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ORIGINAL ARTICLE

Utilization of crushed clay brick in concrete industry

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Abstract A comprehensive experimental program regarding the use of recycled aggregates produced from demolition of brick buildings is presented. The brick wastes were crushed, sorted and classified into coarse and fine aggregates as well as powder (CBP). The first phase of the research focuses on the effect of incorporating recycled aggregates on physico-mechanical properties of paste, mortar and concrete. Non-traditional tests including X-ray diffraction (XRD), thermogravimetric analysis (TGA) and micro-structural analysis (MSA) were performed. The second phase of the program explores the effect of using recycled aggregates on properties of concrete masonry units. A total of 44 mixtures were utilized throughout the program. Results show cement paste when modified with 25% CBP achieves smaller pore size and lower weight loss under high temperature than reference paste. Furthermore, the use of recycled aggregates reduces the overall unit weight of concrete masonry units. Actually, modified concrete masonry units incorporating recycled aggregates achieve lower unit weight, higher thermal resistance and absorption rate than reference units. Although considerable strength reduction is noticeable by substitution, compressive strength levels meet the Egyptian specifications limitations. Critical replacement ratios are suggested to produce load bearing-concrete masonry units. Based on experimental evidences, it can be stated that the use of recycled aggregate and dust made of clay bricks is promising in many applications where the thermal resistance, cost and environmental aspects are imperative.

1. Introduction

During the last two decades, many structures in Egypt reached their design life times or were defected due to the use of non-conforming materials or bad construction execution. In addition, the presence of old demolished constructions resulting from modernization and urbanization may play a major role [1]. In fact, tremendous quantities of construction and demolition wastes are produced every year. Actually, the waste storage disposals are becoming a serious environmental problem,

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Figure 1 Constructions and demolition waste disposal site in Alexandria, Egypt.

especially for main cities that lack disposal sites [2]. Typical examples of construction and demolition wastes disposal sites in Alexandria are shown in Fig. 1. In fact, Crushed clay brick is not considered a recyclable material in the middle-east region as opposed to recycled concrete aggregate. The first use of crushed brick with Portland cement was recorded in Germany (1860) for the manufacture of concrete products, but the first significant use of crushed brick as aggregates in new concrete has been recorded for reconstruction after World War II [3].

Several studies have been conducted to investigate the potential of using crushed clay brick as an alternate aggregate. Poon and Chan [4] investigated the possibility of using crushed clay brick as aggregates in sub-base materials. Akhtaruzzaman and Hasnat [5] studied the use of crushed clay brick aggregate as a 100% replacement of coarse natural aggregate in concrete. The physical and mechanical properties of solid cement brick manufactured with crushed clay brick as a recycled aggregate have been reported by Sadek [6]. Ge et al. [7] studied the effect of clay brick powder on concrete mechanical properties.

From previous researches, the main advantages of using crushed brick aggregates as alternative aggregates are reducing concrete density, reducing natural aggregate consumption, and being considered environmental friendly approach. Contradictorily, such problems may constitute serious barriers to both recycling activities and applications. These obstacles can be summarized in these points: 1. High porosity, high absorption rate and variation in quality. 2. Specifications are insufficient in place. 3. Uncertainties on regular supply and the lack of confidence and experience in use of these materials are considered the common barriers.

2. Research significance

This paper presents a comprehensive study on the use of recycled aggregates and powder produced from clay brick demolition wastes in concrete industry. The main focus of the research is to present an additional information in the field of recycling clay masonry rubbles in order to explore the possible uses of these recyclable materials in structural applications. The assessment of different properties of cement paste, mortar and concrete as well as field applications of using clay brick recycled aggregate in masonry units' production is presented. The current work concludes performance-based guidelines that are imperative from the cost and environmental aspects and that also can be followed when specifying the subject recycled aggregate and powder in concrete. But, actually is that true? Can we really use such materials to achieve special properties, reduce the cost and improve the environment without affecting the overall concrete performance? From that point, this study is undertaken.

3. Phase I: cement paste, mortar and concrete

3.1. Experimental program

This phase of the program involved laboratory testing of cement paste, mortar and concrete incorporating recycled aggregates and powder produced from clay brick wastes as mentioned earlier. The lab program consisted of a total of 24 concrete mixtures. In addition to traditional tests, the lab program consisted of a total of 24 concrete mixtures. In addition to traditional tests, X-ray diffraction (XRD), thermo-gravimetric analysis (TGA) and micro-structural analysis (MSA) were performed.

