Journal of the Korea Concrete Institute
Vol. 32, No. 6, pp. 583~592, December, 2020
https://doi.org/10.4334/JKCI.2020.32.6.583

pISSN 1229-5515
eISSN 2234-2842
www.jkci.or.kr

파쇄벽돌을 굵은 골재로 사용한 콘크리트의 가격 최소화를 위한 배합설계

밀리언 타페세 [1)] · 김락현 [2)] · 양범주 [3)] · 김형기 [4)*]

[1)]조선대학교 건축공학과 박사후 연구원 [2)]포스코 E&C 대리 [3)]충북대학교 토목공학부 조교수 [4)]조선대학교 건축공학과 교수

Mix Proportioning of Concrete Containing Brick Chips as Coarse Aggregate for Cost Minimization

Million Tafesse,[1)] Rak-hyun Kim,[2)] Beomjoo Yang,[3)] and Hyeong-Ki Kim[4)]*

[1)]Postdoctoral Researcher, Department of Architectural Engineering, Chosun University, Gwangju 61452, Rep. of Korea
[2)]Assistant Manager, POSCO E&C, Incheon 22009, Rep. of Korea
[3)]Assistant Professor, School of Civil Engineering, Chungbuk National University, Cheongju 28644, Rep. of Korea
[4)]Professor, Department of Architectural Engineering, Chosun University, Gwangju 61452, Rep. of Korea

ABSTRACT Mix proportioning in terms of cost minimization was conducted for concrete containing brick chips as coarse aggregate. First, the physical and chemical characteristics of the brick chips were evaluated in detail, including computed tomography scanning, direct compressive strength measurement, and X-ray diffraction analysis, to further understand their effect on the properties of concrete. Second, the strength of brick chips concrete with various mix proportions was measured, and the proportioning of mixtures for material cost minimization based on the equivalent strength design was carried out using linear regression of the results following the local market price in the project area. By using the proposed proportioning method for brick chips concrete, it was possible to obtain a cost reduction of 5~24 % for mixtures with strengths of 25~33 MPa.

Keywords : brick chips, mix proportioning, coarse aggregate, cost minimization, regression analysis

1. Introduction

In concrete, aggregates generally have the largest volume compared to water and binders. In some locations without quarries like islands or sand deserts finding natural coarse aggregates is difficult due to limited rock deposits, and the aggregates need to be transported from another area (Butler et al. 2013). In case the haul distance is too long, the material costs will rise. Consequently, this will increase the total construction cost as well. One of the ways to solve this problem is adapting nearby alternative materials such as artificial granules, or various types of byproducts (de Brito et al. 2005; Binici 2007).

Brick chips, crushed clay, or shale bricks, can be applied as aggregates in this way. In the literature, two types of applications of brick chips for concrete have been reported: newly manufactured brick and old brick from building demolition (Mansur et al. 1999; Kim et al. 2008; Cachim 2009). The former is generally produced as alternative aggregates for a site without natural aggregates, while the latter is applied to consume the waste from building demolition (Mohammed et al. 2015). In addition, the types of bricks could also be classified by two in general: one is the sintered bricks produced by clay or silt, and another is cement-based bricks; and the former has been more frequently applied in the concrete rather than the latter (de Brito et al. 2005; Madrid et al. 2017). Furthermore, the performance of the brick chips might vary depending on manufacturing method and the source materials, but they generally have specific gravity of around 2.0 at saturated condition and water absorption of about 10 % or more (Debieb and Kenai 2008; Bolouri Bazaz and Khayati 2012). It was reported that the Los Angeles abrasion loss of brick chips was within the range of 30~40 % (Debieb and Kenai 2008), which was slightly higher or similar to natural aggregates, i.e., within the range from 15~45 %, even the strength of the brick chips was much lower than natural aggregates (Kahraman and Fener 2007). In most of the literature, the utilization of brick chips led to decreases in the compressive

*Corresponding author E-mail : hyeongki@chosun.ac.kr
Received September 14, 2020, Revised October 14, 2020, Accepted October 19, 2020

strength and elastic modulus of hardened concrete, and its effect on the slump value and density is dependent on the types of brick chips (Mansur et al. 1999; Debieb and Kenai 2008; Kim et al. 2008; Cachim 2009).

Even though there are many of researches on brick chips mechanical properties, however, most of the papers lack to analysis the brick chips physical and chemical properties in a systematic way before studying their effect as an aggregate inside a concrete. Moreover, the amount of cement in the concrete must be increased to compensate for the decrease in strength by brick chips, but no calculation examples have been reported on how much the cement content should be increased along with the brick chips content. Above all, there is limited studies showing the economical perspective of using brick chips inside a concrete in detail. Note that the decrease in cost due to the replacement of brick chips aggregate will be affected by the addition of cement to compensate the strength, which will raise the overall cost again due to an increase in binder cost. In the following study these two factors were considered in to account while finding the optimum price for the overall cost of the concrete.

In this study, brick chips were used as coarse aggregates for normal strength concrete. First, the physical and chemical characteristics of the brick chips were evaluated in detail to further understand their effect on the properties of concrete. Along with the measuring the basic physical properties of brick chips, including specific gravity, particle size distribution, and water absorption, computed tomography (CT) scanning and direct compressive strength measurements were conducted to visualize the microcracks in the particles and their effects on strength. Crystalline phases of the particles were evaluated by X-ray diffraction (XRD) spectra. Second, the strength of brick chips concrete with various mix proportions was measured, and the proportioning of mixtures for material cost minimization was carried out using linear regression of the results.

2. Materials and methods

2.1 Materials

A clay-based brick chips was supplied from local brick manufacturers of Matarbari in Bangladesh. The site is in the seashore area and there is no source of natural coarse aggregates. In this site, it is common to use brick chips as concrete aggregate for small-scale low-rise buildings. The sintering temperature of the brick was approximately 600~800 °C and the original brick was crushed by the brick manufacturer using a hand crusher. For comparison, crushed gravel was used as the natural coarse aggregate. The characterizations of brick chips and crushed gravel are described in the next section.

