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Recycling of concrete as coarse aggregate: An extended study

M.T. Uddin, M. Alam, M. Hoque, M.I. Miraz & M. Fuad
Department of Civil and Environmental Engineering, Islamic University of Technology (IUT), Organization of Islamic Cooperation (OIC) Gazipur 1704, Bangladesh

ABSTRACT: A detailed investigation was carried out to investigate the possibility of recycling of concrete made with brick aggregate as coarse aggregate. Demolished concrete blocks were collected from 11 demolished building sites of different ages and then crushed into coarse aggregate manually. Physical properties of recycled brick aggregate, such as specific gravity, absorption capacity and abrasion were evaluated. More than 300 cylindrical concrete specimen of diameter 100 mm and height 200 mm were made using recycled aggregates with W/C = 0.45 and 0.55. The specimens were tested at 7, 14, 28 days for compressive strength, Young's modulus and UPV. Specimens were also tested at 28 days for tensile strength. The results were compared with virgin brick aggregate as control aggregate. The experimental results revealed that recycled brick aggregates have lower absorption capacity compared to the virgin brick aggregate. The average strength of concrete made with recycled brick aggregate was found to be 22.8 MPa and 20.5 MPa for W/C=0.45 and 0.55 respectively.

1 INTRODUCTION

From the view of sustainability, consumption reduction of natural resources is an important factor for sustainable natural resources. Concrete is a material which is known for using a lot of non-renewable natural resources and also has a huge demand in the rising construction industries. It has been reported that concrete consumption in the world is estimated at 2.5 tons per capita per year which is equivalent to 17.5 billion tons for seven billion populations in the world (Mehta, 2001). To prepare this huge volume of concrete, 1.75 billion tons of water, 2.62 billion tons of cement, 13.12 billion tons of aggregate are necessary (Mohammad et al, 2014). Generally, aggregates are produced by crushing rocks which are collected by cutting mountains or breaking river gravels or boulders or by breaking clay bricks. A significant amount of natural resources can be saved if demolished concrete is recycled for new construction works. Construction and demolition waste (CDW) in USA has been reported to be close to 170 million tons in 2010 and the global demolition waste has been reported to be 2~3 billion tons (Torring & Lauritzen, 2002; Arora & Singh, 2016). In general, this huge amount of demolished waste is dumped in open places which does not only occupy a lot of space but also increases the environmental concerns related to disposal. Utilizing CDW in concrete as aggregate can make natural resources sustainable. In addition, recycling of demolished concrete will also provide some other benefits, such as creation of additional business opportunities, saving cost of disposal, saving money for local government and other purchaser, helping local government to meet the goal of reducing disposal, etc. Sixty to seventy percent of demolished concrete is used as sub-base aggregate for road construction (Yanagibashi et al, 2002). By recycling of demolished concrete, 30% of normal aggregates can be saved. It has been also estimated that in the next ten years, the amount of demolished concrete will increase to 7.5~12.5 billion tons Torring & Lauritzen, 2002). If technology and public acceptance of using recycled aggregate can be developed, then there will be no necessity for virgin aggregate if 100% of demolished concrete is recycled for new construction works.

In Bangladesh, the volume of demolished concrete is rapidly increasing due to the deterioration of concrete structures as well as the replacement of many low-rise buildings by relatively high-rise buildings due to the flourishment of real estate business. Disposal of the demolished concrete is turning to be a great concern to the developers of buildings. If demolished concrete can be used for new construction, the disposal problem will be solved, the demand for new aggregates will also reduce and at last consumption of the natural resources for making virgin brick aggregate will be reduced. In some project sites, it was found that a portion of the demolished concrete is used as aggregate in foundation works without any research on recycled aggregates (Mohammed et al, 2019). In most of the old buildings, brick chips have been used as coarse aggregate of concrete. Studies related to the recycling of demolished concrete are generally found for stone chips made concrete (Alan, 1997; Gomez et al, 2002). Therefore, detail investigations on recycling of brick made demolished concrete are necessary. With this background, this study was planned in 2004 with an objective of sustainable development of construction materials in Bangladesh (Mohammed, 2007). Extensive investigations on recycling of demolished concrete as coarse aggregate were conducted after collecting demolished concrete blocks from 39 demolished building sites. The results revealed that demolished concrete blocks can be recycled as coarse aggregate for utilization in structural concrete (Mohammed et al, 2015; Mohammed et al, 2019)**.** To make a strong foundation of this research work, it has been decided to extend the study to 11 additional demolished building sites to make total sample size to aggregate collected from demolished building sites to 50. Therefore, demolished concrete blocks from eleven different demolished building sites were collected for further detail investigation. There is a plan to make a complete guideline of recycling of concrete utilizing all data collected from 50 different demolished building sites. In this report, the results related to this extended investigation are only reported. To improve compressive strength of recycled aggregate concrete, some cases were also investigated with low W/C and application of super-plasticizer and these results are also summarized in this report.

