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Comparative Study of Physical and Mechanical Properties of Machine and Manually Crushed Brick Aggregate Concrete

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ABSTRACT

With technological advancement on the rise, manual crushing of bricks is gradually being replaced by machine crushing to obtain coarse aggregates for construction. However, properties of the brick aggregates obtained from these two methods vary which in turn, may affect the properties of the concrete matrix as well. This study represents a comparison between the machine crushed and manually crushed brick aggregates to be used as coarse aggregates in preparation of concrete. Four types of bricks, namely first class, second class, picket (over burnt) and ceramic were investigated, and each was crushed both manually and mechanically to a usable form of aggregates. The physical and mechanical properties of the brick aggregates derived from the two methods were tested and compared. In all types of brick, aggregates size, shape and strength properties such as flakiness and elongation indices, aggregate impact and crushing values and Los Angeles abrasion value showed lower values for manually crushed aggregate indicating better properties compare to machine crushed aggregates. This was evident while comparing compressive and tensile strength of concrete prepared with both manually and machine crushed first class and picket brick aggregates. Concrete with manually crushed brick aggregates showed marginally higher compressive and tensile strength in both types of brick aggregates.

1. INTRODUCTION

There is a growing concern that urges a sustainable construction practice to be undertaken because concrete is one of the largest consumers of natural resources worldwide. About 60% to 75% of the volume of concrete is composed of aggregates and the primary source of such are the natural stone reserves. As concrete is the second largest consumed material after water, it is imperative that a suitable substitute for natural stone aggregates is introduced. Brick aggregate concrete is an effective alternative to natural stone aggregate concrete in regions like Bangladesh where scarcity of stone reserves exists. In addition, to allow considerable savings in non-renewable resources, bricks are widely available and a cost-effective solution to the ever-increasing demand for concrete construction. The use of brick chips as coarse aggregates dates back to the Second World War (Hansen, 1992). After concrete, brick remains as the second most important building material around the world (RMIT University, 2006). The damaged or broken bricks during its production can be reused as coarse aggregates in concrete which can alleviate the excessive waste disposal problems into the landfills (Lennon, 2005).

Despite the common disadvantages that include high porosity and absorption capacity along with lower compressive strength than its stone counterpart (Afroz *et al.*, 2015), brick chips are used as aggregates in different parts of the world including Bangladesh. As reported by Cachim (2009), crushed bricks can be utilized as coarse aggregates by up to 15% replacement of the conventional stone aggregates without affecting the strength of concrete keeping all other factors constant. Studies also reported that high strength concrete can be achieved using crushed well-burned brick as aggregates of proper gradation (Akhtaruzzaman *et al.*, 1983). When proper gradation of brick chips is obtained, their performance as aggregates is excellent in both lightweight and high strength concrete structures (Rashid *et al.*, 2009). In a study by Khalaf and DeVenny (2004) it is seen that brick aggregate concrete can perform well or even superior to conventional stone aggregate concrete when subjected to high temperatures. The properties of crushed clinker brick aggregates and recycled brick aggregates are investigated by Khaloo (1994) and Hansen (1992) respectively where it is reported that both the types of brick aggregates increase the tensile strength of the concrete. Adamson *et al.* (2015) studied the durability properties of concrete where brick aggregates were partially replaced by natural stone aggregates. Their results revealed that brick aggregates can be used in place of stone aggregates without prominent changes in the durability of concrete provided no steel reinforcement are present.

The properties of concrete including compressive and tensile strength are highly dependent upon the properties of the constituent aggregates (Ayub *et al.*, 2012). Therefore, it is of prime importance that the strength and physical characteristics of the brick chips are tested before being used as coarse aggregates in concrete. The effects of parameters related to the shape and strength of coarse aggregates on the properties of the resulting concrete are studied by many researchers. A higher proportion of flaky and elongated aggregates tend to reduce the impermeability, workability, and compressive strength of the concrete (Islam *et al.*, 2020; Yu *et al.*, 2015). Crushing and impact value of aggregates are very helpful in estimating the compressive strength of the concrete especially when the performance of the aggregates being used in the concrete is not known (Neville, 1995). In addition to the above-mentioned properties, void content, absorption capacity, unit weight and toughness of the aggregates do play vital roles in indicating the quality of concrete.

Crushing of bricks can be done in two ways, by machine and by hand. In Bangladesh, both the processes are incorporated whichever appears to comply within the constraints of a project. One of the main reasons for using a machine to crush bricks is that it requires less time than crushing the bricks manually. Therefore, when time is a constraint and labor cost not a significant issue, the developers often opt for machine crushed brick aggregates for concrete construction. However, such a choice made during the production of concrete does not always take account of the fact whether machine crushed aggregates provide the desired quality concrete over the manually crushed ones. The properties of the brick aggregates obtained by manual crushing vary significantly to that produced by machine crushing and in turn, are expected to affect the properties of concrete. There is hardly any literature that addressed this phenomenon enlightening the comparison of the properties of the machine and manually crushed brick aggregates. To the authors' best knowledge, no research has yet to be reported that compared the properties of concrete prepared with machine crushed brick aggregate to that with manually crushed brick aggregate as coarse aggregates. The choice of aggregate crushing method may vary on many factors, such as labor cost, project duration, availability, and affordability of the technology, and many more. However, in terms of only concrete properties, it is important to carry out this comparative study to develop a plan that helps to decide which method of crushing bricks shall be followed during construction.