The Portland Type I cement from South Korea satisfying ASTM C150 (2020) was used. The strength of the cement at 28 days measured following the ASTM C109 (2016) was 38 MPa. Crushed sand with the fineness modulus (FM) of 2.85 having 2.3 % water absorption and 2.54 specific gravity was used as fine aggregate. Crushed granite gravel was used as coarse aggregate, and its properties were compared with those of brick chips in the next section.

2.2 Characterization of brick chips

2.2.1 Physical properties

The basic properties of the brick chips and crushed gravel used in the present work are listed in Table 1. The results in the table

Table 1 Basic properties of brick chip and crushed gravel

Properties (unit)		Brick chips	Normal aggregate (crushed stone)
Specific gravity	Saturated, surface dry (SSD) condition	2.12	2.69
	Oven dry (OD) condition	1.84	2.69
Apparent specific gravity (SSD)		2.57	2.71
Average bulk specific gravity		1.84	2.71
Absorption of water (wt.%)		15.33	0.37
Moisture contents after transportation (wt.%)		3~4	0.1
Bulk density (compacted) (kg/m^3)		1,130	1,580
Void in bulk aggregates (%)	Loose	38.6	41.8
	Compacted	28.9	41.1
Clay lump (%)		0.06	-
Loss on ignition (wt.%)		0.26	0.1
Fineness modulus (-)		6.83	6.50
Shape factor (-)		1.14	1.02
Sphericity (-)		0.62	0.70
Soundness against Na_2SO_4 (%)		4	-
Los Angeles abrasion loss weight (%)		47.6	-
ASR expansions (mortar-bar methods at 16 days result) (%)		0.041	-
ASR potential (chemical methods)[1)]		Innocuous[2)]	-

[1)]Withdrawn at 2016, no replacement

[2)]No potential of alkali silicate reaction (ASR) (test results of ASTM C 289-07: R_c=961~1,124 mmol/l, S_c=72~503 mmol/l; where, R_c is reduction of silica in alkalinity, and S_c is dissolved silica) demonstrate that the properties of the brick chips aggregate are all under the limitations for aggregates for structural concrete. In addition, sieve analysis results carried out according to ASTM C136 (2019) are depicted in Fig. 1, which confirms that the brick chip had almost the same particle size gradation as the crushed gravel, and the portion smaller than 1 mm, that is, crushed fines and dust, was less than 2 %. The shape factor and sphericity of the brick chips aggregates were also similar to the crushed stone.

Normalized water absorption for the brick chips by time, indicating the kinetic moisture transfer in the aggregates, are plotted in Fig. 2 along with that of a commercialized artificial lightweight aggregate, expanded shale (ES), having identical particle size and water absorption of 21.3 % (Kim and Lee 2018).

The normalized water absorption of the ES, a type of conventional porous aggregates have been used in structural

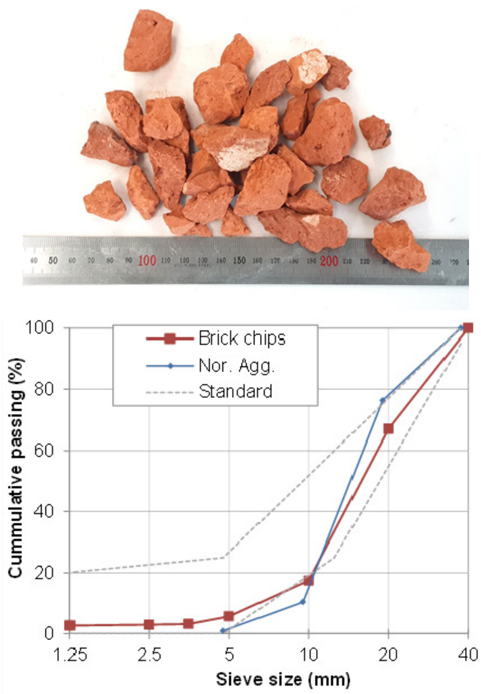

Fig. 1 Photo of brick chips (upper) and particle size distribution of normal aggregate (Nor. Agg.) and brick chips aggregate (lower)

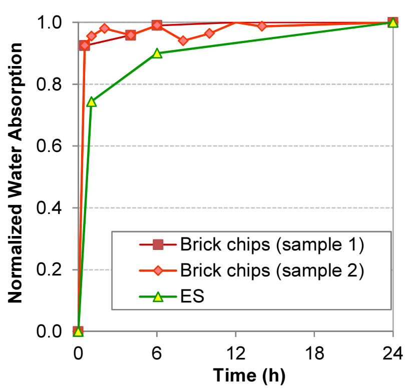

Fig. 2 Normalized water absorption of brick chip aggregate

concrete, by time was demonstrated for comparative analysis of the kinetic moisture transfer of the brick chips. Oven-dried particles were immersed in water, removed after a certain time, and then the moisture content was measured per ASTM C127-15. The moisture content of the particles was normalized by immersing in water for 24 h. Note that the normalized water absorption of ordinary gravel at first 1 h about 91 % of that at 24 h, which was similar to those of the brick chips. The absorption rate of the porous aggregates greatly influences the quality control of fresh concrete considering the losses of workability and pumpability (Choi et al. 2018).

If the aggregate has moisture content lower than the saturated surface-dry (SSD) condition, slump loss occurs because the aggregate absorbs water during compounding and transportation (Poon et al. 2004). Note that, since the absorption of natural aggregates is very low, their absorption rate over time is not considered. As shown in Fig. 2, the normalized absorption of brick chips after initial immersion was higher than that of the ES, which means that the absorption rate is faster than that of artificial lightweight aggregate. The pore connectivity of brick chips may be higher than that of artificial lightweight aggregate. If the aggregate has moisture content lower than the SSD condition, the workability decrease is proportional to the water absorption rate, and the faster the absorption rate the faster is the workability decrease (Mefteh et al. 2013).