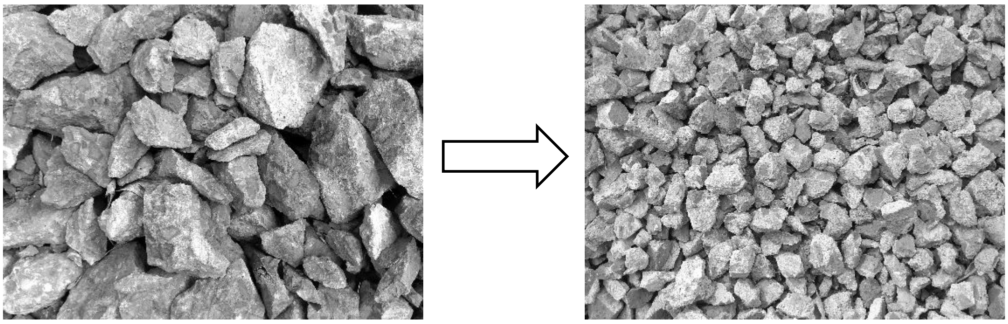

Figure 1. Demolished concrete blocks and recycled coarse aggregate.

2 EXPERIMENTAL METHODS

2.1 *Material Properties*

Demolished concrete blocks of structural members from eleven separate demolished buildings were collected. The ages of the buildings at the time of demolition were 24 years to 60 years. The collected concrete blocks samples were broken into pieces manually in three particular sizes as 25 mm to 20 mm, 20 mm to 10 mm, and 10 mm to 5 mm. The demolished concrete blocks and recycled aggregates are shown in Figure 1. After breaking into pieces, the aggregates were mixed as 5% from 25 mm to 20 mm, 57.5% from 20 mm to 10 mm, and 37.5% from 10 mm to 5 mm as per ASTM C33-01. Physical properties of the aggregates were tested such as specific gravity, unit weight, absorption capacity, and abrasion. The specific gravity and absorption capacity are determined according to ASTM C128, unit weight according to ASTM C29, and abrasion value according to ASTM C131. For comparison first class brick aggregates which are generally available in Bangladesh were used as a control case. River sand was used as fine aggregate. The fineness modulus (FM), water absorption and specific gravity of sand were 2.70, 3.83%, and 2.49, respectively. Tap water was used as mixing water. The temperature of the mixing water was around 20^{0}C. Saturated surface dry sand and coarse aggregate were used for preparing concrete specimens.

2.2 *Mixture Proportion and Cases Studied*

To investigate workability, compressive strength, splitting tensile strength, UPVs and Young's modulus of concrete, 26 mixture proportions were prepared by using recycled brick aggregates collected from 11 different demolished building sites. The investigated cases and detailed mixture proportions are summarized in Table 1 and Table 2 respectively. Water-to-cement ratios (W/C) of concrete were 0.45 and 0.55. Cement content of concrete was 340 kg/m^3. Sand to aggregate (fine aggregate plus coarse aggregate) ratio was 0.44. To produce high strength concrete using recycled aggregate, several mixture proportions with cement content of 500 kg/m^3 and 450 kg/m^3 and W/C of 0.40 and 0.35 were also prepared. Sulfonated naphthalene polymer based superplasticizer was used for these cases to improve workability of concrete.

Table 1. Cases investigated (26 Cases).