2. MATERIALS

A. Cement

As a binding material, Type I Portland cement conforming to ASTM C150 (2015*e*) specification was used in this study. Physical properties were tested according to ASTM C204 (2011*b*) for fineness using Blaine air-permeability apparatus, ASTM C430 (2015*h*) for fineness by $45\ \mu m$ sieve, ASTM C191 (2013*c*) for initial and final setting time, ASTM C187 (2011*a*) for normal consistency, ASTM 151 (2015*f*) for soundness by autoclave expansion method and ASTM C109 (2013*a*) for compressive strengths. The specific gravity was recorded as 3.15. The physical properties of the cement are presented in Table 1.

B. Fine Aggregates (Sand)

Local Sylhet sands were used as fine aggregates for the present study. The sample was first collected from a local supplier. It was then cleaned from different debris and other organic materials. Its physical properties, like gradation, specific gravity, and absorption capacity, were determined according to ASTM standards (ASTM C128 (2015*c*) and ASTM C136 (2014)). Table 2 represents the physical properties of the sand, whereas Figure 1 shows the gradation of the sand along with ASTM upper and lower limits. As shown in the figure, the particle size distribution of the sand falls well within the ASTM limits. Fineness modulus of 2.89 also falls within the recommended range of 2.3 to 3.1 according to ASTM C33 (2013*b*) standard.

Table 1
Physical properties of cement

Physical Properties		**Unit**	**Specification**	**Test Results**
Fineness (Specific Surface)		(m^2/Kg)	260 min 430 max	370
Fineness (By 45 Micron)		(%)	-	97.9
Initial Setting Time		Minutes	45 minutes (min.)	182
Final Setting Time		Minutes	375 minutes (max.)	374
Normal consistency		(%)	-	27.5
Soundness (By Autoclave method)		(%)	Maximum 0.80	0.01
Compressive Strength	$3\ days$	MPa (psi)	12 (1740)	22.4 (3240)
	$7\ days$	MPa (psi)	19 (2760)	29.8 (4320)
	$28\ days$	MPa (psi)	28 (4060)	39.2 (5690)

C. Properties of Bricks

Four types of brick specimens commercially available in Bangladesh were used in this study namely first class, second class, picket (over burnt) and ceramic. Among these first class, second class and picket bricks are handmade bricks. However, ceramic bricks are machine made bricks. Figure 2 displays the four different types of bricks. As shown in Figure 2(a) and 2(b), first class brick has the well-defined shape with dimension tolerance within 3% and deep red; whereas, second class brick has shown with under burnt physical appearance with irregular shape and size with dimension tolerance within 8% (Sahu *et al.*, 2015). Picket brick, as shown in Figure 2(c), has an irregular shape with dark color and rough surfaces (Sahu *et al.*, 2015). Finally, ceramic brick, also known as perforated brick, has a well-defined size and shape, glassy surface, and uniform reddish color (Sahu *et al.*, 2015). These four types of brick have distinctive compressive strength as shown in Table 3. Picket brick, has the highest compressive strength of $29.67\ MPa$; whereas, ceramic brick has the second highest compressive strength $(23.90\ MPa)$ and the first class brick has the third highest compressive strength (18.38 MPa). However, second class brick has the lowest compressive strength (9.84 MPa). Unit weights of all four types of bricks have been also measured as described in Table 3. Similar to compressive strength, picket showed the highest unit weight of 1989 kg/m^3; whereas second class brick displayed the lowest unit weight of 1603 kg/m^3.

Table 2
Physical properties of fine aggregate

Components Name	**Fine Aggregate (Sand)**
Maximum size	4.75 mm
Minimum size	0.15 mm
Fineness modulus	2.89
Bulk specific gravity	2.43
Apparent specific gravity	2.62
Water absorption Capacity	3.00 %

All types of brick specimens were crushed both manually and mechanically to produce brick aggregates. In the case of manual crushing, two labors with comparable strength crushed bricks using hammer over a period of 2 days as shown in Figure 3(a). For the machine crushing of bricks, a heavy-duty crushing machine is used as depicted in Figure 3(b). The portable (3 wheels) crusher has a set of mild steel jaw crusher and attached sieve. It can crush 1000 – 15000 bricks per hour. Prior to brick crushing, bricks were soaked with water to reduce the production of dust during the crushing process. Larger particle sizes were separated using the sieve and put into the jaw crusher again. However, the machine crusher creates a larger quantity of finer particles. Figure 4 presents the comparison of cumulative percentages of finer particles passing the sieve opening of 2.36 mm for all four types, such as first class brick aggregate (FCA), second class brick aggregate (SCA), picket brick aggregate (PBA), ceramic brick aggregate (CBA), of manual and machine crushed bricks. As shown in the figure, machine crushing produces as high as 14.49% finer particles compare to a maximum of 2.98% of finer particles for manually crushed bricks. Thus, it can be said that machine crushing is uneconomical as it produces an average of 5 times more wastage than that produced in manual crushing.

