000g)

S/N	Sieve size (mm)	Weight Retained (g)	Percentage Retained (%)	Cumulative Percentage Retained (%)	Percentage Passing (%)
1	37.5	0.00	0.00	0.00	100
2	31.5	17.00	1.70	1.70	98.30
3	25.0	22.50	2.50	3.95	96.05
4	19.0	142.30	14.23	18.18	81.82
5	16.0	128.50	12.85	31.03	68.97
6	12.5	230.30	23.03	54.06	45.94
7	9.5	243.00	24.30	78.36	21.64
8	6.25	136.80	13.68	92.04	7.96
9	4.75	67.30	6.73	98.77	1.23
Total		987.70	98.77		

Table 4: Gradation of Natural Coarse Aggregate (initial weight=1000g)

S/N	Sieve size (mm)	Weight Retained (g)	Percentage Retained (%)	Cumulative Percentage Retained (%)	Percentage Passing (%)
1	37.5	0.00	0.00	0.00	100.00
2	31.5	0.00	0.00	0.00	100.00
3	25.0	32.50	3.25	3.25	96.75
4	19.0	192.30	19.23	22.48	77.52
5	16.0	188.80	18.88	41.36	58.64
6	12.5	239.30	23.93	65.29	34.71
7	9.5	173.00	17.30	82.59	17.41
8	6.25	106.80	10.68	93.27	6.73
9	4.75	44.30	4.43	97.70	2.30
Total		977	97.7		

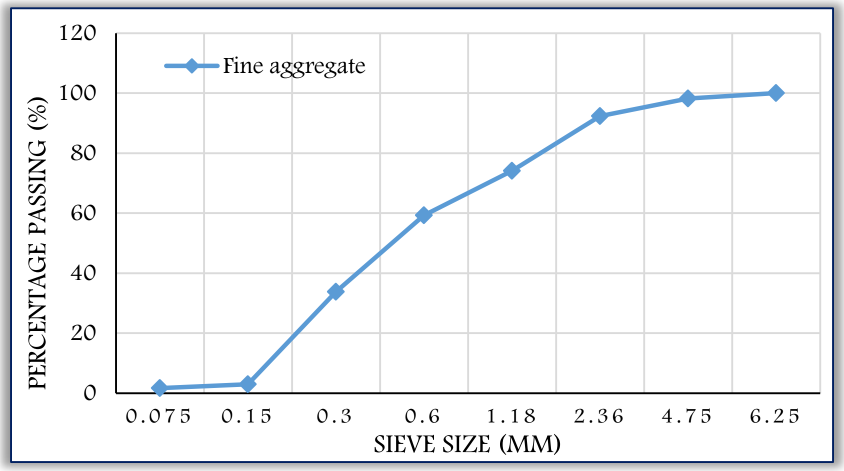

Figure 1: Sieve Analysis curve of Fine Aggregates

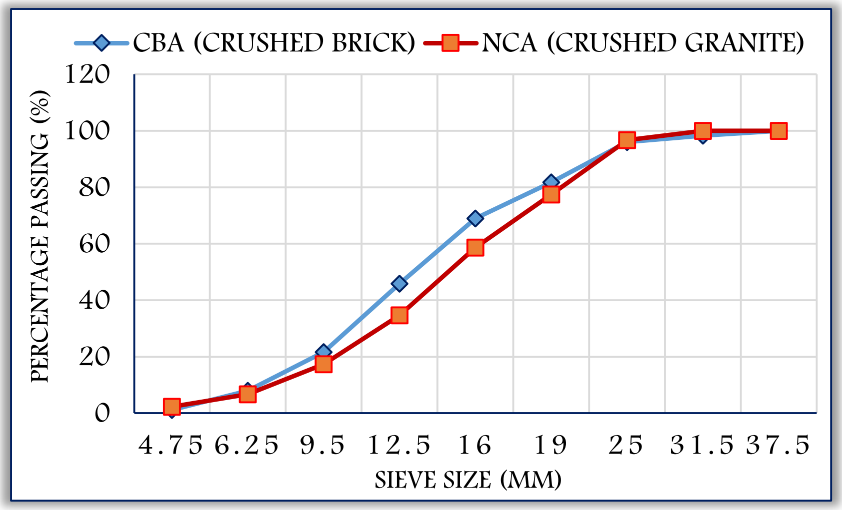

Figure 2: Sieve Analysis of crushed brick aggregate (CBA) and natural coarse aggregate (NCA)