3.1.1. Materials

Portland cement CEM-I 42.5N from one local source was used in all mixes. This cement was known by the time of casting as ordinary Portland cement (ASTM Type I). Table 1 displays the physical and mechanical properties of the used cement. Natural siliceous graded sand with fineness modulus of 2.63 was used as a fine aggregate, while crushed limestone having nominal maximum size of 19 mm was used as a natural coarse aggregate for concrete mixtures. Recycled aggregates and powder produced from clay bricks wastes were obtained through specific crushing process. Clay bricks were crushed manually using a steel hammer, then screened and grouped to different sizes in accordance with ASTM C33 to comply sizes from 19 mm to 4.75 and from 4.75 mm to 0.15 mm for coarse and fine aggregate, respectively. Table 2 presents the physical properties and the grading of the used aggregates.

In addition, the crushing process produced dust that was separated by sieving on 75 μm-square mesh-sieve. In fact, ASTM C 618 specifications limit the maximum amount retained on Sieve No. 325 (45 μm) for natural Pozzolan by 34%. The used CBP was therefore sieved to meet this requirement. Table 3 shows the sieve analysis of CBP. Evaluation of the particles shape showed that CBP grain has a semi-oval shape and a semi-smooth surface. Fig. 2 shows the particle shape of two different sizes of clay brick powder grains. These micrographs of mortar samples that contained high amount of CBP instead of sand are presented for illustration. The chemical analysis of clay brick powder and cement are given in Ta-

Table 1 Physical and mechanical properties of the cement used.

Test	Test results	Limits of ESS No. 2421, 1993
Standard water required, (w/c)	27%	–
Initial setting, min	157	⩾45[a]
Final setting, min	381	⩽600[a]
Le chatelier expansion, mm	4	⩽10[a]
3 day-mortar compressive strength, MPa	21.5	⩾18[a]
7 day-mortar compressive strength, MPa	27.5	⩾27[a]
Specific gravity	3.15	–

Table 2 Properties of the used aggregates.

Properties	Natural aggregate		Crushed clay brick aggregate		Limits	
	19 mm	Fine	19 mm	Fine		
Specific gravity (SSD)	2.56	2.63	2.04	2.08	–	
Water absorption (%)	0.65	1.3	15.5	18.3	⩽1.0[a] for coarse agg. and ⩽2.0[a] for fine agg.	
Fine materials%	1.1	1.54	1.95	5.9	⩽3.0[a]	
Fineness modulus	–	2.63	–	3.07	–	
Los Angeles%	25.7	–	34.7	–	⩽30[a]	
Particle size distribution (mm)	Percent passing, %				19 mm (Nominal size)	Fine
25 mm	100	–	100	–	100	–
19 mm	95.7	–	95.1	–	90–100	–
12.5 mm	55.9	–	43.8	–	–	–
9.5 mm	20.1	–	21.1	–	20–25	–
4.75 mm (No. 4)	1.9	99.0	1.4	100	0–10	95–100
2.36 mm (No. 8)	0	95.3	0	80.5	0–5	80–100
1.18 mm (N. 16)	–	81.1	–	51.2	–	50–85
600 μm (No.30)	–	48.4	–	31.3	–	25–60
300 μm (No.50)	–	9.8	–	20.3	–	5–30
150 μm (No.100)	–	3.1	–	9.7	–	0–10

[a] According to ESS No.1109, 1971.

Table 3 Wet sieve analysis of clay brick powder.

Sieve size (μm)	Percentage passing (%)
150	100
75	100
63	N/A
45	66

Table 4 Chemical composition of cement and powder.

Chemical composition (%)	Cement	Clay brick powder
Silicon dioxide (SiO_2)	18.9	54.2
Iron oxide (Fe_2O_3)	3.1	7.6
Aluminum oxide (Al_2O_3)	5.1	15.4
Calcium oxide (CaO)	63.3	6.8
Magnesium oxide (MgO)	2.1	2.5
Sulfur trioxide (SO_3)	3.2	1.1
Loss on ignition (LOI)	2.05	6.2

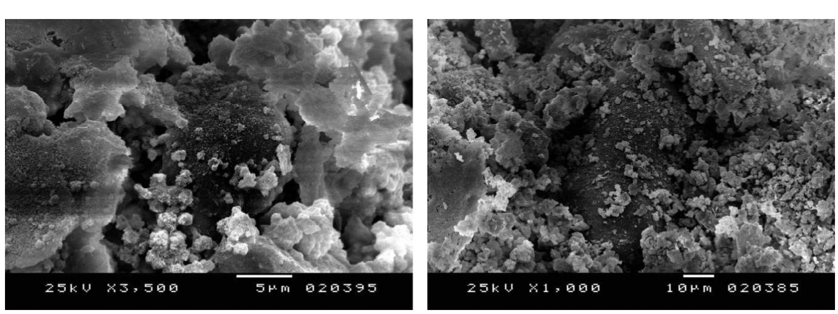


Figure 2 Microstructure of CBP particles.