For the machine crushing process, the production of finer particles is highest for the first-class bricks and lowest for the ceramic bricks. During the machine crushing procedure, first class bricks initially produced a high percentage of aggregate larger than 25 mm sieve opening and those aggregate went through the crusher one more time compared to the second-class bricks. Because of this additional crushing, first class bricks produced higher percentages of finer particles than the second-class bricks. These finer particles have very low mechanical properties, and thus, discarded from the next phase of the study, that is, material testing and concrete preparation.

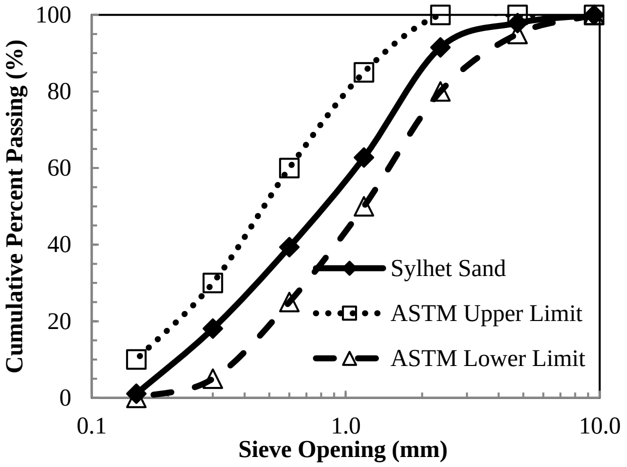


Figure 1: Particle size distribution of fine aggregates (sand)

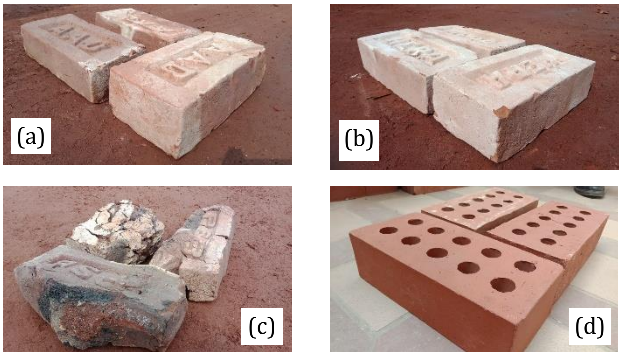


Figure 2: Pictures of four types of bricks: (a) first class; (b) second class; (c) picket and (d) ceramic

Table 3
Strength of brick specimens

Types of Bricks	**Unit weight (kg/m^3)**	**Standard Deviation (kg/m^3)**	**Average Compressive Strength (MPa)**	**Standard Deviation (MPa)**
First Class (FC)	1797	44	18.38	2.21
Second Class (SC)	1603	16	9.84	0.38
Picket Brick (PB)	1989	84	29.67	0.64
Ceramic Brick (CB)	1771	31	23.90	2.48

Figure 3: Brick crushing method: (a) manual process, (b) machine crushing

D. Physical Properties of Brick Aggregates

The particle size distribution of aggregate is an important factor for properties of concrete, such as workability, density, and strengths. Therefore, sieve analysis of all the brick aggregates were performed following ASTM C 136 (2014). Figure 5 displays the particle size distribution of both manually and machine crushed brick aggregates after discarding particles those passing through the 2.36 *mm* sieve. The figure also includes the upper and lower limits for cumulative percent passing proposed by ASTM C 33 (2013*b*) for concrete aggregate. As shown in the figure, manually crushed brick aggregates are coarser than the machine crushed brick aggregates. Especially, FCA and PBA are coarser among all the aggregate types. Furthermore, all the curves fall outside the ASTM lower limit indicating coarser aggregate types. Fineness modulus of brick aggregates have also showed similar phenomenon. Figure 6 compared the fineness modulus of both manually and machine crushed brick aggregates. These results are also consistent with the previous findings.