— Concrete mix ratio and slump

Concrete specimens were batched at 1:3.5:3 mix ratio of cement, fine aggregate and coarse aggregate as shown in Table 5. The mix ratio satisfied the specifications of PCA EB215.02. (2002), PCA IS009. (2004), PCA IS328. (2005), USDOT–FHWA FP–14 (2014), WSDOT M41–10 (2016) and FHWA HIF – 07 – 004 (2007). The fine aggregate to total aggregate ratio is 0.5385 and the coarse aggregate to total aggregate ratio is 0.4615. This satisfies the fine aggregate to total aggregate ratio specifications of 0.50 to 0.55 and the coarse aggregate to total aggregate ratio of 0.45 to 0.5 for roller compacted concrete pavement specified in the above standard specifications. The water cement ratio was maintained constant for all the concrete specimens. Figure 3 shows the relationship between the measured Slump and the Percentage Replacement of natural coarse aggregate (NCA) (crushed granites) with crushed bricks aggregate (CBA). It can be observed that increase in percentage replacement of natural coarse aggregate with crushed bricks aggregate reduces the slump value. This is due to the change in the volume proportion of the remaining concrete components as a result of the remaining concrete components as a result of the mass conversion of coarse granite (NCA) into brick aggregate (CBA). The high water absorption of crushed bricks aggregate was reduced by pre–wetting the brick aggregate before concrete batching.

RCC mixtures typically have a lower volume of cementitious materials, coarse aggregates, and water than conventional concrete mixes and a higher volume of fine aggregates, which fill the air voids in the pavement system. The fine aggregates in RCC are more closely packed than in conventional concrete. This close packing initially provides high friction (aggregate interlock) between the particles and contributes to the pavement's initial load carrying capacity. The construction of all concrete pavements involves mechanical (consolidation) and chemical (hydration) processes. For conventional concrete pavement, consolidation occurs through internal paving machine vibrators. Through the hydration process, the paste hardens to bind the aggregate particles together. For RCC pavements, consolidation occurs through conventional or high–density paving screeds followed by steel drum and rubbertired rollers. As with conventional concrete, the paste hardens through hydration to bind aggregate particles together within the RCC mixture. The result is a dense pavement that has properties similar to those of conventional concrete pavement.

Table 5: Concrete Mix Proportioning at **1**: **3**. **5**: **3** mix ratio

Concrete mark	Percentage replacement of natural coarse aggregate (NCA) with crushed bricks aggregate (CBA)	Water–cement ratio	Cement (kg)	Fine aggregate (kg)	Natural coarse aggregate (kg)	Crushed bricks aggregate (kg)
RP1	0	0.55	100	350	300	0.00
RP2	20	0.55	100	350	240	60
RP3	40	0.55	100	350	180	120
RP4	60	0.55	100	350	120	180
RP5	80	0.55	100	350	60	240

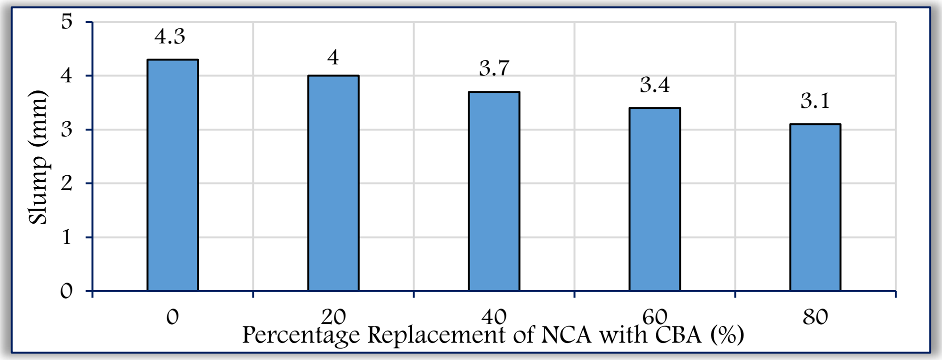

Figure 3: The Relationship between the Measured Slump and the Percentage Replacement of natural coarse aggregate with crushed bricks aggregate.