Fig. 3 presents selected cross-section images of 3D CT scans of brick chips and normal aggregate. A CT scanner with 0.7 μm spatial resolution was used (ZEISS Xradia 520 Versa). Three 1 mm^3 specimens for each material were prepared for the CT. The relatively darker areas in the figure are pores and cracks, while the brighter areas are solid skeleton. Note that the magnifications of scanning images for both materials in Fig. 3 are identical. Natural aggregates seem to have cracks that were hardly detected by the porosimetry. In contrast, brick chips had large pores, with small pores spreading in the matrix. As a result of performing 3D scanning on a number of cross-sections in addition to those shown in this paper, it was not possible to find cracks in the brick chips.

The percentage of void on the sand-gravel mixture with various sand-to-aggregate ratio (S/a) were measured in a loose

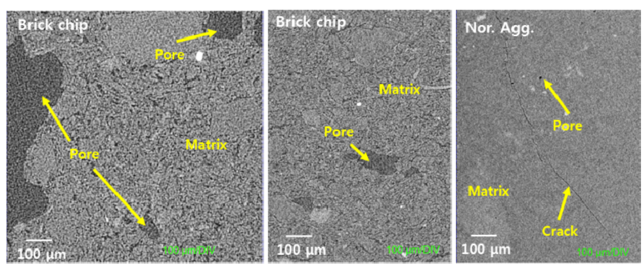

Fig. 3 CT scanning images of brick chips and normal aggregate

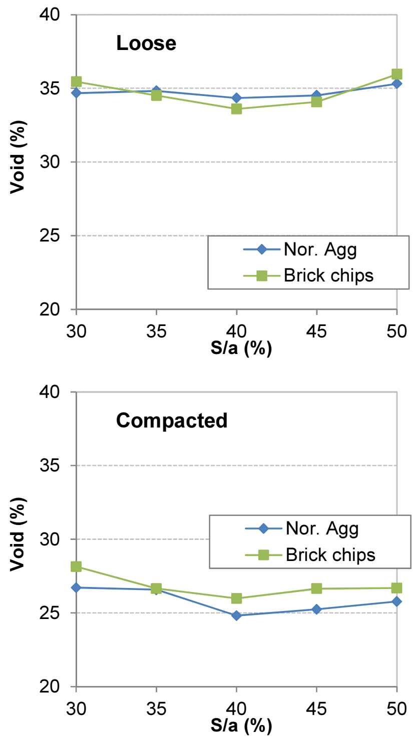

Fig. 4 Percentage of voids for loose and compacted sand to aggregate ratio percentage for normal aggregate and brick chip aggregate

and compacted situation according to ASTM C 29. The result of the void percentage is shown in Fig. 4. Here, the void content is a factor influenced by packing degree between blended aggregates. Smaller voids mean less cement paste to fill the space. That is, when the same volume of paste is added, the slump of the concrete can be increased unless the roughness of the aggregate surface is taken into consideration. The difference between ratios of the brick chips and the natural aggregate was within the range of ±3 % for all cases, which was considered insignificant.

Uniaxial compressive strength of the aggregates was measured. The aggregate retained on a 25 mm-mesh sieve was shaped to 1×1×1 cm^3 using a diamond cutter with a clamp as shown in Fig. 5. Both aggregates (natural and brick chips) were tested using UTM with 5 kN-capacity. From the results, brick chips aggregate showed strength up to a maximum of 26.6 MPa and a minimum of 5.9 MPa. Alternatively, the crushed stones showed maximum and minimum strengths of 309.4 MPa and 38 MPa, respectively. The fluctuation of strength of each aggregate was induced by several causes, such as eccentric loadings or microcracks in the aggregates. To verify the cause of the fluctuation, the porosity, that is, the volume of water-permeable pores in the aggregates matrix, was measured and the relationship between it and the strength was evaluated. Vacuum saturation and oven drying were applied to measure the porosity of each shaped aggregate sample (ASTM C127-15). To measure the mass of the single samples a high-accuracy balance having a maximum capacity of 220 g with

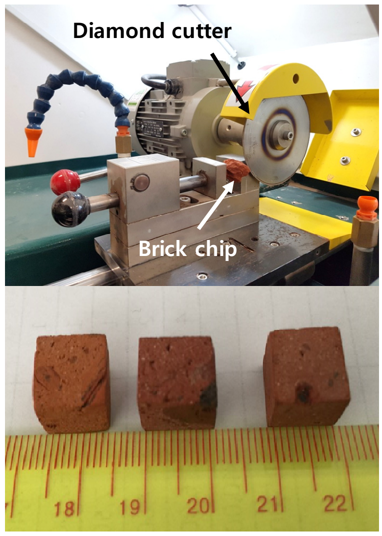

Fig. 5 Shaping of aggregates for uniaxial compression test (upper) and shaped samples (lower)

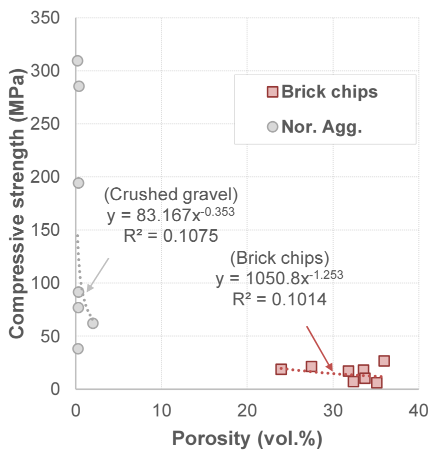

Fig. 6 Compressive strength vs. porosity of aggregates

an accuracy of 0.0001 g was used.

The porosity versus strength of the aggregate samples is plotted in Fig. 6. The strength of the normal aggregate varied highly, from 40 MPa to 300 MPa, having a maximum of 4 % porosity in volume. On the other hand, the brick chips showed a higher porosity ranging from 25 % to 35 %, with a relatively uniform strength of 10 to 20 MPa. The brick chips generally had lower strength than natural aggregates. From this, we inferred that the clay particles in the brick chips were weakly bound to each other.