Table 5 Concrete mix proportions.

Mix no.	Replacement category		Replacement of recycled aggregates%	w/c	Mix proportions (kg/m^3)					
					Cement	Water	Coarse aggregate (SSD)		Fine Aggregate (SSD)	
							Natural	Recycled	Natural	Recycled
1	Series(I)	Control	0%	0.5	350	175	1108	0	739	0
2		Fine aggregate replacement%	25%	0.5	350	175	1108	0	554	146
3			50%	0.5	350	175	1108	0	369	292
4			75%	0.5	350	175	1108	0	184	438
5			100%	0.5	350	175	1108	0	0	584
6		Coarse aggregate replacement%	25%	0.5	350	175	831	221	739	0
7			50%	0.5	350	175	554	442	739	0
8			75%	0.5	350	175	277	662	739	0
9			100%	0.5	350	175	0	883	739	0
10		Both aggregate replacement%	50%	0.5	350	175	554	442	369	292
11			100%	0.5	350	175	0	883	0	584
12			100% F and 50% C	0.5	350	175	554	442	0	584
13			50% F and 100% C	0.5	350	175	0	883	369	292
14	Series(I I)	Control	0%	0.7	250	175	1158	0	772	0
15		Fine aggregate replacement%	25%	0.7	250	175	1158	0	579	153
16			50%	0.7	250	175	1158	0	386	305
17			75%	0.7	250	175	1158	0	193	458
18			100%	0.7	250	175	1158	0	0	610
19		Coarse aggregate replacement%	25%	0.7	250	175	868	231	772	0
20			50%	0.7	250	175	579	461	772	0
21			75%	0.7	250	175	289	692	772	0
22			100%	0.7	250	175	0	922	772	0
23		Both aggregate replacement%	50%	0.7	250	175	579	461	386	305
24			100%	0.7	250	175	0	922	0	610
25			100% F and 50% C	0.7	250	175	579	461	0	610
26			50% F and 100% C	0.7	250	175	0	922	386	305

F: Fine aggregate and C: Coarse aggregate.

ble 4 that show that the sum of silicon, ferric and aluminum oxides of CBP is 77.2%. This finding coincides with the restrictions of ASTM C618 that limits the sum of those oxides to be at least 70% for pozzolans.

3.1.2. Mix proportions

Three mixtures of cement pastes were prepared with various clay brick powder ratios as a partial replacement of cement by weight. The percentages used were 0%, 15% and 25% with a water-to-cement ratio (w/c) of 0.40. With respect to mortar, mix proportions were selected in accordance with ASTM C109. All mixtures were set to achieve comparable flow (110 ± 5 mm) using different dosages of Type F super-plasticizing admixture. Cement-to-sand ratio was kept constant at 1:2.75, while water-to-cement ratio was 0.484 in all mixes. Clay brick powder was used as cement replacement and cement addition. The percentages used were 0%, 5%, 10%, 15%, 20% and 25% by weight of cement.

On the other hand, concrete trial mixtures confirmed that the high water absorption rate of crushed clay brick adversely affected the workability of fresh concrete. Thus, aggregate pre-wetting was respected during this study to avoid this problem. This approach was previously recommended by Khalaf and DeVenny [8,9]. Based on this argument, the aggregates used in the current program were in saturated surface dry conditions (SSD). Coarse aggregates were pre-wetted for 24 h before mixing and then surface dried. Fine aggregate could not be fully soaked; thus, the needed water for absorption was added to fine aggregates and tightly covered by plastic sheets for 24 h before mixing. Two cement contents were pre-selected. These contents are 250 and 350 kg/m^3 simulating typical plain and reinforced concrete applications, respectively. Recycled brick aggregates were incorporated as alternative aggregate for fine and/or coarse aggregates. The used replacement percentages were 0, 25, 50, 75 and 100 by volume. All mixes have comparable concrete workability (slump = 120 ± 10 mm). A high range water reducer Type F (naphthalene type) was also used in all concrete mixes to ensure workability. Potable water was used for mixing and curing processes for all specimens. Twenty-six concrete mixtures were designed with various replacement ratios. Table 5 displays concrete mix proportions.