- **Compressive strength:**

According to NRMCA CIP–16 (2000), National Ready Mixed Concrete Association (NRMCA) and American Concrete Pavement Association (ACPA) have a policy that compressive strength testing is preferred method of concrete acceptance. ACI 325.9R–15 (2015) and ACI 330R–08 (2008) point to the use of compressive strength as more convenient and reliable to judge the quality of concrete. The average compressive strength and densities of the various mixtures of percentage replacement of natural coarse aggregate (NCA) with crushed bricks aggregate (CBA) at an age of 3rd, 7th, 14th, 28th, 56th, and 91st days are given in Table 6. Figure 4 shows the relationship between the compressive strength (N/mm^2) and Curing age (days). From Table 6 and Figure 4, it can be seen that all the concrete mixtures show increase in strength with increase in the curing age. From the compressive strength test results presented it can be observed the compressive strength of concrete mixtures containing 0% to 80%, replacement of NCA with CBA satisfied the USDOTFHWA F–14 (2014), WSDOT M41–10 (2016), ACI 325.9R–15 (2015), ACI 330R–08 (2008), ACI 325. (2004), ACI 327R–14 (2014), FHWA HIF – 07 – 004 (2007), PCA EB215.02. (2002) and PCA IS009 (2004) 28 days minimum compressive strength specifications of 31N/mm^2 to 41N/mm^2 and 35N/mm^2 to 41N/mm^2 for standard and high performance concrete pavement. This indicates that crushed bricks aggregate (CBA) used in this study were of good quality and can be used as a partial replacement of coarse granite in construction of roller compacted concrete pavement.

Table 6: Average Compressive Strength Test Results (fck).

Cube mark	Replacement of NCA with CBA (%)	Density (Kg/m³)	3rd day (N/mm²)	7th day (N/mm²)	14th day (N/mm²)	28th day (N/mm²)	56th (N/mm²)	91st day (N/mm²)
RP1	0	2427	18.10	23.20	29.58	38.21	48.88	62.67
RP2	20	2413	15.20	21.60	26.08	36.92	46.61	62.67
RP3	40	2400	13.08	19.50	22.30	35.08	44.32	60.56
RP4	60	2381	11.40	15.80	18.60	32.37	41.86	57.42
RP5	80	2322	9.01	13.40	15.90	27.68	37.48	54.33

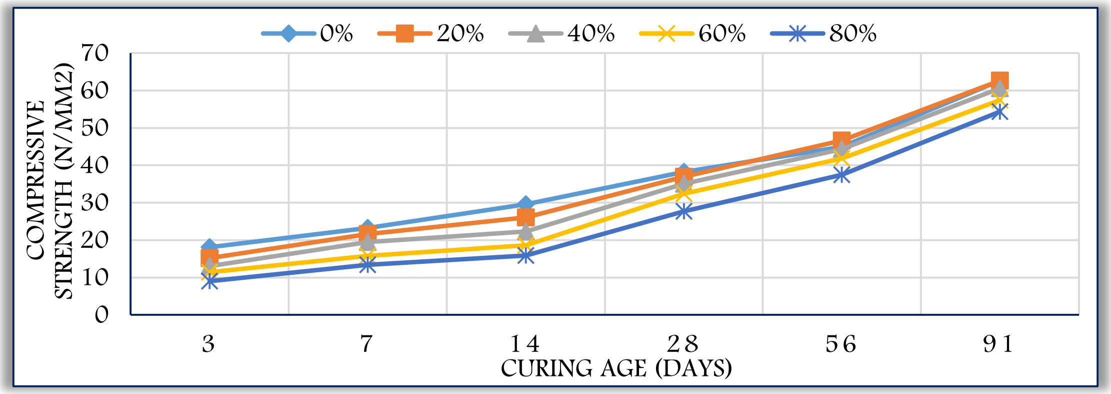

Figure 4: Relationship between the compressive strength (N/mm²) and Curing age (days)