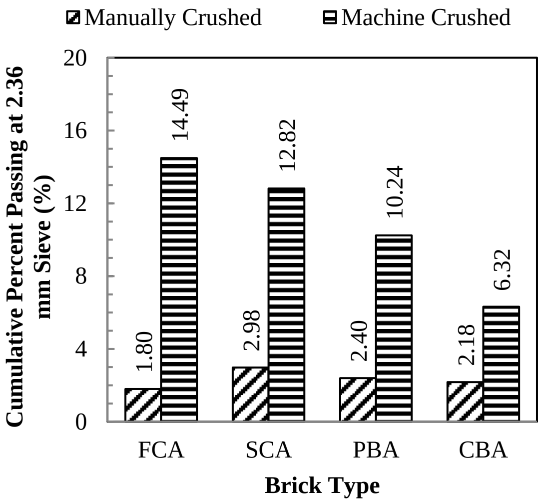
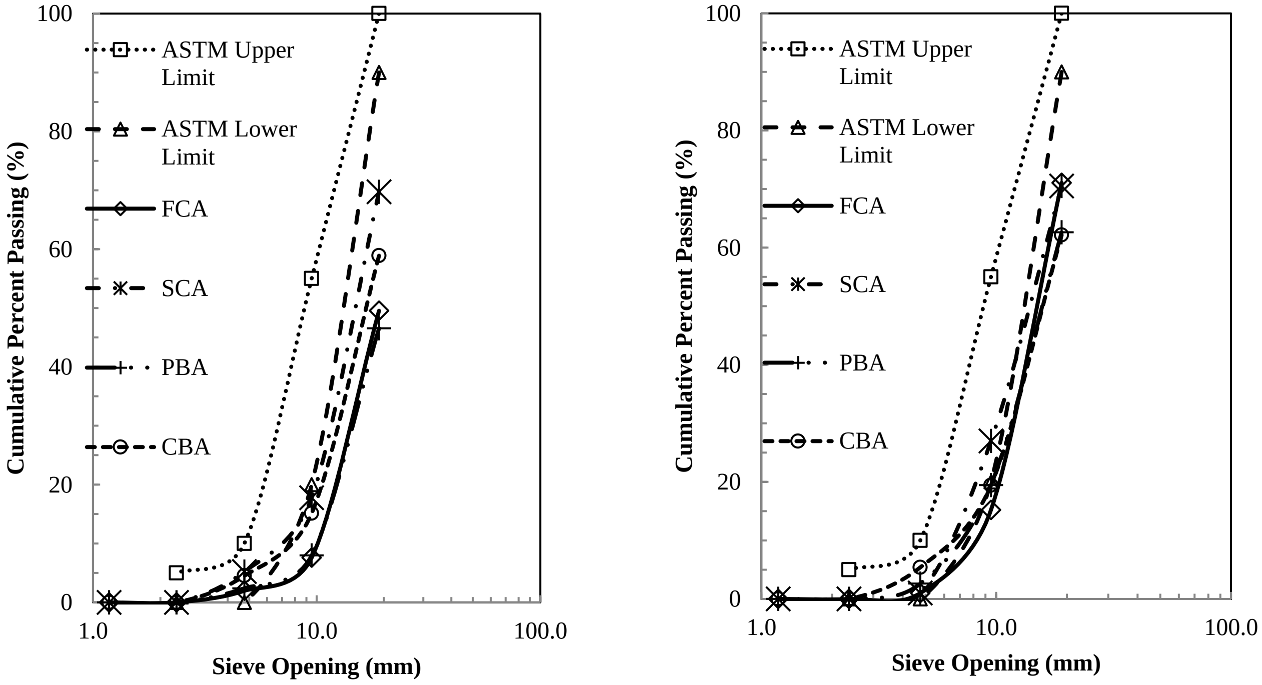


Figure 4: Cumulative percent passing at 2.36 *mm* sieve for four types of manually and machine crushed brick aggregates



(a)

(b)

Figure 5: Particle size distribution of (a) manually crushed brick aggregates (b) machine crushed brick aggregates

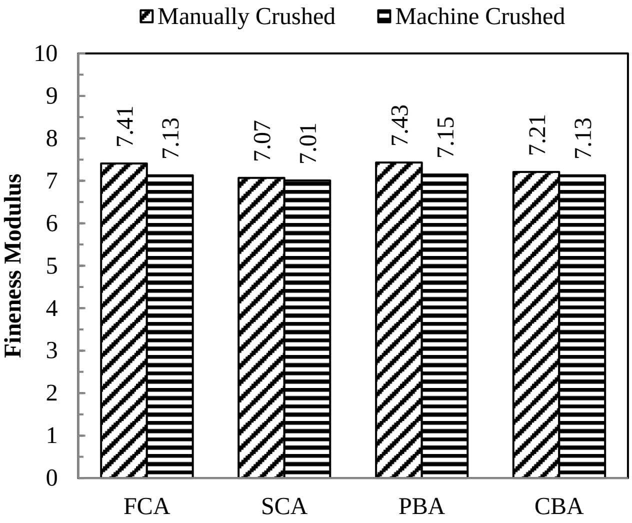


Figure 6: Fineness modulus for four types of manually and machine crushed brick aggregates

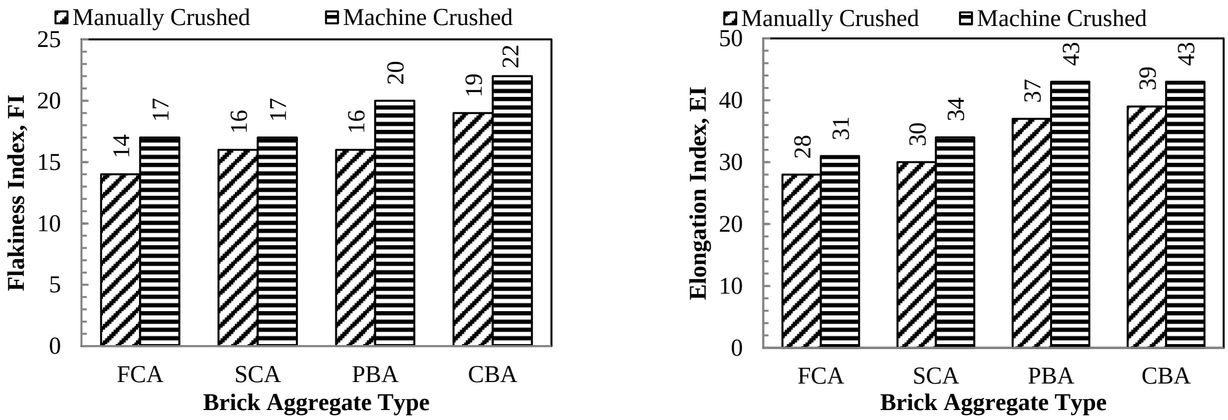
Unit weights and void ratios of brick aggregates were measured following the ASTM C29 (2009) standard. The results are presented in Table 4. Table 4 also includes the ACI recommended values for aggregate used in concrete (ACI, 2016). The unit weight of manually crushed brick aggregate varies between 1039 to 1112 kg/m^3. On the other hand, for machine crushes brick aggregate, unit weight ranges between 1015 to 1102 kg/m^3. In both cases, second class brick aggregates show the lowest unit weight and ceramic brick aggregate shows the highest unit weight. However, unit weight for all four types of bricks with different crushing methods below the ACI recommended value (1280 kg/m^3) for the dry rodded unit weight. It is seen that the unit weight of ceramic bricks derived by both machine and manual crushing processes is the highest. Void percentages were also measured. The test results indicate that picket aggregate has the least void percentage (42.6%) among the four aggregate types.