3.1.3. Testing

The powder method of X-ray diffraction was adopted in the present study for the identification of the most probable phases of cement paste modified with clay brick powder. Test was carried out using P analytical computer-certified program. A diffract-meter 'PW3209' with an X-ray source was used. The X-ray tube voltage and current were fixed at 40 kV and 30 mA respectively. Thermo-gravimetric analysis (TGA) was also conducted to provide quantitative measurement of mass change in materials associated with thermal degradation. In fact, TGA uses heat to force reactions and physical changes in materials. Micro-structural evolutions of specimens were also observed by scanning electron microscope (SEM) on gold-coated sections. For cement mortar specimens, compressive strength and strength activity index tests were performed. In addition, series of tests were conducted on concrete specimens to determine the compressive strength, splitting-tensile strength, elastic modulus, ultrasonic pulse velocity and porosity. The relevant specifications are presented in Table 6.

3.2. Results and discussion

3.2.1. Cement paste

3.2.1.1. X-ray Diffraction Analysis (XRD). Although X-ray qualitative diffractometry does not provide any quantitative information, it is considered a reasonable technique which gives acceptable information about the most feasible phases. In all paste samples, diffraction peaks indicate the presence of portlandite, ettringite, calcite, quartz and C–S–H. No significant changes in X-ray patterns are observed due to the incorporation of CBP as clearly shown in Fig. 3. In fact, this finding implies that the presence of CBP in the matrix (up to 25%

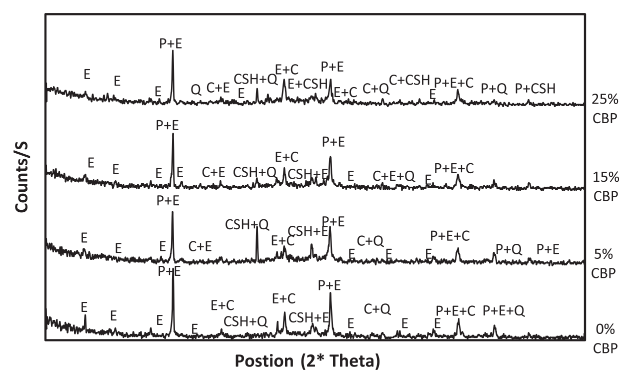


Figure 3 X-ray diffraction patterns of pastes contain different CBP content. C: calcite, E: Ettringite, Q: quartz, CSH: calcium silicate hydrate, and P: Portlandite.

Table 6 Summary of tests performed and relevant standards.

Properties	Specifications	Specimen dimensions	Category	Age of testing
Compressive strength	BS 1881: Part 3	Cubes 150 ∗ 150 ∗ 150 mm	Concrete	7, 28, 90 days
	ASTM C 109	Cubes 50 ∗ 50 ∗ 50 mm	Mortar	7, 28, 90 days
Splitting tensile strength	ASTM C 496	Cylinder D = 75 mm and L = 150 mm	Concrete	7, 28, 90 days
Static Elastic modulus	ASTM C469	Cylinder D = 75 mm and L = 150 mm	Concrete	28 days
Ultrasonic pulse velocity	BS 1881: Part 203	Cubes 150 ∗ 150 ∗ 150 mm	Concrete	7, 28, 90 days
Porosity	ASTM C 642	Cubes 150 ∗ 150 ∗ 150 mm	Concrete	28 days
Strength reactivity index	ASTM C311	Cubes 70 ∗ 70 ∗ 70 mm	Mortar	7, 28 days
	ASTM C618			

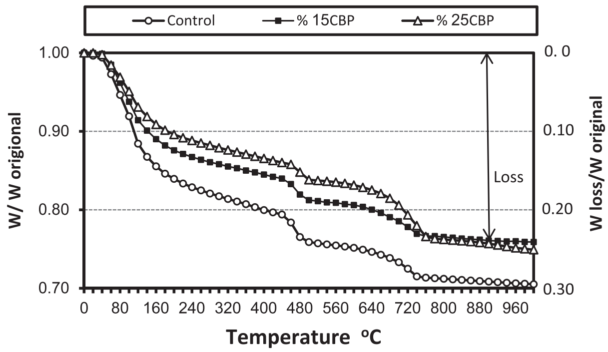


Figure 4 Thermo-gravimetric analysis curves for paste samples.

replacement) has a minimal effect on mineral compositions of the matrix.