— **Flexural strength and splitting tensile strength:**

The flexural strength and split tensile strength of concrete mixtures incorporating crushed bricks aggregate were evaluated at the 14th, and 28th day age. The results are presented in Figures 5 and 6. From Figures 5 and 6 it can be seen that there is increase in splitting tensile strength and flexural strength values with the increase in age. The maximum strengths for all the mixtures under study occurs at 0% natural coarse aggregate replacement at all the ages.

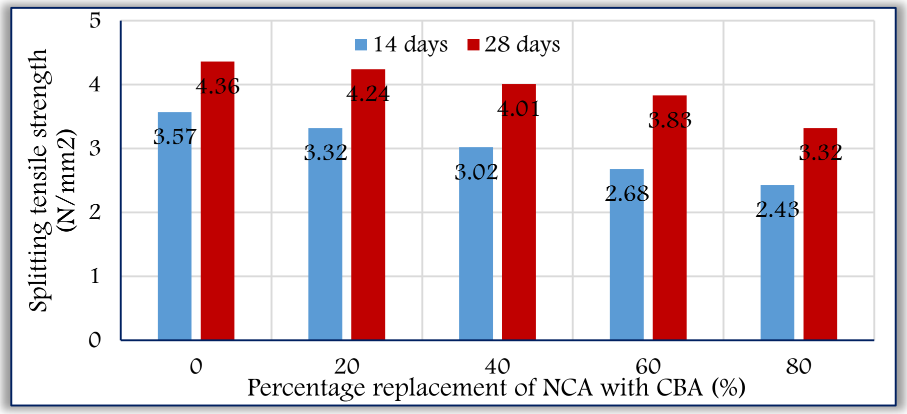

Figure 5: Relationship of the 14th and 28th days splitting tensile strength with percentage replacement of NCA with CBA

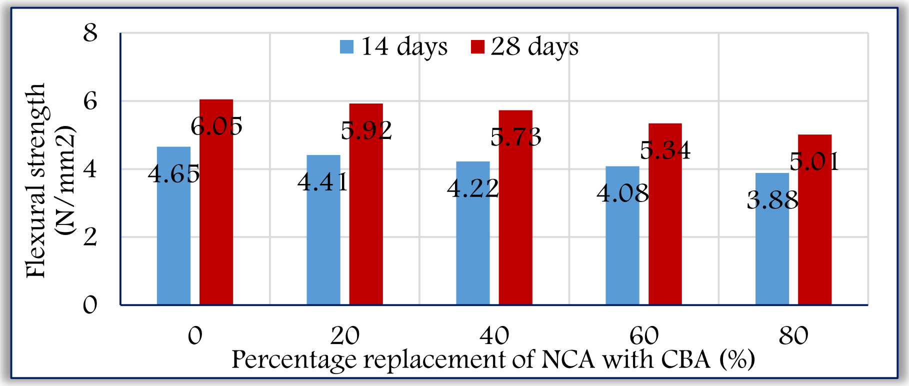

Figure 6: Relationship of the 14th and 28th days flexural with percentage replacement of NCA with CBA

- **Water absorption and Volume of permeable voids in hardened concrete:**

Table 6: Water absorption and Volume of permeable pore space (voids) in hardened concrete at 28thday age.