Cases	Description
FB45	1st class Brick Aggregate - W/C Ratio 0.45
FB55	1st class Brick Aggregate - W/C Ratio 0.55
R25WC45	Recycled Brick Aggregate - 25 Years Old - W/C Ratio 0.45
R25WC55	Recycled Brick Aggregate - 25 Years Old- W/C Ratio 0.55
R30WC45	Recycled Brick Aggregate - 30 Years Old- W/C Ratio 0.45
R30WC55	Recycled Brick Aggregate - 30 Years Old- W/C Ratio 0.55
R60WC45	Recycled Brick Aggregate - 60 Years Old- W/C Ratio 0.45
R60WC55	Recycled Brick Aggregate - 60 Years Old- W/C Ratio 0.55
R38WC45	Recycled Brick Aggregate - 38 Years Old- W/C Ratio 0.45
R38WC55	Recycled Brick Aggregate - 38 Years Old- W/C Ratio 0.55
R24WC45	Recycled Brick Aggregate - 24Years Old- W/C Ratio 0.45
R24WC55	Recycled Brick Aggregate - 24Years Old- W/C Ratio 0.55
R52WC45	Recycled Brick Aggregate - 52 Years Old- W/C Ratio 0.45
R52WC55	Recycled Brick Aggregate - 52 Years Old- W/C Ratio 0.55
R45WC45	Recycled Brick Aggregate - 45 Years Old- W/C Ratio 0.45
R45WC55	Recycled Brick Aggregate - 45 Years Old- W/C Ratio 0.55
R32WC45	Recycled Brick Aggregate - 32 Years Old- W/C Ratio 0.45
R32WC55	Recycled Brick Aggregate - 32 Years Old- W/C Ratio 0.55
R50WC45	Recycled Brick Aggregate - 50 Years Old- W/C Ratio 0.45
R50WC55	Recycled Brick Aggregate - 50 Years Old- W/C Ratio 0.55
R48WC45	Recycled Brick Aggregate - 48 Years Old- W/C Ratio 0.45
R48WC55	Recycled Brick Aggregate - 48 Years Old- W/C Ratio 0.55
R48WC40-500	Recycled Brick Aggregate - 48 Years Old- W/C Ratio 0.40 and cement content=500 kg/m^3
R48WC35-450	Recycled Brick Aggregate - 48 Years Old- W/C Ratio 0.35 and cement content=450 kg/m^3
R33WC45	Recycled Brick Aggregate - 33 Years Old- W/C Ratio 0.45
R33WC55	Recycled Brick Aggregate - 33 Years Old- W/C Ratio 0.55

Table 2. Mixture proportions of concrete (26 Cases).

Case	*W/C*	*s/a*	Unit Content (kg/m^3)				Chemical Admixture (ml/kg cement)
			Cement	Water	Fine Aggregate	Coarse Aggregate	
FB45	0.45	0.44	340	153	786	884	0
FB55	0.55	0.44	340	187	749	842	0
R25WC45	0.45	0.44	340	153	786	832	0
R25WC55	0.55	0.44	340	187	749	792	0
R30WC45	0.45	0.44	340	153	786	840	0
R30WC55	0.55	0.44	340	187	749	800	0
R60WC45	0.45	0.44	340	153	786	815	0
R60WC55	0.55	0.44	340	187	749	777	0
R38WC45	0.45	0.44	340	153	786	815	0
R38WC55	0.55	0.44	340	187	749	777	0
R24WC45	0.45	0.44	340	153	786	787	0
R24WC55	0.55	0.44	340	187	749	750	0
R52WC45	0.45	0.44	340	153	786	848	0
R52WC55	0.55	0.44	340	187	749	807	0
R45WC45	0.45	0.44	340	153	786	864	0
R45WC55	0.55	0.44	340	187	749	823	0
R32WC45	0.45	0.44	340	153	786	840	0
R32WC55	0.55	0.44	340	187	749	800	0
R50WC45	0.45	0.44	340	153	786	836	0
R50WC55	0.55	0.44	340	187	749	796	0
R48WC45	0.45	0.44	340	153	786	845	0
R48WC55	0.55	0.44	340	187	749	807	0
R48WC40-500	0.40	0.44	500	200	678	731	10
R48WC35-450	0.35	0.44	450	158	742	800	10
R33WC45	0.45	0.44	340	153	786	836	0
R33WC55	0.55	0.44	340	187	749	796	0

Concrete cylinders of diameter 100 mm and height of 200 mm were made for evaluation of compressive strength at 7, 14, and 28 days as per ASTM C39-03. Total time of concrete mixing was controlled at 5.5 minutes. After mixing concrete, the workability of concrete was immediately measured by slump cone test. Cylinder concrete specimens were made and demolded after one day of casting. Then the specimens were cured in a curing tank keeping the specimens in submerged condition in tap water. The compressive strength of concrete was measured at 7, 14, and 28 days by using a 2000 KN compression machine. Split tensile strength tests were also carried out at 28 days. During compression test, a compressometer with two dial gauges (one small division = 0.001 mm) was fastened over the specimens. The gauge length was 100 mm. The deformations were measured corresponding to the applied loads. The Young's modulus of concrete was determined from the stress-strain curves. The secant modulus method was used to determine the Young's modulus of concrete. Ultrasonic Pulse Velocity (UPV) through concrete was also measured before crushing of the specimens for compressive strength. All together 312 concrete specimens were investigated.