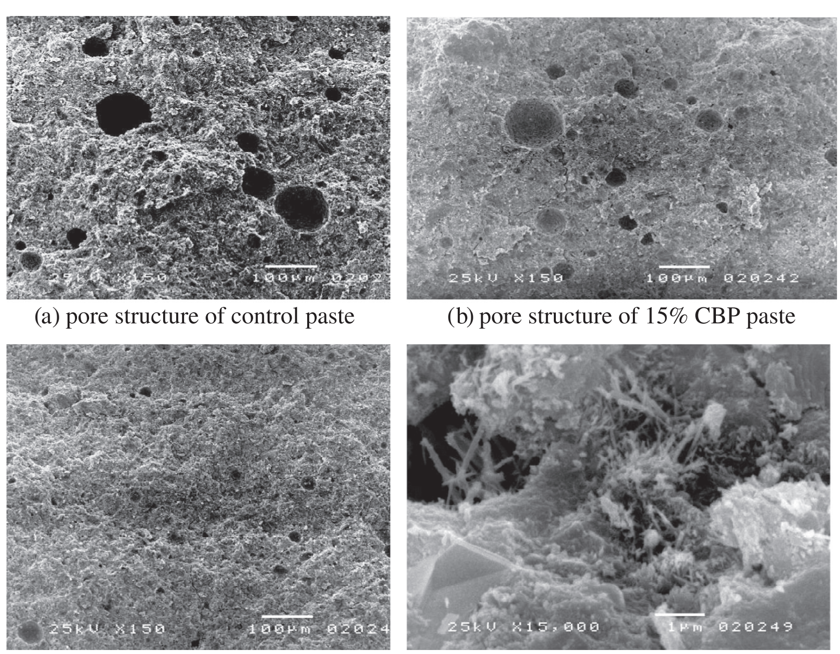
3.2.1.2. Thermo gravimetric analysis (TGA). Analyzing thermo-gravimetric curves depends on the relation between the temperature increase and the change in mass as result of dehydration, decomposition and oxidation. These curves can be divided into different important zones. Zone (I), between 100 and 300 °C, is attributed to the dehydration of C–S–H and ettringite. Zone (II), between 290 and 350 °C, characterizes the decomposition of calcium aluminate silicate hydrate, calcium aluminate hydrate and calcium chloro-aluminate. The third zone (III), ranging from 450 to 510 °C, is attributed to the dehydration of calcium hydroxide. An endo-therm around 700 °C indicates the de-carbonation of calcium carbonate in the hydrated compound [12]. Fig. 4 shows the relation between the relative weight of specimen to the original weight of sample ($w/w_{original}$) and the applied temperature. The figure clearly demonstrates that the incorporation of CBP reduces the weight loss of cement paste under high temperature.

Based on the argument mentioned above, the presented curves meet with logic and recorded results. At temperature between 100 and 300 °C, the reference paste has the highest weight loss implying that the reference paste has the highest C–S–H and ettringite contents that are attributed to the highest cement content. At temperature between 450 and 510 °C, the reference paste also has the highest weight loss indicating the presence of the highest calcium hydroxide content among the group. This finding may be attributed to the high cement content and the pozzolanic reactivity of CBP.

3.2.1.3. Micro-structural analysis (MSA). Fig. 5 displays the pore structure of the investigated paste specimens. It is clear that the sample containing 25% CBP has the smallest pore size and the best pore structure. These micrographs are in good agreement with TGA and strength activity index results presented later. Actually, it is evident that the additional hydrates; produced by pozzolanic reactivity and possibly the re-hydration of un-hydrated cement particles in attached mortar, increase the density of the matrix and refine the pore structure. Again, these micrograph results confirm that CBP can be considered as promising filler.

3.2.2. Cement mortar

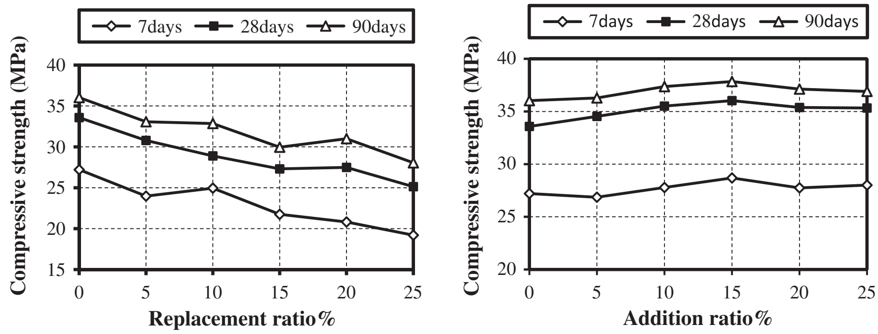
3.2.2.1. Compressive strength. As mentioned earlier, the powder CBP is introduced in the mortar as a partial replacement of cement weight in some mixtures and also as an additive in others. Results indicate that the presence of clay brick powder as a partial replacement of cement by weight reduces the mortar compressive strength as shown in Fig. 6. Mortar that contains the highest cement replacement by CBP (25%) exhibits about 25.2% reduction in 28-day compressive strength with respect to the control mortar. In fact, reductions in mortar compressive strength at 28 days on the order of 8.3%, 14.0%, 18.7%, 14.2% and 25.2% are noticeable for mortar modified