S/N	Description and units	Symbols and equations.	Percentage replacement of natural coarse aggregate (NCA) with crushed brick aggregate (CBA)				
			0%	20%	40%	60%	80%
1.	Volume of sample (cm^3)	V	393	393	393	393	393
2.	Mass of oven dry sample in air (g)	A	954	948	943	936	913
3.	Mass of surface–dry sample in air after immersion (g)	B	990	986	984	978	960
4.	Mass of surface–dry sample in air after immersion and boiling (g)	C	993	990	988	983	966
5.	Apparent mass of sample in water after immersion and boiling (g)	D	600	597	595	590	573
6.	Absorption after immersion (%)	$= \left[\frac{(B-A)}{A}\right] X\, 100$	3.8	4.0	4.4	4.5	5.2
7.	Absorption after immersion and boiling (%)	$= \left[\frac{(C-A)}{A}\right] X\, 100$	4.1	4.4	4.8	5.0	5.8
8.	Density of water (g/cm^3)	$\rho = 1$	–	–	–	–	–
9.	Bulk density, dry (g/cm^3)	$g_1 = \left[\frac{A}{C-D}\right] X\, \rho$	2.43	2.41	2.40	2.38	2.32
10.	Bulk density after immersion (g/cm^3)	$= \left[\frac{B}{C-D}\right] X\, \rho$	2.52	2.51	2.50	2.49	2.44
11.	Bulk density after immersion and boiling (g/cm^3)	$= \left[\frac{C}{C-D}\right] X\, \rho$	2.53	2.52	2.51	2.50	2.46
12.	Apparent density (g/cm^3)	$g_2 = \left[\frac{A}{A-D}\right] X\, \rho$	2.70	2.70	2.71	2.71	2.69
13.	Volume of permeable pore space or voids, (%)	$= \left[\frac{g2-g1}{g2}\right] X\, 100$ Or $= \left[\frac{(C-A)}{(C-D)}\right] X\, 100$	10.00	10.74	11.44	13.45	13.76

Table 7: Water absorption and Volume of permeable pore space (voids) in hardened concrete at 91stday age.

S/N	Description and units	Symbols and equations.	Percentage replacement of natural coarse aggregate (NCA) with crushed brick aggregate (CBA)				
			0%	20%	40%	60%	80%
1.	Volume of sample (cm^3)	V	393	393	393	393	393
2.	Mass of oven dry sample in air (g)	A	954	948	943	936	913
3.	Mass of surface–dry sample in air after immersion (g)	B	975	971	969	964	946
4.	Mass of surface–dry sample in air after immersion and boiling (g)	C	978	975	973	970	952
5.	Apparent mass of sample in water after immersion and boiling (g)	D	585	582	580	577	559
6.	Absorption after immersion (%)	$= \left[\frac{(B-A)}{A}\right] X\, 100$	2.2	2.4	2.8	3.0	3.6
7.	Absorption after immersion and boiling (%)	$= \left[\frac{(C-A)}{A}\right] X\, 100$	2.5	2.9	3.2	3.6	4.3
8.	Density of water (g/cm^3)	$\rho = 1$	–	–	–	–	–
9.	Bulk density, dry (g/cm^3)	$g_1 = \left[\frac{A}{C-D}\right] X\, \rho$	2.43	2.41	2.40	2.38	2.32
10.	Bulk density after immersion (g/cm^3)	$= \left[\frac{B}{C-D}\right] X\, \rho$	2.49	2.48	2.48	2.47	2.45
11.	Bulk density after immersion and boiling (g/cm^3)	$= \left[\frac{C}{C-D}\right] X\, \rho$	2.49	2.48	2.48	2.47	2.42
12.	Apparent density (g/cm^3)	$g_2 = \left[\frac{A}{A-D}\right] X\, \rho$	2.59	2.59	2.60	2.61	2.58
13.	Volume of permeable pore space or voids, (%)	$= \left[\frac{g2-g1}{g2}\right] X\, 100$ Or $= \left[\frac{(C-A)}{(C-D)}\right] X\, 100$	6.26	7.00	7.69	8.81	10.08