Bulk specific gravity and absorption capacity of the aggregates are determined by the standard procedure of ASTM C127 (2015*b*). ACI E-16 recommended value for bulk specific gravity for coarse aggregate is a range between 2.30 to 2.90 (ACI, 2016). Although CBA has the highest specific gravity (2.06) for all aggregates it is still below the ACI E-16 recommended value. The absorption capacities of aggregates are well within the recommended value. It should be noted that all the aggregates have similar absorption capacity ranging between 4.4 to 5.8%.

Table 4
Brick aggregate properties

Parameters	Machine-crushed				Manually crushed				ACI E1-16 (2016)
	FCA	SCA	PBA	CBA	FCA	SCA	PBA	CBA	
Unit Weight (kg/m^3)	1018	1015	1087	1102	1062	1039	1108	1112	1280 – 1920
Voids (%)	45.6	46.3	42.6	45.5	45.9	45.0	43.1	49.0	–
Specific Gravity (OD)	1.97	1.89	1.93	2.04	1.96	1.89	1.91	2.06	2.30 – 2.90
Absorption (%)	4.9	5.3	5.8	4.4	4.7	5.3	5.7	4.6	0.0 – 8.0

The flakiness and elongation indices of the brick chips are determined as per the standards BS 812-105.1 (1990*a*) and BS 812-105.2 (1990*b*) respectively. Figure 7 shows the variation in flakiness and elongation Indices among the different classes and crushing methods. Both the indices of the manually crushed brick aggregates are less than that of the machine crushed brick aggregates. The flakiness index of machine crushed brick aggregates is 21.4%, 6%, 25%, and 15.7% higher than manually crushed brick aggregates of FCA, SCA, PBA and CBA, respectively. Flakiness index of machine crushed FCA and SCA is found to be the same whereas the value for manually crushed SCA and PBA are observed to be similar. Interestingly, the flakiness index of the machine crushed ceramic brick aggregate is found to be the highest (22). The orientation of these flaky aggregates play an important role in the strength of the concrete samples. Flakier nature of machine crushed brick aggregates might lead to lower workability and strength in concrete. The Elongation Indices of machine crushed FCA, SCA, PBA and CBA are 10.7%, 13.3%, 16.2%, and 9.3% greater than the same aggregates produced by manual crushing, respectively. It is seen that both PBA and CBA provided the highest elongation index at 43; whereas, manually crushed FCA shows the lowest index at 28.



(a)

(b)

Figure 7: (a) Flakiness and (b) elongation indexes of four types of manually and machine crushed brick aggregates

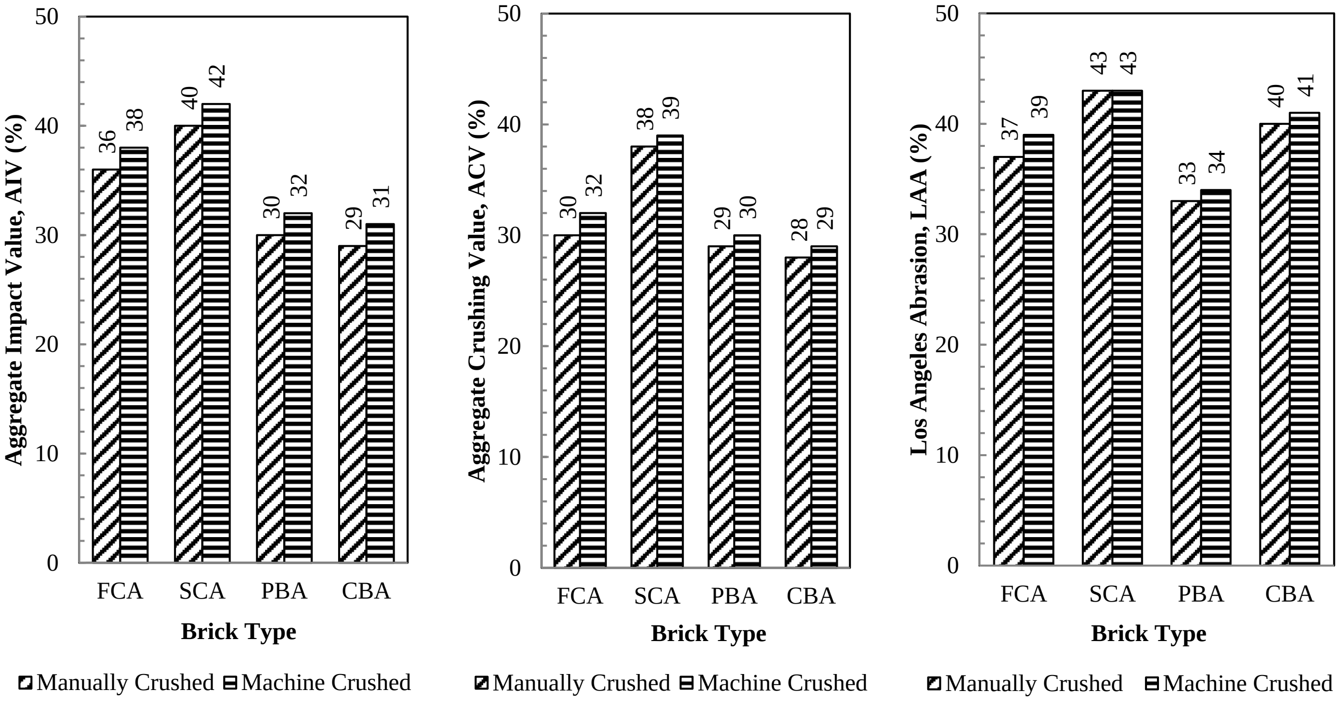
E. Mechanical Properties of Brick Aggregates