Table 3. Properties of aggregates investigated.

Type	Age (Years)	Specific gravity	Unit weight (kg/m^3)	Absorption capacity (%)	Abrasion (%)
FB	-	2.20	1411	17.1	39
RCA25	25	2.07	1027	10.6	41
RCA30	30	2.09	1058	10.8	43
RCA60	60	2.03	1068	12.6	46
RCA38	38	2.03	972	13.6	47
RCA24	24	1.96	920	14.1	49
RCA52	52	2.11	1033	14.0	44
RCA45	45	2.15	1072	11.6	43
RCA32	32	2.09	1050	13.7	44
RCA50	50	2.08	1044	16.0	41
RCA48	48	2.11	1076	15.1	42
RCA33	33	2.08	1028	12.4	44

3 RESULTS AND DISCUSSION

3.1 *Properties of Aggregate*

The properties of recycled brick aggregates are summarized in Table 3. Also properties of first class brick aggregate were investigated for comparison. The ages of the recycled brick aggregate collected from 11 different demolished reinforced concrete building sites were 25, 30, 60, 38, 24, 52, 45, 32, 50, 48 and 33 years. Brick aggregate was used during construction of these buildings. In general, the absorption capacity of the recycled aggregates was lower than the first class brick aggregates. The abrasion value of recycled brick aggregate (41% ~ 49%) was higher than the same for the first class brick aggregate (39%). However, the abrasion value of recycled aggregate is lower than the maximum abrasion value (50%) as specified in ASTM C33-01. From these data, it is understood that recycled brick aggregate is better in terms of absorption capacity compared to the control aggregate, i.e. brick aggregate; but in terms of abrasion resistance not superior compared to the good quality brick aggregate commonly used in Bangladesh. Similar results were also observed in a different study conducted on recycled aggregate collected from 6 different building sites (Mohammed et al, 2019).

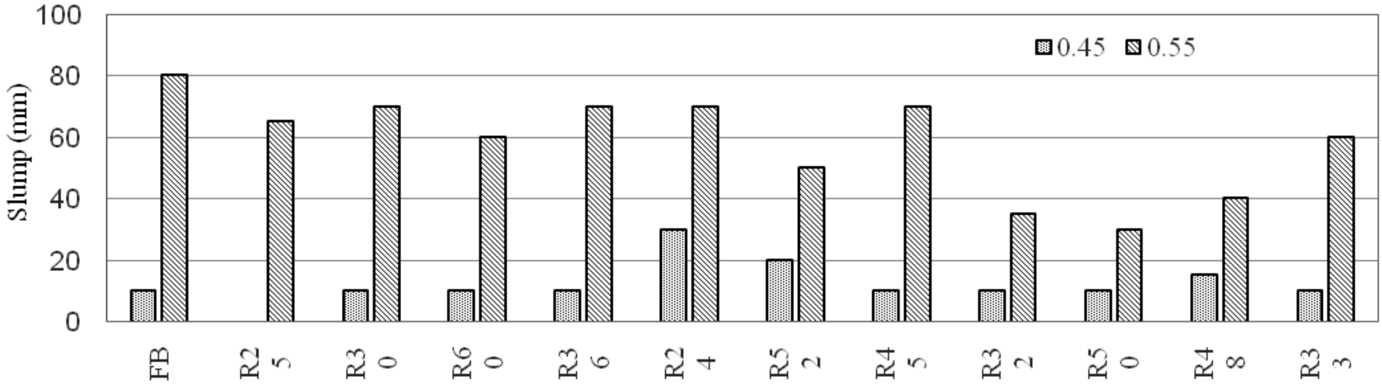

Figure 2. Workability of concrete (W/C-0.45 and 0.55).

3.2 *Workability of Concrete*

The workability of concrete as slump (in mm) is shown in Figure 2 for W/C=0.45 and 0.55. More workability of concrete is found for concrete made with higher W/C. For W/C=0.55, it has been found that workability of the recycled brick aggregate concrete is relatively lower compared to the first class brick aggregate concrete (FB).