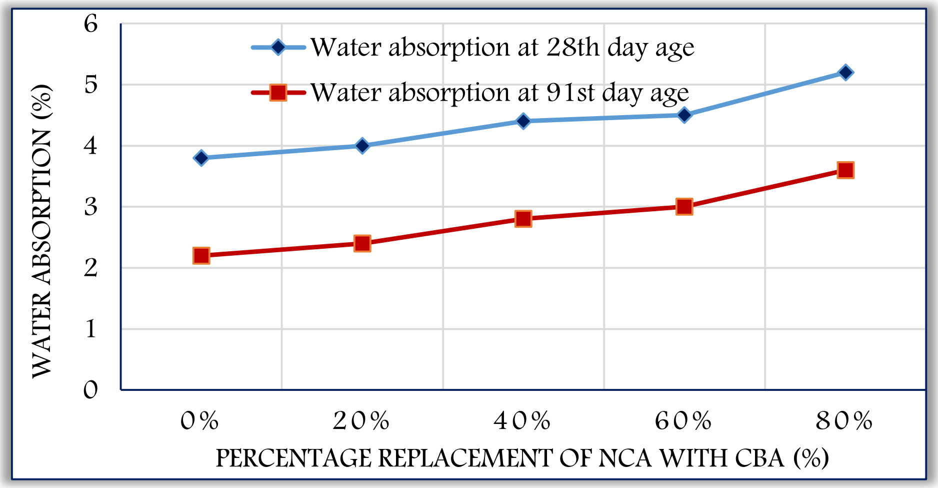

Figure 7: Water absorption after immersion in hardened concrete at 28th and 91stdays (%)

The specimen use for the Water absorption and Volume of permeable pore space (voids) in hardened concrete at 28th and 91st day age satisfied the specifications of ASTM C642 (2013). From Tables 6 and 7 and Figure 7 it can be observed that water absorption and volume of permeable pore space (voids) increase with increase in percentage replacement of NCA with CBA. These values also reduce with increase in curing age as can be seen in Tables 6 and 7. This indicates that the CBA concrete has reliable durability qualities and will perform favorable if used in roller compacted concrete pavement.

4. CONCLUSIONS

The following conclusions were drawn at the end of this study:

- Crushed bricks aggregate (CBA) used in this study are of good quality and can be used as partial replacement of natural coarse aggregate (NCA) in roller compacted concrete pavement.
- Good quality CBA can replace NCA up to 80% in roller compacted concrete pavement.
- Using a mix design specified by relevant standards that contains quality well graded crushed bricks aggregate (CBA) as coarse aggregate, concrete containing up to 40% replacement of NCA with CBA exhibits similar characteristics compared to non CBA concrete.
- Compressive strength of roller compacted concrete containing up to 80% crushed brick aggregate (CBA) increase with increase in curing age and the later days compressive strength are relative the same with that of non CBA roller compacted concrete.

References

[1] ACI 225R. (2016). Guide to the Selection and Use of Hydraulic Cements, American Concrete Institute, Farmington Hills, MI, USA. https://www.concrete.org/225R
[2] ACI 325.9R–15 (2015). Guide for construction of concrete pavements. American Concrete Institute, Farmington Hills, MI, USA. https://www.concrete.org/325.9R
[3] ACI 330R–08 (2008). Guide for the design and construction of concrete parking lots. American Concrete Institute, Farmington Hills, MI, USA. https://www.concrete.org/330R–08, ISBN 9780870312793.
[4] ACI 121R–08. (2008). Guide for Concrete Construction Quality Systems in Conformance with ISO 9001, American Concrete Institute, Farmington Hills, MI, USA. https://www.concrete.org/121R
[5] ACI 214R–11. (2011). Guide to Evaluation of Strength Test Results of Concrete, American Concrete Institute, Farmington Hills, MI, USA. https://www.concrete.org/214R–11
[6] ACI 325. (2004). "State–of–the–Art Report on Roller–Compacted Concrete Pavements," ACI Report 325.10R–95, American Concrete Institute, Farmington Hills, MI, USA.
[7] ACI 327R–14 (2014). Guide to Roller Compacted Concrete Pavements. American Concrete Institute, Farmington Hills, MI, USA. https://www.concrete.org/327RR
[8] Apebo, N. S., Agunwamba, J. C., Ezeokonkwo, J. C. (2014). The suitability of crushed over burnt bricks as coarse aggregates for concrete. International Journal of Engineering Science and Innovative Technology, Vol. 3 (1), Pp.315–321.
[9] ASTM C150 / C150M, (2017). Standard Specification for Portland cement, ASTM International, West Conshohocken, PA. https://www.astm.org/C150
[10] ASTM 127 (2015), Standard Test Method for Relative Density (Specific Density) and Absorption of Coarse aggregates. ASTM International, West Conshohocken, PA, www.astm.org.
[11] ASTM C78/C78M (2016). Standard test method for flexural strength of concrete (using simple beam with third–point loading). ASTM International, West Conshohocken, PA,