2.2.2 Chemical composition

Table 2 shows the chemical composition of brick chips aggregate evaluated by X-ray fluorescence (XRF). In addition, the X-ray diffraction (XRD) spectrum of brick chips is also shown in Fig. 7. The main constituents are quartz [SiO_2], hematite [Fe_2O_3], feldspar (-$AlSi_3O_8$) series (bytownite [$NaAlSi_3O_8$], sanidine [$K(AlSi_3O_8)$]), forsterite [Mg_2SiO_4] and enstatite

Table 2 Chemical compositions of brick chip aggregate (XRF result) in percent

SiO_2	65.64	SO_3	0.05
Al_2O_3	18.32	BaO	0.05
Fe_2O_3	6.57	CeO_2	0.04
K_2O	2.99	ZrO_2	0.03
MgO	2.35	Cr_2O_3	0.03
Na_2O	1.64	ZnO	0.02
CaO	1.09	SrO	0.02
TiO_2	0.83	Rb_2O	0.02
P_2O_5	0.19	CuO	0.01
MnO	0.1	LOI	0.26

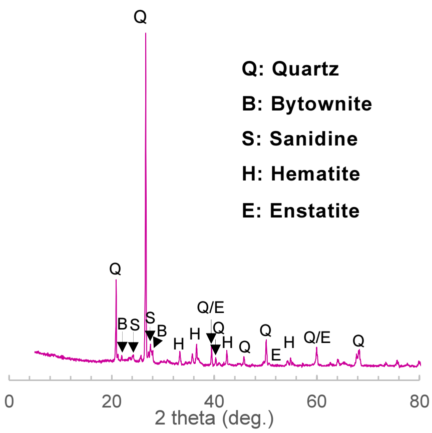

Fig. 7 XRD spectrum of brick chip aggregate

[$MgSiO_3$]. Due to low CaO content, no amount of calcium-based feldspar (i.e., Anorthite [$CaAl_2Si_2O_8$],) was found in the spectrum. In the figure, the peak intensities of quartz were too strong, and the humps related to (calcium-)aluminosilicate glass, generally shown in the ranges of 25±10° of 2 theta, could not be found.

Fernandez et al. (2011) reported that the hump of the range for clay was strengthened by calcination around 800 °C, and this calcined clay could be the pozzolanic binder. The result of XRD analysis was correlated with the alkali silicate reaction (ASR) potential evaluated by chemical methods (ASTM C289-07) as shown in Table 1. The chemical potential of ASR of brick chips was judged to be low, and this meant high crystallinity of silica.

2.3 Specimen preparation and testing methods

Mix proportioning was carried out in accordance with the ACI mix design process (ACI 211.1) (1991). The condition for mix proportion was as follows: desired slump of 80 mm, maximum aggregate size of 25 mm, and non-air-entrained concrete. The target strength was not determined and only w/c was varied, in order to establish the relationship between w/c and strength of the concrete with brick chips. Prior to mixing all the aggregates, including the fine, natural, and brick chips were set to be at SSD condition. Over-wet fine aggregates were prepared and dried in air until they leached to SSD condition, and then packed in plastic bag to prevent further drying. Natural coarse aggregate and brick chips were saturated in water tank and wiped by wool towels.

Table 3 Mix proportions

w/c	Brick chips Cont. (vol. %)	Mix proportion (kg/m^3)				
		W	C	S	G	Brick chips
0.45	0	193	430	722	1,032	0
	25		430	722	774	198
	50		430	722	516	395
	75		430	722	258	593
	100		430	722	0	791
0.50	0		387	764	1,032	0
	25		387	764	774	198
	50		387	764	516	395
	75		387	764	258	593
	100		387	764	0	791
0.55	0		352	800	1,032	0
	25		352	800	774	198
	50		352	800	516	395
	75		352	800	258	593
	100		352	800	0	791
0.60	0		322	828	1,032	0
	25		322	828	774	198
	50		322	828	516	395
	75		322	828	258	593
	100		322	828	0	791
0.65	0		297	854	1,032	0
	25		297	854	774	198
	50		297	854	516	395
	75		297	854	258	593
	100		297	854	0	791
0.70	0		276	874	1,032	0
	25		276	874	774	198
	50		276	874	516	395
	75		276	874	258	593
	100		276	874	0	791

The calculated mix proportions for the test are listed in Table 3. A total of 30 different kinds of mixtures were prepared for this study. Note that the mass of aggregates in the table considered the SSD condition, so that there is no further absorption into the aggregates after mixing.

A 60-L capacity vertical mixer was used for mixing fresh mixture. All materials including water were mixed for 2 min. Directly after mixing, the slump of the fresh mixture was measured according to ASTM C143 (2020). It should be noted that the slump of fresh concretes for all mixtures, measured by ASTM C143 (2020), was within a range of 10~15 cm when a very small amount of commercialized superplasticizer (polycarboxylic acid-base, solid contents 15 %), 0.1 wt.% cement, was incorporated. Moreover, there was no difference in slump loss with time for the concrete with or without brick chips aggregates. Note that the effect of w/c in the mixture was constant even with brick chips replacement variation. For each mixture, 20-cylinder specimens 100×200 mm were prepared for compressive strength measurement. All specimens were cured in water after demolding after 1 day. The curing temperature was 21±2 °C while mixing and until the compressive strength testing day. The measurement of compressive strength was conducted in accordance with the ASTM C39 (2020). A total of 10 specimens were used for one formulation.