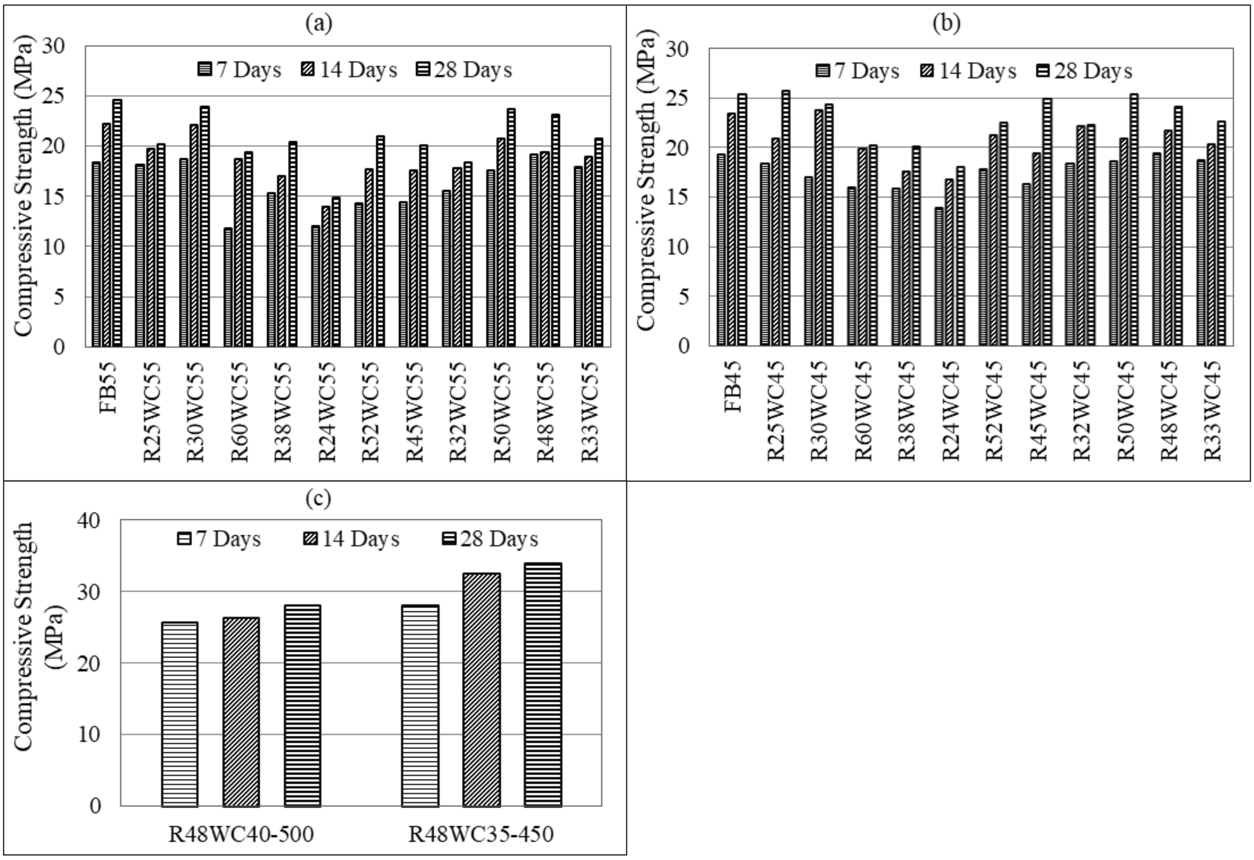

Figure 3. Compressive strength of concrete (a) W/C-0.45; (b) W/C-0.55; (c) W/C-0.40 and 0.35.

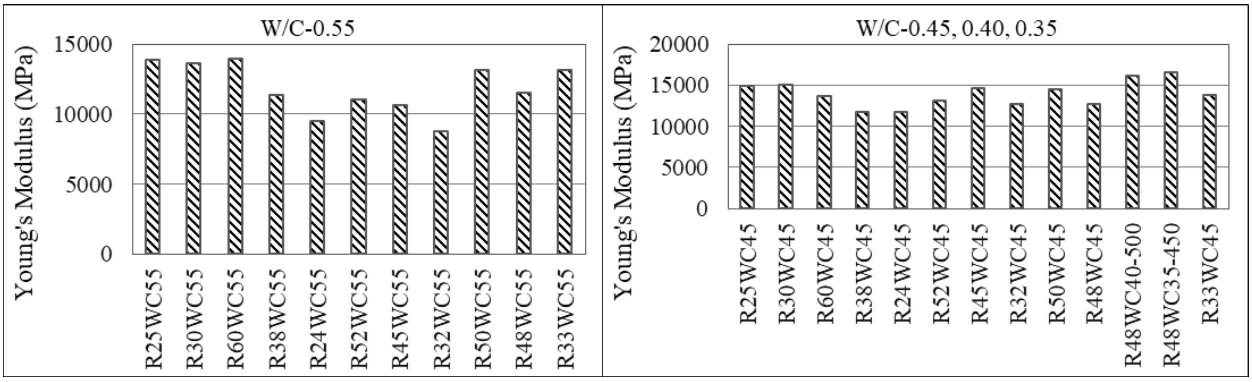

Figure 4. Young's modulus of concrete.