(a) pore structure of control paste (b) pore structure of 15% CBP paste

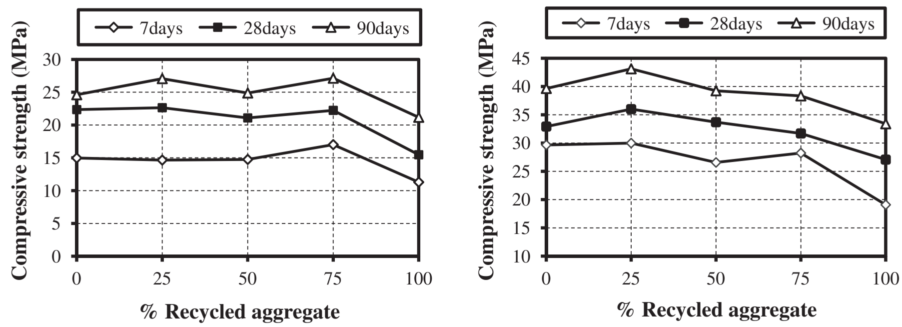
(c) Pore structure of 25% CBP paste (d) Micro structure of 25% CBP paste

Figure 5 Microstructure of paste samples.



(a) Effect of CBP replacement (b) Effect of CBP addition

Figure 6 Effect of CBP replacement or addition on mortar compressive strength.



(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70 (b) Cement content=350 kg/m^3 and w/c ratio= 0.5

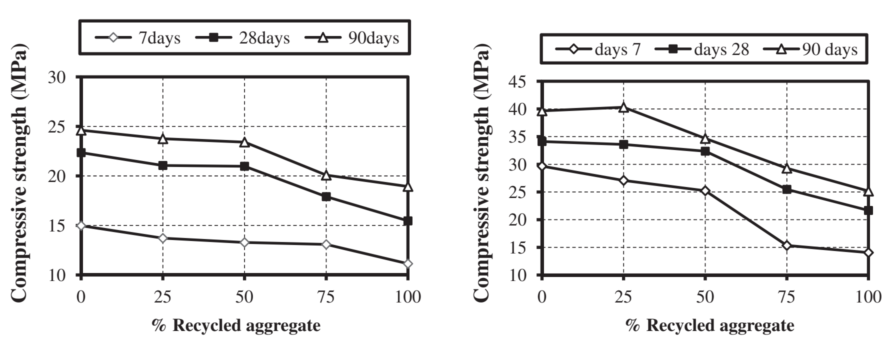
Figure 7 Effect of fine recycled aggregates content on concrete compressive strength.

with 5%, 10%, 15%, 20% and 25%, respectively, of CBP as compared with control mortar. Contradictorily, slightly beneficial effect in compressive strength is noticeable when CBP is incorporated as an additive to cement.

3.2.2.2. Strength activity index. It is generally agreed that all types of burned clay may not be considered Pozzolanic materials. In fact, clay containing high proportions of very crystalline minerals, such as quartz and feldspar, do not produce reactive material and therefore cannot be considered Pozzolan. On the contrary, during the manufacturing process of clay brick, exposure of clay to temperatures ranging from 600 to 1000 °C often changes the crystal structures of its silicates to an amorphous compound that reacts with lime at room temperature [10,11]. In the current study, the assessment of pozzolanic reactivity was based on strength activity index specified by ASTM C618 and outlined in ASTM C311. According to the requirement of ASTM C618, the cement mortar modified with 20% CBP should provide at least 75% of the strength of the control mortar at both ages of 7 and 28 days to be considered as pozzolanic material. Results obtained herein indicate that the strength activity index at the ages of 7 and 28 days are 76.5% and 81.8% respectively indicating that clay brick powder has pozzolanic properties.

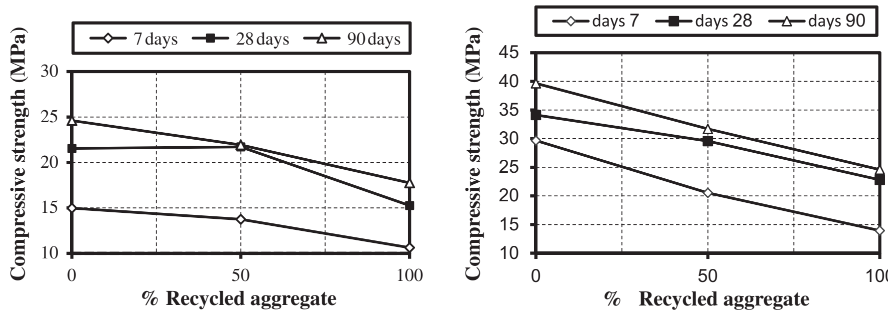
3.2.3. Concrete

3.2.3.1. Compressive strength. From general prospective, Figs. 7–9 imply that the increase in the recycled aggregates content decreases the concrete compressive strength except for fine aggregates replacement where strength remains compa-



(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70 (b) Cement content=350 kg/m^3 and w/c ratio = 0.5

Figure 8 Effect of coarse recycled aggregates content on concrete compressive strength.