3. Result and discussion

3.1 Compressive strength

It is a natural phenomenon that the strength of the concrete to reduce by an increase in w/c and brick chips content. Considering the fact that the strength of brick chips alone was about 20 MPa or less, the use of brick chips significantly influenced the concrete with lower w/c. However, when w/c is as high as 0.70, there is no difference in strength with different aggregate. Concrete strength with w/c of 0.45 and 0.50 was reduced about 26~29 % by a 100 % replacement of the natural aggregates by brick chips, while that with 0.70 was unchanged. Note that, in the study of Cachim (2009), the two different types of crushed bricks from construction waste were used to replace natural aggregate with up to 30 % for the concrete with w/c 0.45-0.50, and the strength of concrete was varied from -30 % to +5 % of the strength of concrete with natural aggregate. The decrease in concrete strength due to the use of brick chips in this study was induced by the low strength of the brick chips themselves, i.e., 5.9~26.6 MPa, as shown in Fig. 6.

In some cases, the average value of the strength at 7 days was slightly higher than those at 28 days, and these gaps were negligible considering the coefficient of variation in Fig. 8. It was hard to find tendencies on the change of the coefficient of variation by w/c and brick chips content while the variation is close to zero, below 0.2 (20 %), which indicates that the variation of the compressive strength results was not large even in the case where brick chips were replaced.

It should be noted that, as mentioned in the introduction section, even if the content of brick chips in the concrete were determined based on the equivalent strength, the toughness and durability of the concrete materials should also be evaluated for structural design purpose (Song et al. 2018). Subsequent studies will perform various experiments related to this, such as the bending test to evaluate fracture toughness, or resistance to chloride penetration and carbonation (Narasimhan andd Chew 2009).

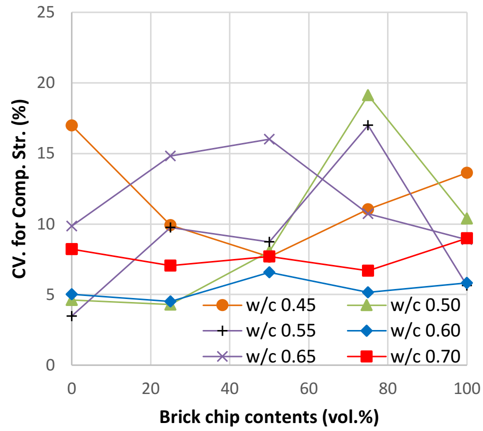

Fig. 8 Coefficient of variation for compressive strength of concrete at 28 days

3.2 Regression analysis of compressive strength

In this part of the study, linear regression analyses were used to establish a model of 28-day compressive strength related with w/c and brick chips content. It was assumed that the strength of concrete decreased ‘linearly’ with increases in w/c and brick chips content (Yoon and Yang 2015; Kim 2015). Similar assumptions have been adopted in the mix design method based on ‘the equivalent strength concept’ by the European Committee for Standardization (Gruyaert et al. 2013). It should worth to mention that, of course, the actual experimental results are not all theoretically linear on the relationships between strength and w/c or brick chips content, and the results used here may vary depending on the size and type of brick chips.

First, the relationship between compressive strength and w/c of the concrete was given by (Gruyaert 2013):

$$f_c = a_1(w/c) + a_2 \quad (1)$$

where, a_1 and a_2 were regression coefficients.

The values of a_1 and a_2 were assumed to be changed linearly by the replacement ratio of brick chips aggregate by normal aggregate (R, %). The model of strength with the independent variables of w/c and R was then given as.

$$f_c = [b_1(R) + b_2]\left(\frac{w}{c}\right) + [b_3(R) + b_4] \quad (2)$$
$$= d_1(w/c) + d_2(R) + d_3(w/c)(R) + d_4$$

where, b_i and d_i are also regression coefficients. The values of the regression coefficients d_i in Eq. (2) were calculated using SPSS software for the experimental results, and the results are listed in Table 4. The coefficient of determination, r^2, of Eq. (2) was smaller than 0.5 due to the variations in experimental results.

Table 4 Regression coefficients of Eq. (2) obtained from experimental results

Regression coefficients				r^2
d_1	d_2	d_3	d_4	
-49.0	-0.30	0.424	59.5	0.478

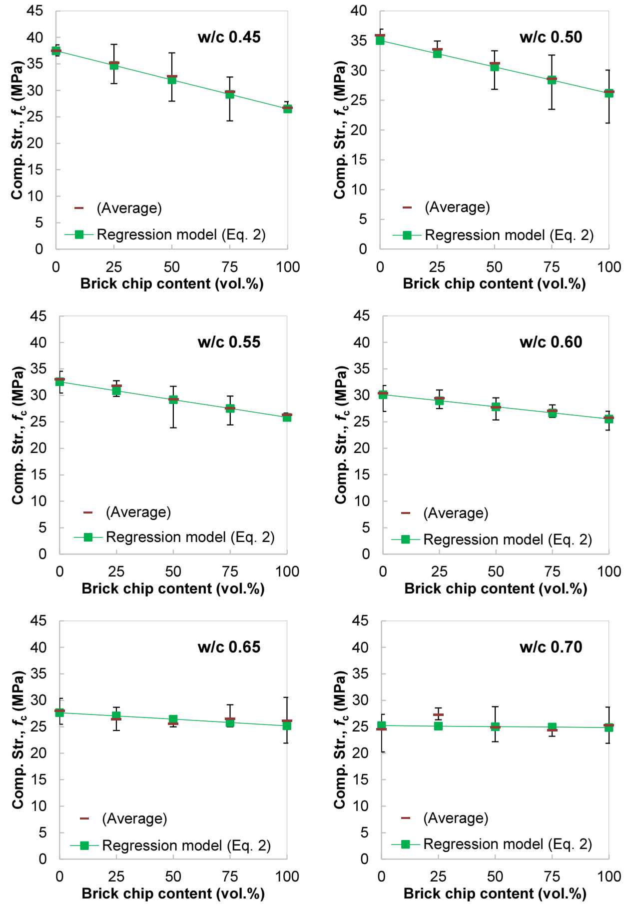

Fig. 9 Experimental results and regression model of compressive strength of concrete with various w/c and brick chip content

The experimental results and regression model of the 28-day compressive strength of the concrete are shown in Fig. 9. A comparison of the average values from experiments and regression models shows a variation of less than 3 MPa in almost all cases.