3.3 *Compressive Strength of Concrete*

Compressive strengths of concrete at 7, 14 and 28 days are shown in Figure 3. For most of the cases made with W/C= 0.55, a reduction (8% ~ 40%) in strength for recycled brick aggregate concrete is found compared to the first class brick aggregate concrete (FB55). But for W/C=0.45, the compressive strength of recycled aggregate concrete becomes closer to the first class brick aggregate concrete (FB45) for several cases. For some cases, the compressive strength is reduced by 30% compared to the brick aggregate. The results also indicate that for a low W/C, recycled brick aggregate concrete shows better performance compared to concrete made with high W/C with respect to compressive strength. It has been understood that, for recycling of demolished aggregate concrete as coarse aggregate, it is necessary to reduce W/C.

An attempt was also made to increase compressive strength of recycled aggregate concrete by reducing W/C (such as 0.40 and 0.35) and increasing cement content (500 kg/m^3 and 450 kg/m^3). Sulfonated naphthalene polymer based superplasticizer was used for these cases to improve workability. These results are also shown in Figure 3. It is found that compressive strength of recycled aggregates concrete is increased to 33.9 MPa due to increase of cement content and reduction of W/C.

3.4 *Young's Modulus of Concrete*

Young's modulus of concrete was investigated at 28 days only. The results are shown in Figure 4. As found for compressive strength of concrete, the Young's modulus of concrete is higher for W/C=0.45 compared to W/C=0.55. Also, the performance of recycled brick aggregate concrete is improved with the reduction of W/C to 0.40 and 0.35. Same as compressive strength data, Young's modulus data also indicate that for effective utilization of recycled brick aggregate, it is necessary to reduce W/C.

3.5 *Tensile Strength and Compressive Strength Relationship*

The variation of tensile strength with square root of compressive strength of concrete is shown in Figure 5. The following linear relationship between tensile strength, f_t (MPa) and square root of compressive strength, f'_c (MPa) of concrete is proposed.

$$f_t = 0.56\,\gamma\,\sqrt{f_c'} \qquad (1)$$

where γ is a factor that is to be introduced in the empirical equation of ACI 318 for the case of recycled brick aggregate concrete. The value of $\gamma$is found to be 0.806. In another study, the value of γ was reported as 0.68 (Mohammed et al, 2019).

3.6 *Young's Modulus and Compressive Strength Relationship*

The variation of Young's modulus (E_c in MPa) and square root of compressive strength of concrete ($f'c$) is shown in Figure 6. The following linear relationship between Young's modulus, E_c (MPa) and square root of compressive strength, $f'c$ (MPa) of concrete is proposed:

$$E_c = 4700\,\alpha\,\sqrt{f_c'} \qquad (2)$$

where α is a factor that is to be introduced in the empirical equation of ACI 318. The value of α is found to be 0.59 for recycled brick aggregate concrete. In another series of study on recycled brick aggregate, the value of αhas been reported as 1.08 (Mohammed et al, 2019).

3.7 *Strength Verses Time Relationship*

The strengths of recycled aggregate concrete for 7 and 14 days were normalized by the corresponding 28-day strength. The results are shown in Figure 7. The following logarithmic relationship between normalized compressive strength with age of concrete is proposed.

$$\frac{f'c(t)}{f'c} = 0.1801\,ln\,t + 0.4289 \qquad (3)$$

where $f'_c(t)$ is compressive strength (MPa) age at t days and compressive strength, f'_c(MPa) at 28 days. From this relationship, compressive strength of recycled brick aggregate concrete at 28 days can be obtained, if compressive strength of concrete is known at 3 days, 7 days, or 14 days.