(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70 (b) Cement content=350 kg/m^3 and w/c ratio = 0.5

Figure 9 Effect of fine and coarse recycled aggregates content on concrete compressive strength.

rable or slightly improved. This improvement may be attributed to the good grading of the crushed clay brick aggregate and the pozzolanic reactivity of super fine portion of crushed brick aggregate.

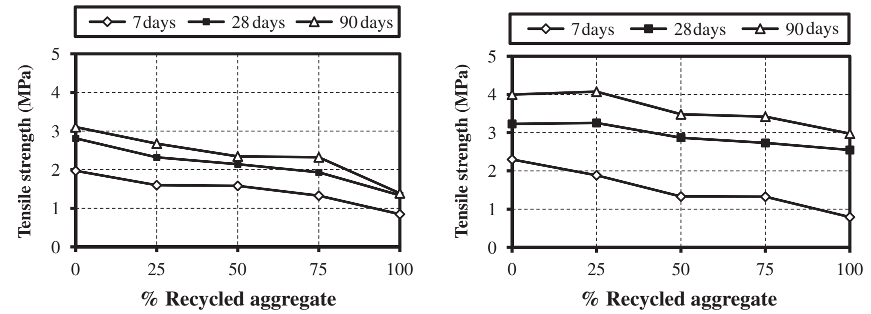
Results clearly indicate that the highest reduction in compressive strength due to the presence of recycled aggregate is associated with the highest cement content at comparable replacement level. This may be attributed to the weak porous structure of crushed clay brick that affect the mode of failure under compression. Furthermore, no significant reduction in concrete compressive strength of concrete was noticeable in specimens containing 250 kg/m^3 cement content up to 50% coarse aggregate replacement level, and also in specimens with 350 kg/m^3 cement content but up to only 25% replacement level. On the other hand, the drastically reduction in compressive strength associated with higher replacement levels is highly observed. This finding agrees with Debieb and Kenai [2], Poon and Chan [4], Cachim [13] and Poon [14].

It should be pointed out that the improvement in compressive strength due to fine aggregates replacement, up to the authors' knowledge, has not been previously reported by other researchers implying that not all burned clay possess pozzolanic reactivity. In fact, the authors strongly believe that the presence of super fine crushed clay brick powder covers the fine aggregates and hence improve the transition zone between aggregates and cement paste. In addition, the higher water absorption of crushed clay brick enhances the hydration of cement as it acts as self-curing agent which leads to higher hydration products.

3.2.3.2. Splitting-tensile strength. Results presented in Table 7 and Fig. 10–12 indicate that use of crushed clay brick aggregates, generally, decreases the splitting-tensile strength of concrete. This finding may be true for fine and coarse aggregate replacement. The effect of using 25% of recycled fine aggregates replacement is also clear for concrete mixes with

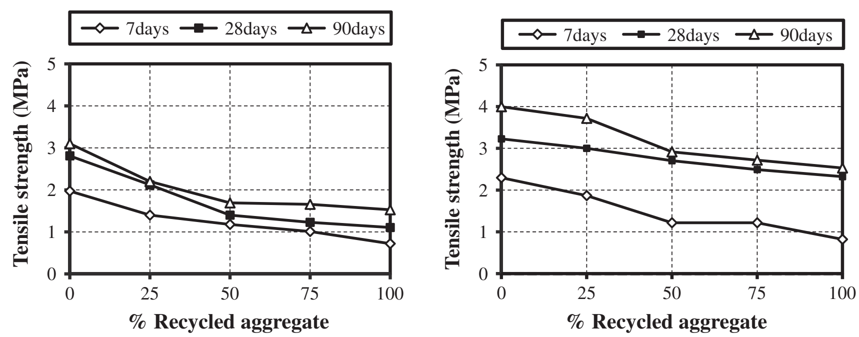
Table 7 The change percentages in concrete properties.