3.3 Mix proportioning for cost minimization

The total cost of concrete by unit volume (C_{conc}, USD/m^3) is assumed to be the summation of water (C_w), cement (C_c), sand (C_s), gravel (C_g), and brick chips (C_b) market value by mass (USD/kg) as shown in Eq. (3). Note that the chemical admixtures cost were excluded because of a trivial amount of admixture were used to make the mixtures workable.

Table 5 Costs for raw material at site (USD/kg)

Cement	Sand	Sand	Natural aggregate (exported)	Brick chips
0.09	0.03	0.03	0.06	0.0285

$$C_{\text{conc}} = C_w w + C_c \frac{1}{(w/c)} w + C_s s + C_g g + C_b b \qquad (3)$$

where, w, c, s, g, and b are the required mass for unit volumes of water, cement, sand, gravel, and brick chips in concrete (kg/m^3), respectively.

Assuming the air content in concrete is constant regardless of the w/c and R, the unit volume and weight of sand would be influenced by w/c. Considering that the volume of the water and the coarse aggregates are constant throughout the study as the mixtures in Table 3, Eq. (3) could be expressed as follows:

$$C_{\text{conc}} = c_w w + c_c \frac{1}{\left(\frac{w}{c}\right)} w + c_s[1000 - v_c - v_{ca} - v_{air}]\rho_s \qquad (4)$$

$$+ c_g[v_{ca}(1-R)]\rho_g + c_b[v_{ca}R]\rho_b$$

$$v_c = \frac{w}{(w/c)\rho_c} \qquad (5)$$

where, v_c, v_{ca}, and v_{air} are volume of cement, coarse aggregate (sum of gravel and brick chips), and air, respectively (L/m^3); ρ_c, ρ_s, ρ_g, ρ_b are the densities of cement, sand, gravel, and brick chips under SSD conditions, respectively (kg/m^3). Except for w/c and R, the remaining values of v_j and ρ_j (where, j refers to each material) in Eqs. (4) and (5) were constant, in overall.

Therefore, Eq. (4) can be simplified as follows:

$$C_{\text{conc}} = h_1 \frac{1}{(w/c)} + h_2 R + h_3 \qquad (6)$$

The cost of each material (j) per kg at the local market near the construction site, i.e., Matarbari in Bangladesh, is listed in Table 5, including the brick chips in USD. The values for h_1, h_2, and h_3 were calculated to be -0.395, 11.828, and 96.091, respectively, using the market value listed in Table 5 into Eqs. (4) and (5).

For mix proportioning based on the cost minimization, Eq. (2), which is the regression model for the compressive strength and Eq. (6), which is calculated based on the material cost, were combined to define the cost of the concrete solely by the w/c ratio. For that Eq. (2) can be rewritten in terms of R, as shown in Eq. (7) by predetermining the target strength of the concrete.

Using the rearranged formula, Eq. (7), into Eq. (6) the cost of the concrete can be defined only by the w/c ratio, as shown in Eq. (8). This implies that the optimized production cost can be extracted from the mix proportion in the range of w/c ratio from 0.45 to 0.70 using the targeted strength. Following that, the parameters of w/c and R for minimized concrete cost can be obtained as well from Eq. (7).

$$R = \frac{f_c - d_1\left(\frac{w}{c}\right) - d_4}{d_2 + d_3\left(\frac{w}{c}\right)} \tag{7}$$

$$C_{\text{conc}} = h_1 \frac{1}{(w/c)} + h_2 \frac{f_c - d_1(w/c) - d_4}{d_2 + d_3(w/c)} + h_3 \tag{8}$$

In general, from Eqs. (7) and (8), the C_{conc} and R can be quantified based on the target strength, as shown in Fig. 10. Considering the material price listed in Table 5, the mixtures with brick chips would be cheaper than mixtures with the most natural aggregates. Note that this is true even though more cement was required to secure an equivalent strength for mixtures with brick chips. Since, as the cement content increase forcing the mixture to have a low w/c ratio, the R value will also increase while maintaining a constant strength making the overall C_{conc} value to decrease. Fig. 10 shows the relative cost of a mixture at a target strength with brick chips to that of a mixture without brick chips. It was possible to get a cost reduction of up to 24 % for mixtures with 24 MPa strength. A reduction of cost for mixtures with 27, 30, and 33 MPa strength was also achieved up to 19 %, 12 %, and 5 %, respectively.

The above model is feasible to calculate the C_{conc} of concrete only if the f_c is on the range of 24 MPa-33 MPa with a corresponding range of w/c and R being 0.45~0.70 and 0~100 %, respectively (Fig. 11). Regardless of the model, the cost of the concrete can be reduced up to 70 % if the f_c is lower than 24 MPa. The R would not affect mixtures with a strength of less than 24 MPa even if 100 % of brick chips are used in the mixture having a constant w/c. However, note that the overall result in this study could be altered in case the price of cement is different from this study.

In addition, a static approach should be applied to the practical proportioning of the mixture. In many regulations, the required strength of the concrete for structural design, f_{cr} and experimental strength, f_c, generally have the following relationship:

$$f_c = f_{cr} + m\sigma \tag{9}$$

where, m is a confidence interval, which is a statistical parameter considering a normal distribution of the compressive strength, and σ is the standard deviation of the actual concrete.