The strength of concrete is highly dependent on the mechanical properties of its constituent aggregates (Islam *et al.*, 2020; Neville, 1995). Figure 8 illustrates the mechanical properties, such as aggregate impact value (AIV), aggregate crushing value (ACV) and Los Angeles abrasion (LAA) value of brick chips as aggregates. The resistance to impact loading (aggregate impact value, AIV) and gradual crushing (aggregate crushing value, ACV) of the brick chips were measured following the specifications of BS 812-112 (1990*d*) and BS 812-110 (1990*c*) respectively. On the other hand, to determine the resistance of the brick chips against abrasion, the LA Abrasion test was carried out following the standard procedure of ASTM C131 (2015*d*).

As seen in Figure 8(a) and (b), both the AIV and ACV of manually crushed brick aggregates are less than that of the machine crushed brick aggregates. Variations in AIV mount up to an average of 6% among the machine and manually crushed brick aggregates. On the other hand, the difference in ACV among the machine and manually crushed brick aggregates is about 4% on average. A higher AIV and ACV signify that machine crushed brick aggregates have inferior quality compare to manually crushed brick aggregates. Among both the manual and machine crushed brick aggregates, the SCA has the highest ACV and AIV whereas the CBA has the lowest ACV and AIV. Among the four different types of brick aggregate CBA has the best mechanical properties and PBA has almost similar values. This is consistent with the brick crushing strength properties of PB and CB, two of the highest compressive strength brick types. As expected, the machine crushed brick aggregates had higher LAA value compared to manually crushed brick aggregates among all types of brick aggregates, as shown in Figure 8(c). However, the differences are negligible with a maximum of 5.4% for FCA. Among the four aggregate types, PBA showed the lowest LAA value whereas the variation of LAA values for manually crushed FCA, SCA and CBA are 12%, 30%, and 21%, respectively.

F. Selection of Brick Aggregate

The physical and mechanical properties of aggregates have a notable effect on the strength properties of concrete (Islam *et al.*, 2020). Based on the size, shape, and strength properties study, it is evident that FCA, PBA and CBA have good properties and can be used as coarse aggregate in concrete. However, CBA has higher flakiness, elongation and LAA values compare to FCA and PBA for manually and machine crushing processes. Therefore, for the present study only FCA and PBA were used for the preparation of concrete.



(a) (b) (c)

Figure 8: Mechanical properties comparison of four types of manually and machine crushed brick aggregates: (a) aggregate impact value (AIV), (b) aggregate crushing value (ACV), and (c) Los Angeles abrasion (LAA) value

3. CONCRETE PREPARATION

Concrete cylinders of a target strength of 25 MPa were prepared to investigate the compressive and tensile strength imparted by the brick aggregates derived from the two said methods of crushing in the previous sections. The concrete mix was designed using ordinary Portland cement, Sylhet sand and the number of mix designs followed the number of variations in the coarse aggregates. Four types of aggregates, namely FCA - machine crushed, FCA - manually crushed, PBA - machine crushed and PBA - manually crushed were adopted as coarse aggregate for the present study. In all four mix designs, the water-cement ratio was kept constant to 0.5. Mix proportions were performed according to ACI 211.1 (1994). Table 5 describes the mix proportions for 1 cum of concrete with four different aggregate types. ASTM C192 (2015*g*) was followed during the mixing and curing of concrete cylinders having 100 mm diameter and 200 mm height. For each combination 12 cylinders were prepared.