www.astm.org/C78. ASTM C33/C33M –16e1 (2016), Standard Specifications for concrete Aggregate. ASTM International, West Conshohocken, PA, www.astm.org. ASTM C131/C131M, (2006), Standard Test Method for Resistance to Degradation of Small size Coarse Aggregate by Abrasion and Impact inthe Los Angeles Machine, ASTM International, West Conshohocken PA, https://www.astm.org.

[12] ASTM C143/C143M –15a (2015).Standard Test Method for Slump of Hydraulic Cement Concrete.ASTM International West Conshohocken, PA.www.astm.org.

[13] ASTM C39 / C39M–16b (2016), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, www.astm.org ASTM D448–12 (2012). Standard classification for sizes of aggregates for roads and bridge construction. ASTM international, West Conshohocken, PA, www.astm.org.

[14] ASTM C642 (2013). Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM international, West Conshohocken, PA, www.astm.org/C642–13.

[15] Cachim, P.B., (2009). “Mechanical Properties of brick aggregate concrete,” Construction and Building Materials, 23(3) Pp.1292–1297.

[16] Chetan V. H., Halil C., Peter T., Kasthurirangan G., Kejin W., and Fatih B. (2013). Use of Chemical Admixtures in Roller–Compacted Concrete for Pavements. National Concrete Pavement Technology Center, Iowa State University, USA.

[17] Fadia S. K. (2009). Use of Crushed Bricks as Coarse Aggregate in Concrete. Tikrit Journal of Engineering Sciences. Vol.16 (3/S). Pp. 64–69.

[18] FHWA HIF – 07 – 004 (2007). Integrated Materials and Construction Practices for Concrete Pavement: A State–of–the–Practice Manual, Federal Highway Administration, United States Department of Transportation, Office of Pavement Technology, Washington D.C, USA. https://www.fhwa.dot.gov/pavement/07–004

[19] Kesegic, I., Netinger, I. and Bjegovic, D. (2008). Recycled Clay Brick as an aggregate for concrete, Technical Gazette 15(3), Pp. 35–40.

[20] NRMCA CIP–16 (2000), Concrete in practice– flexural strength concrete. Technical information, National Ready Mixed Concrete Association (NRMCA), https://www.nrmca.org PCA EB215.02. (2002).

[21] PCA IS009. (2004). Guide Specification for Construction of Roller–Compacted Concrete Pavements. Publication IS009. Skokie, IL: Portland Cement Association. https://www.concrete.org/IS009

[22] PCA IS328. (2005). Roller–Compacted Concrete Pavements for Highways and Streets. Publication IS328. Skokie, IL: Portland cement Association. http://www.cement.org/IS328

[23] Rashid, M. A., Hossain, T. and Islam M. A. (2009). Properties of higher strength concrete made with crushed brick as coarse aggregate, Journal of Civil Engineering (IEB), 37(1), Pp43–52.

[24] USDOT–FHWA FP–14 (2014).Standard specification for construction of roads and bridges on federal highway projects. United States department of transportation, Federal highway administration. http://www.fhwa.dot.gov/fp–14

[25] WSDOT M41–10 (2016). Standard Specification for Road, Bridge, and Municipal Construction. Construction Administration Office, Engineering and Regional Operations Division, Washington State Department of Transport, State of Washington, USA. https://www.wsdot.wa.gov/M41–10

[26] WSDOT M46–01. (2016). Materials manual, Materials laboratory, Engineering and Regional Operations Division, Washington State Department of Transport, State of Washington, USA. https://www.wsdot.wa.gov/M46–10

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