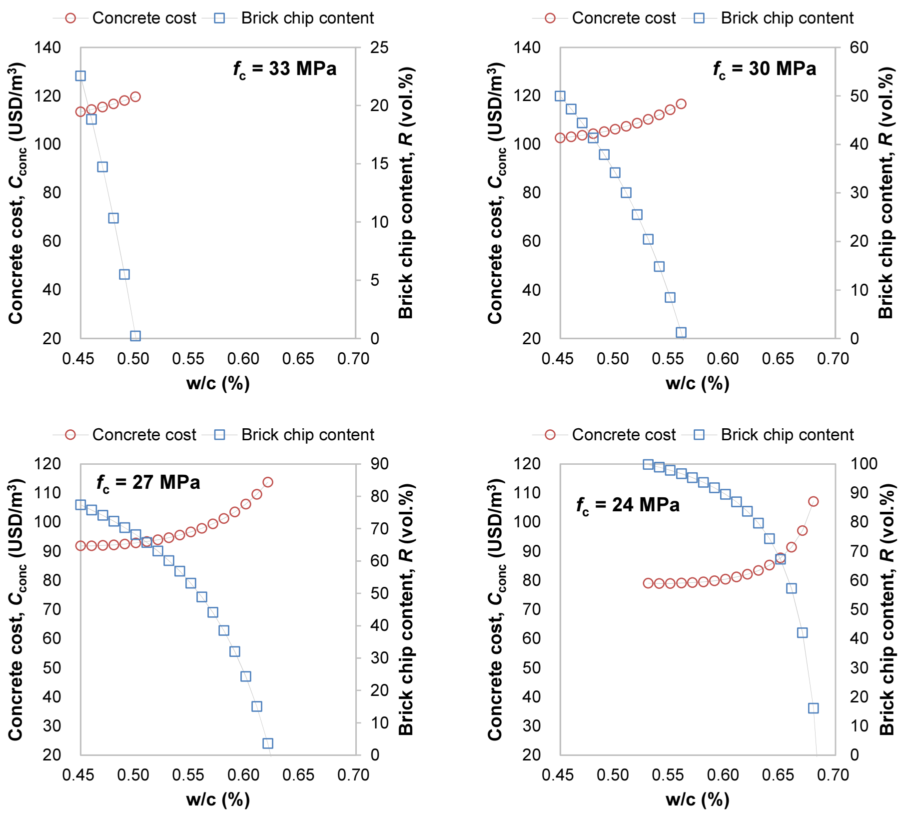

Fig. 10 R and C_{conc} vs. w/c of concrete for specific strengths

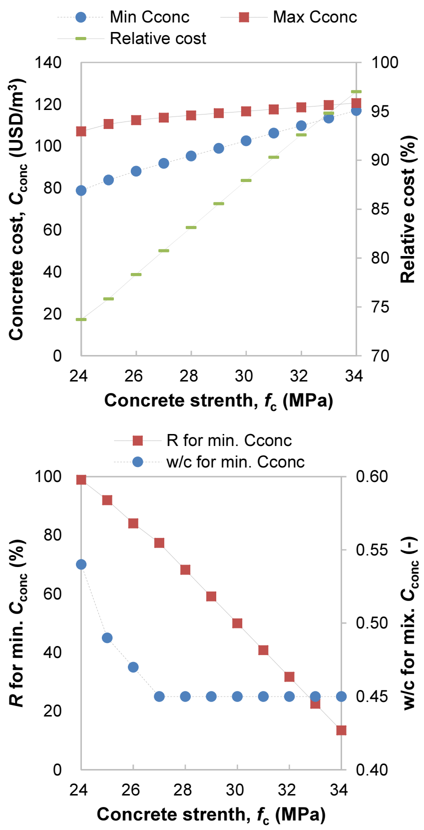

Fig. 11 Maximum and minimum values of C_{conc}, relative cost, R, and w/c for minimized C_{conc} vs. concrete strength

As shown in Fig. 8, the standard deviations in this study did not show any significant change by w/c and R values. Therefore, it is considered that a fixed value of σ could be adopted for practical mix proportioning even when w/c and R are varied.

4. Conclusions

This study investigated the use of brick chips aggregate in concrete. The following conclusions have been drawn based on the results.

Physical properties of brick chips aggregate, such as density, specific gravity, loss of ignition, and clay lump are all under the requirements set by ASTM C33. The direct strength for a single brick chip was within the range of 15~27 MPa.

The chemical composition of the brick chips aggregates is mostly Quartz, Hematite, and Feldspar. The soundness, abrasion loss, and ASR expansion test results showed that the brick chips aggregate has fully satisfied the standards set by ASTM C33 (2018). The brick chips are chemically stable against alkali silicate reaction.

The compressive strength result of concretes incorporating brick chips have shown a strength between 20 MPa and 35 MPa for the range of w/c from 0.45 to 0.70 and of replacement ratio of brick chips to normal gravel from 0 % to 100 %. In general, as the replacement ratio of brick chips increased, the strength of the concrete shows a clear decrease for mixtures with low w/c but constant for those with high w/c.

A linear regression was used to establish a model of 28-day compressive strength relating w/c and brick chips content, and mix proportioning for cost minimization was conducted based on the regression model. By substituting natural aggregates with brick chips and adjusting mix proportion, it was possible to reduce the cost to fabricate the mixture with equivalent strength by 5~24 %.

Acknowledgement

This research was supported by grants from the National Research Foundation of Korea (NRF) [2019R1A4A1028116] and POSCO Engineering and Construction (POSCO E&C).

References

ACI Committee 211 (1991) *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)*. Farmington Hills, MI; American Concrete Institute (ACI).

ASTM C109 (2016) *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*. West Conshohocken, PA; ASTM International.

ASTM C127-15 (2015) *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. West Conshohocken, PA; ASTM International.

ASTM C136/C136M-19 (2019) *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. West Conshohocken, PA; ASTM International.

ASTM C143/C143M-20 (2020) *Standard Test Method for Slump of Hydraulic-Cement Concrete*. West Conshohocken, PA; ASTM International.

ASTM C150/C150M-20 (2020) *Standard Specification for Portland Cement*. West Conshohocken, PA; ASTM International.

ASTM C289-07 (2007) *Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method) (Withdrawn 2016)*. West Conshohocken, PA; ASTM International.

ASTM C33/C33M-18 (2018) *Standard Specification for Concrete Aggregates*. West Conshohocken, PA; ASTM International.

ASTM C39/C39M-20 (2020) *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA; ASTM International.