Table 5
Mix proportion for 1 cum of concrete (by weight)

Designation	w/c ratio	Water (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
FCA-Manual	0.5	200	400	773	658
FCA-Machine	0.5	200	400	777	658
PBA-Manual	0.5	200	400	729	687
PBA-Machine	0.5	200	400	752	674

4. COMPARISON OF CONCRETE STRENGTH

Concrete cylinders were prepared with four different types of aggregates. Strength tests were conducted at 14 and 28 days after 14 and 28 days curing, respectively. Just before the test, samples were gathered from the curing tank. Samples were then surface dried, measured and weighed. Compressive and tensile strengths were measured in a 2000 kN capacity ELE 36-4150/01 compression testing machine. Compressive strength of concrete was obtained following ASTM C39 (2015a) and split tensile strength was performed according to ASTM C496 (2011c).

A. Compressive Strength

The compressive strength of concrete with FCA and PBA was determined at 14 and 28 days. At each of the 14th and 28th days, three samples per combination were tested and their average was calculated. Compressive strength results are presented in Figure 9 for both manually and machine crushed brick aggregate concrete. As shown in the figure all the specimens have compressive strength greater than 25 MPa at 28 days of age. Moreover, concrete with manually crushed FCA produced the highest compressive strength (26.7 MPa at 28 days) and it was only 1% higher than the manually crushed PBA concrete. As discussed in the previous section, PBA has better strength properties, lower AIV, ACV and LAA values, compare to FCA. However, FCA has better shape properties, lower flakiness, and elongation values, compare to PBA. Therefore, it can be summarized that the better shape properties of FCA concrete compensate for the inferior strength properties while considering the concrete compressive strength.

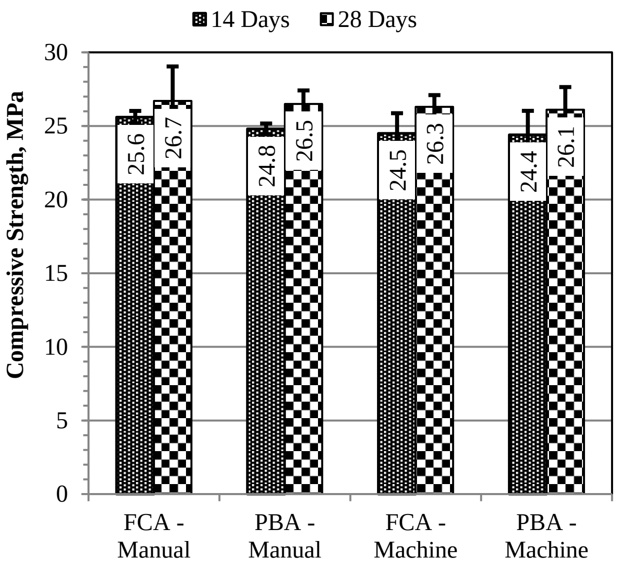


Figure 9: Variation of compressive strength with different concrete types

In both the types of bricks studied for compressive strength, manual crushing of the aggregates yields higher strength compared to the machine crushed ones. A possible reason for this may be due to the difference in the quality of the aggregates. It is observed in Figure 7 that machine-crushed aggregates have higher flakiness and elongation Indices. As a higher number of flaky and elongated particles leads to lower strength of the aggregate, this could be one of the main reason for lower compressive strength of concrete specimens made with machine crushed brick aggregates compare to the manually crushed brick aggregate. The maximum decrease (2.2%) in compressive strength is found in PBA - Machine concrete at 28 days when compared between manual and machine crushing.

B. Tensile Strength

Splitting tensile strength of concrete was measured at 14 and 28 days and the results are presented in Figure 10. Both manually crushed FCA and PBA concrete had similar tensile strength at both 14 and 28 days, and higher tensile strength compared to the machine crushed brick aggregate concrete. Although the reduction in tensile strength at 28 days for FCA – Machine is 3.7% the reduction is found to be the largest (18.5% at 28 days) for PBA - Machine when it is compared between manually and machine crushed. Higher values of flakiness and elongation indices for PBA results in lower compressive strength for machine crushed brick aggregate concrete.

C. Comparison of Strengths with Standard Codes

There is a strong correlation between the compressive and splitting tensile strengths of concrete. Various codes, such as ACI 318-14 (2014) and fib (2010), proposed equations and guidelines to predict splitting tensile strengths from the compressive strengths, as shown in Table 6. However, these equations are heavily influenced by the density of the concrete. ACI 318-14 defines concrete to be normal weight and lightweight if the density of concrete is within 2155 to 2560 kg/m^3 and 1440 to 1840 kg/m^3, respectively (ACI, 2014). On the other hand, according to fib (2010), density of normal weight concrete ranges between 2000 to 2600 kg/m^3. In the present study, densities of FCA and PBA concrete are 2035 kg/m^3 and 2025 kg/m^3, respectively. Therefore, the FCA and PBA concrete can be categorized as normal weight concrete for fib (2010) and the equation proposed in Table 6 can be used for predicting tensile strength. However, these concretes are not either normal weight or lightweight concrete according to ACI 318-14. Hence, the equation proposed by ACI 318-14 has a modification factor (λ) to consider the effect of lightweight concrete. For a normal weight fine aggregate and blended (lightweight and normal weight) coarse aggregate, modification factor may vary between 0.85 to 1 (ACI, 2014).