3.8 *Compressive Strength Verses UPV Relationship*

The variation of compressive strength of recycled aggregate concrete with Ultrasonic Pulse Velocity (UPV) is shown in Figure 8. The following exponential relationship is proposed between compressive strength and UPV through concrete:

$$f'c = 1.1171e^{0.0008\,UPV} \qquad (4)$$

3.9 *Stress-Strain Relationship*

The variation between normalized stress (normalized stress = particular level of stress divided by compressive strength of concrete) with strain of concrete made with recycled brick aggregate is shown in Figure 9. The following nonlinear relationship is proposed between stress and strain of concrete made with recycled brick aggregate:

$$\frac{f_c}{f'_c} = \frac{1.7718\,\varepsilon}{0.0018+\varepsilon};\ \ 0 \le \varepsilon \le 0.0023 \qquad (5)$$

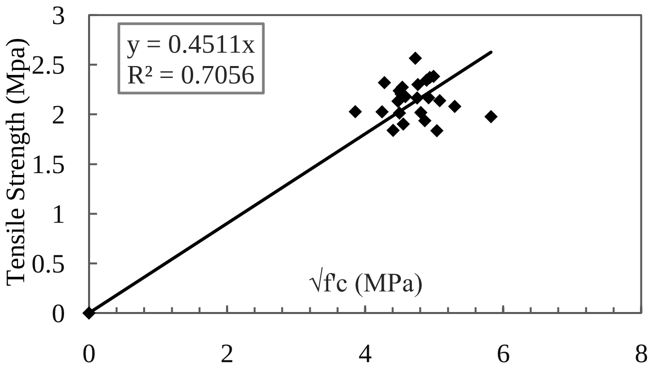

Figure 5. Tensile strength and compressive strength at 28 days.

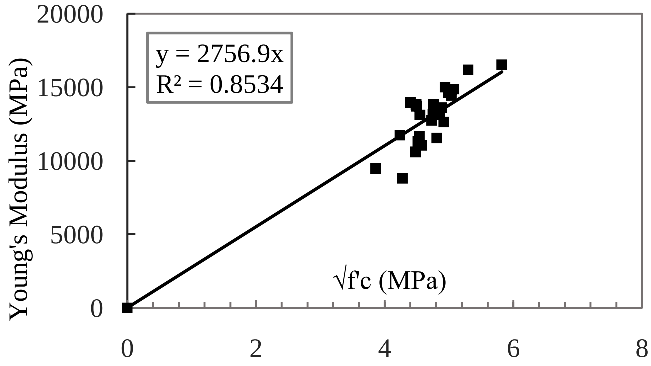

Figure 6. Young's modulus and compressive strength at 28 days.

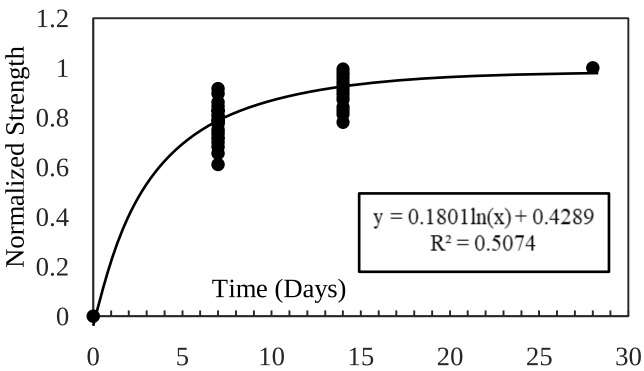

Figure 7. Variation of normalized strength with time.

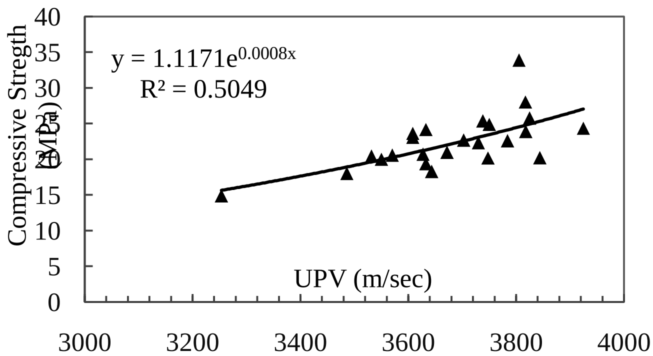

Figure 8. Compressive strength and UPV at 28 days.

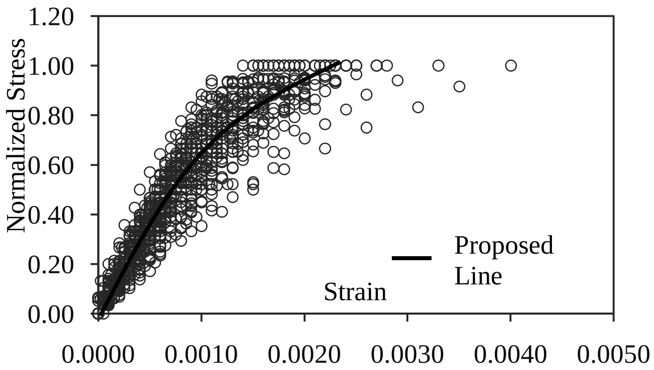

Figure 9. Stress-strain curve of concrete.