Binici, H. (2007) Effect of Crushed Ceramic and Basaltic Pumice as Fine Aggregates on Concrete Mortars Properties. *Const-*

ruction and Building Materials 21(6), 1191-1197.
Bolouri Bazaz, J., and Khayati, M. (2012) Properties and Performance of Concrete Made with Recycled Low-quality Crushed Brick. *Journal of Materials in Civil Engineering* 24(4), 330-338.
Butler, L., West, J. S., and Tighe, S. L. (2013) Effect of Recycled Concrete Coarse Aggregate from Multiple Sources on the Hardened Properties of Concrete with Equivalent Compressive Strength. *Construction and Building Materials* 47, 1292-1301.
Cachim, P. B. (2009) Mechanical Properties of Brick Aggregate Concrete. *Construction and Building Materials* 23(3), 1292-1297.
de Brito, J., Pereira, A. S., and Correia, J. R. (2005) Mechanical Behaviour of Non-structural Concrete Made with Recycled Ceramic Aggregates. *Cement and Concrete Composites* 27(4), 429-433.
Debieb, F., and Kenai, S. (2008) The Use of Coarse and Fine Crushed Bricks as Aggregate in Concrete. *Construction and Building Materials* 22(5), 886-893.
Fernandez, R., Martirena, F., and Scrivener, K. L. (2011) The Origin of the Pozzolanic Activity of Calcined Clay Minerals: A Comparison between Kaolinite, Illite and Montmorillonite. *Cement and Concrete Research* 41(1), 113-122.
Gruyaert, E., Maes, M., and De Belie, N. (2013) Performance of BFS Concrete: K-Value Concept Versus Equivalent Performance Concept. *Construction and Building Materials* 47, 441-455.
Kahraman, S., and Fener, M. (2007) Predicting the Los Angeles Abrasion Loss of Rock Aggregates from the Uniaxial Compressive Strength. *Materials Letters* 61(26), 4861-4865.
Kim, H. K. (2015) Properties of Normal-strength Mortar Containing Coarsely-crushed Bottom Ash considering Standard Particle Size Distribution of Fine Aggregate. *Journal of the Korea Concrete Institute* 27(5), 531-539. (In Korean)
Kim, H. K., and Lee, H. K. (2018). Hydration Kinetics of High-strength Concrete with Untreated Coal Bottom Ash for Internal Curing. *Cement and Concrete Composites* 91, 67-75.
Kim, J. S., Shin, Y. S., Cho, C. H., and No, S. Y. (2008). Effect of the Broken Red Bricks on the Mechanical Properties of Reinforced Concrete Beams. *Journal of Korea Institute for Structural Maintenance and Inspection* 12(2), 83-90. (In Korean)
Madrid, M., Orbe, A., Rojí, E., and Cuadrado, J. (2017) The Effects of By-products Incorporated in Low-strength Concrete for Concrete Masonry Units. *Construction and Building Materials* 153, 117-128.
Mansur, M. A., Wee, T. H., and Lee, S. C. (1999) Crushed Bricks as Coarse Aggregate for Concrete. *ACI Materials Journal* 96(4), 478-484.
Mefteh, H., Kebaïli, O., Oucief, H., Berredjem, L., and Arabi, N. (2013) Influence of Moisture Conditioning of Recycled Aggregates on the Properties of Fresh and Hardened Concrete. *Journal of Cleaner Production* 54, 282-288.
Mohammed, T. U., Hasnat, A., Awal, M. A., and Bosunia, S. Z. (2015). Recycling of Brick Aggregate Concrete as Coarse Aggregate. *Journal of Materials in Civil Engineering* 27(7), B4014005.
Narasimhan, H., and Chew, M. Y. L. (2009) Integration of Durability with Structural Design: An Optimal Life Cycle Cost Based Design Procedure for Reinforced Concrete Structures. *Construction and Building Materials* 23(2), 918-929.
Poon, C. S., Shui, Z. H., Lam, L., Fok, H., and Kou, S. C. (2004) Influence of Moisture States of Natural and Recycled Aggregates on the Slump and Compressive Strength of Concrete. *Cement and Concrete Research* 34(1), 31-36.
Yoon, H. S., and Yang, K. H. (2015) Determination of Water-to-binder Ratios on the Equivalent Compressive Strength of Concrete with Supplementary Cementitious Materials. *Journal of the Korea Concrete Institute* 27(6), 687-693. (In Korean)
Choi B. S., Yoon H. S., Moon H. K., and Yang K. H. (2018) Environmental Impact Assessment of Lightweight Aggregate Concrete according to Replacement Ratio of Artificial Lightweight Fine Aggregates, *Journal of the Korea Concrete Institute* 30(3), 297-304. (In Korean)
Song, G. I., Lee, K. H., Yang, K. H., and Song, J. K. (2018) Creep Characteristics of Artificial Lightweight Aggregate Concrete and Prediction Model. *Journal of the Korea Concrete Institute* 30(5), 517-524. (In Korean)

요　약 파쇄벽돌을 굵은골재로 사용한 콘크리트에 대해 가격 최소화 측면에서의 배합설계를 수행하였다. 파쇄벽돌이 콘크리트 특성에 미치는 영향을 알기 위하여, 우선 이 파쇄 벽돌에 대해 컴퓨터 단층촬영, 직접 압축강도 측정, X선 회절 분석 등을 통해 물리적 및 화학적 특성을 평가하였다. 이후, 다양한 배합비의 파쇄벽돌 콘크리트의 강도를 측정하였고, 이 실험결과를 사용한 선형회귀분석 모델을 통해 등가강도 기반 콘크리트 가격 최소화를 위한 배합비를 설계하였다. 이 모델에는 본 파쇄벽돌 콘크리트를 사용하게 될 지역의 재료가격을 사용하였다. 파쇄벽돌 콘크리트에 대한 배합설계를 통해, 압축강도가 25~33 MPa의 수준에서 5~24 %의 비용절감이 가능함을 확인하였다.

핵심용어 : 파쇄벽돌, 배합설계, 굵은골재, 가격 최소화, 회귀분석