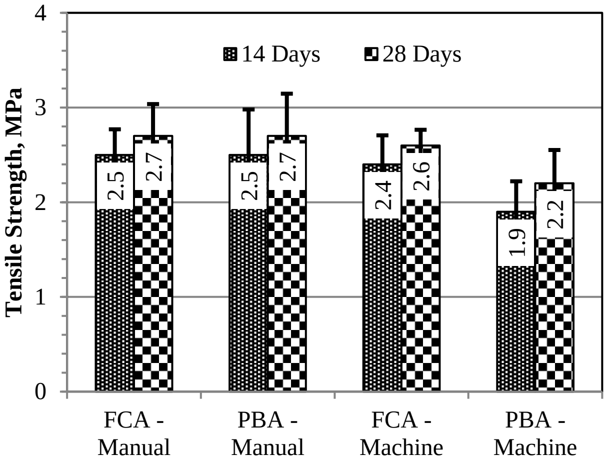


Figure 10: Variation of tensile strength with age for different concrete types

Using equations mentioned in Table 6, splitting tensile strength of concrete can be predicted from the experimental compressive strength as displayed in Figure 11. As observed from the figure, using a modification factor of 0.94, ACI 318-14 equation gives a very good prediction (-0.4% to 3.1%) of the experimental tensile strength data for all concrete types except for the machine crushed PBA concrete. For the machine crushed PBA concrete the variation is 21.4%. On the other hand, fib (2010) underestimates (1%) the tensile strength for manually crushed concrete and overestimate ($2 - 20\%$) for machine crushed concrete.

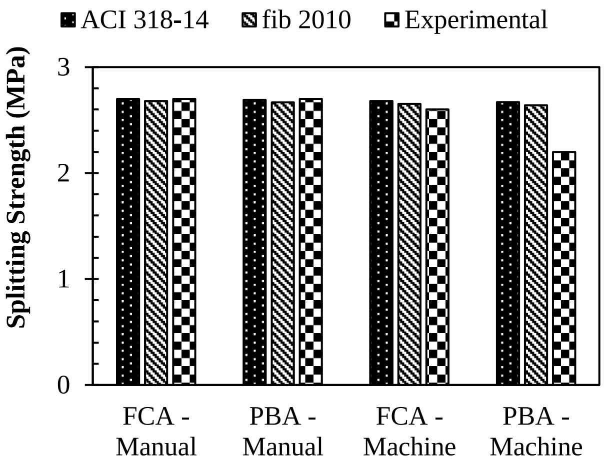


Figure 11: Comparison of splitting tensile strength with different equations

Table 6

Proposed equations and guidelines by various codes

Code	Proposed Equations	Description
ACI 318-14 (2014)	$f_{cts} = 0.556\,\lambda\sqrt{f_C'}$	Where, f_{cts} = mean splitting tensile strength in MPa, f_C' = the compressive strength of concrete in MPa and λ = modification factor
fib (2010)	$f_{ctu} = 0.3\,(f_C')^{\frac{2}{3}}$	Where, f_{ctu} = mean uniaxial tensile strength in MPa, and f_C' = compressive strength in MPa

5. CONCLUSIONS

The results of this present study have led to the following conclusions.

- The strength of the brick has no apparent effect on the strength of concrete specimens. Compressive strengths of picket brick (PB) and ceramic brick (CB) are 61% and 30% higher than the first class (FC) brick, respectively. Whereas compressive and tensile strengths of concrete casted with manually crushed FCA and PBA are varied up to 1%.
- In terms of wastage production (cumulative percent passing $2.36\,mm$ sieve) during brick crushing, the manual crushing procedure is found to be more economical than machine crushing as evidenced by as high as 14.5% of wastage for FC brick after machine crushing. On the contrary, manual crushing for FC results in as low as 1.8% wastage.
- The machine crushed brick aggregates have a substandard size, shape, and strength properties compared to the manually crushed ones as indicated by the higher flakiness index ($6 - 25\%$), elongation index ($10 - 16\%$), aggregate impact value ($5 - 7\%$), aggregate crushing value ($3 - 7\%$), and LA abrasion value ($0 - 6\%$).
- Higher-strength PB has produced better aggregate in terms of aggregate strength. Compared to FCA, PBA has 17% lower AIV, 3% lower ACV and 11% lower LAA value for the manually crushing process. However, higher strength bricks produce flakier and elongated aggregates. In comparison to manually crushed FCA, PBA has a 14% higher flakiness index and a 32% higher elongation index. Although CBA has better strength properties it has 36% and 39% higher flakiness and elongation indices, respectively.
- In general, for high-performance concrete both physical and mechanical properties of aggregate is one of the major conditions for achieving higher strength. However, in the present study for concrete with compressive strength of $27\,MPa$ or less, physical properties (such as size and shape) are found to be more defining factors than the strength properties of aggregates. At 28 days, the compressive strength of concrete made with manually crushed aggregate showed better results than the machine crushed aggregate concrete. Furthermore, manually crushed FCA concrete showed a 1% higher compressive strength than the manually crushed PBA concrete. Machine crushed aggregate concrete showed up to 18.5% lower split tensile strength compares to the manually crushed aggregate concrete and it was significant for machine crushed PBA concrete.
- The available design guidelines and equations can predict the splitting tensile strength of brick aggregate concrete. Except for machine crushed PBA

concrete, both ACI 318 and fib (2010) can predict the splitting tensile strength with good accuracy from the compressive strength of concrete.

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