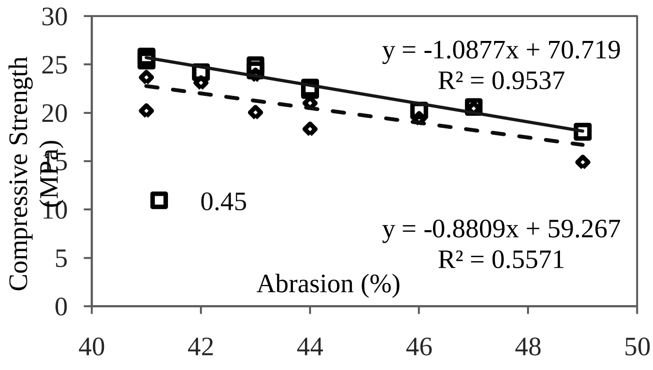

Figure 10. Compressive strength and abrasion (%) of recycled brick aggregate.

3.10 *Compressive Strength and Abrasion Value of Recycled Aggregate*

The variation of compressive strengths with the abrasion values of recycled aggregate is shown in Figure 10. It is observed that irrespective of W/C, the compressive strength is reduced with the increase of the wear value. Similar results were also reported in other studies for concrete made with recycled brick aggregate (Mohammed et al, 2019). The following relationships are proposed between compressive strength of concrete (f'c in MPa) and abrasion values (*A* in %) for W/C-0.45 and 0.55 respectively:

$$f'c = -1.0877\,A + 70.719 \qquad (6)$$

$$f'c = -0.8809\,A + 59.267 \quad (7)$$

If the abrasion value of recycled aggregate (in %) is known, it is possible to predict the compressive strength made with the same recycled aggregate for W/C = 0.45, cement content = 340 kg/m^3 and W/C=0.55, cement content = 340 kg/m^3.

3.11 *Statistical Analysis of Data for Compressive Strength*

Using normal distribution, Probability Density Function (PDF) and Cumulative Density Function (CDF) of 28-day compressive strength of concrete made with recycled brick aggregates collected from 11 different sites were drawn and shown in Figure 11 for W/C=0.45 and W/C=0.55, respectively. The average compressive strength for W/C=0.45 was 22.8 MPa and for W/C=0.55 was 20.5 MPa for cement content = 340 kg/m^3.

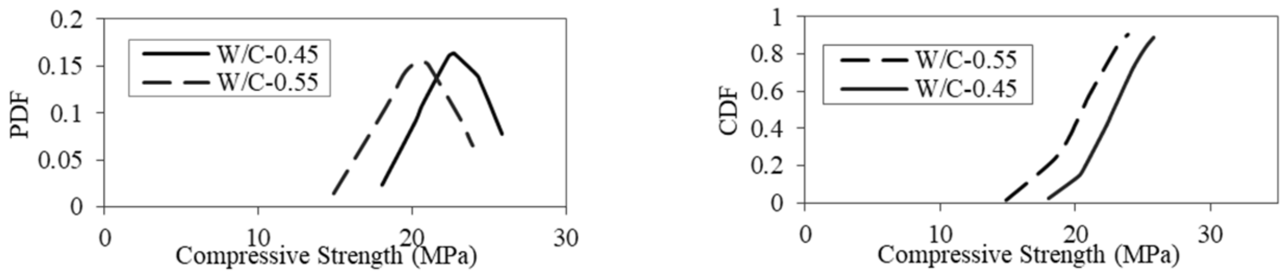

Figure 11. PDF and CDF of compressive strength of concrete made with recycled brick aggregate.

4 CONCLUSIONS

From the scope of this investigation on recycled brick aggregate, the following conclusions are drawn:

- Compared to the first class brick aggregate, recycled brick aggregate shows lower absorption capacity; but higher abrasion value.
- For recycling of brick aggregate concrete in an effective way, it is necessary to reduce W/C.
- The average strength of recycled brick aggregate concrete is found to be 22.8 MPa and 20.51 MPa for W/C=0.45, cement content = 340 kg/m^3 and W/C=0.55, cement content = 340 kg/m^3, respectively. However, by reducing W/C to 0.35 and cement content to 500 kg/m^3, compressive strength of concrete made with recycled brick aggregate can be improved to the level of 33.9 MPa.
- The relationship between Young's modulus and compressive strength of recycled brick aggregate is proposed.
- The relationships between abrasion value and compressive strength of recycled brick aggregate are proposed for W/C 0.45 and 0.55.

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