Properties	Replacement level %	Fine aggregate replacement		Coarse aggregate replacement		All-in-aggregate replacement	
		350 kg/m^3 cement content	250 kg/m^3 cement content	350 kg/m^3 cement content	250 kg/m^3 cement content	350 kg/m^3 cement content	250 kg/m^3 cement content
Compressive strength	25%	+9.9	+1.3	−1.6	−5.8	–	–
	50%	+2.3	−5.7	−5.1	−6.2	−13.4	+0.2
	75%	−3.7	−0.5	−25.3	−19.9	–	–
	100%	−17.8	−30.8	−36.5	−30.8	−33.2	−29.2
Splitting tensile strength	25%	+12.2	−17.5	−7.0	−24.6	–	–
	50%	−1.1	−23.8	−16.2	−50.2	−9.3	−20.9
	75%	−5.9	−31.3	−22.8	−56.3	–	–
	100%	−12.2	−52.4	−28.1	−60.0	−49.6	−37.5
Modulus of elasticity	25%	−11	−0.1	−5.8	−3.0	–	–
	50%	−12.2	−0.2	−21.6	−10.0	−30.6	−22.7
	75%	−15.2	−10.0	−34.1	−28.6	–	–
	100%	−32.3	−56.7	−40.9	−42.9	−59.9	−70.0
Ultrasonic pulse velocity	25%	−3.0	−7.4	−2.0	−7.6	–	–
	50%	−4.6	−7.6	−6.5	−10.7	−7.8	−9.3
	75%	−5.5	−9.1	−11.5	−161	–	–
	100%	−10.8	−9.6	−14.3	−16.9	−24.4	−23.1
Porosity	25%	+4.0	+14.8	+9.3	+9.9	–	–
	50%	+15.1	+18.0	+20.5	+19.8	+25.6	+22.5
	75%	+16.5	+23.7	+23.8	+26.4	–	–
	100%	+24.4	+33.5	+37.3	+38.7	+70.7	+60.4



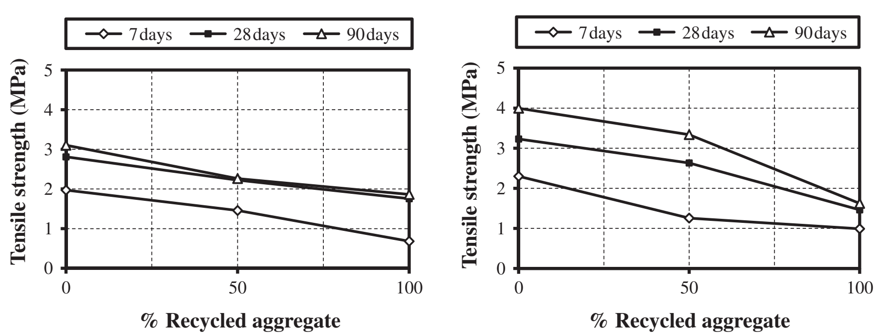
(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70 (b) Cement content=350 kg/m^3 and w/c ratio = 0.5

Figure 10 Effect of fine recycled aggregates content on concrete tensile strength.



(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70 (b) Cement content=350 kg/m^3 and w/c ratio = 0.5

Figure 11 Effect of coarse recycled aggregates content on concrete tensile strength.



(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70 (b) Cement content=350 kg/m^3 and w/c ratio = 0.5

Figure 12 Effect of fine and coarse recycled aggregates content on concrete tensile strength.

350 kg/m^3 cement content. This finding is in good agreement with Poon and Chan [4] and contradicts with Hansen [3] and Khaloo [15] who observed an increase in concrete splitting-tensile strength where crushed brick aggregates are utilized as recycled aggregate. For comparative purposes, all data obtained throughout the program are plotted in Fig. 13 following the format given in the Egyptian code ECP 203. The typical trend of relationship between splitting-tensile and compressive strengths is noticeable; however, the code expression for predicting splitting-tensile strength of concrete from its compression strength seems to be underestimated by up to 20% whenever recycled aggregates are utilized.

3.2.3.3. Static modulus of elasticity. The presence of crushed clay brick aggregates decreases the modulus of elasticity of concrete as shown in Fig. 14. This negative effect is more pronounced where the recycled coarse aggregate is incorporated. For mixes containing 350 kg/m^3 of cement, up to 36% reduction in concrete elastic modulus is observed at 75% replacement level of coarse aggregate as seen in Fig. 14(b), however, up to only 15% reduction in elastic modulus is noticeable at comparable replacement level of fine aggregate of 75%. In fact, the degree of reduction in elastic modulus depends also on the used cement content. The higher the cement content, the more the reduction in elastic modulus as presented in Table 7. This trend is due to the lower modulus of elasticity of

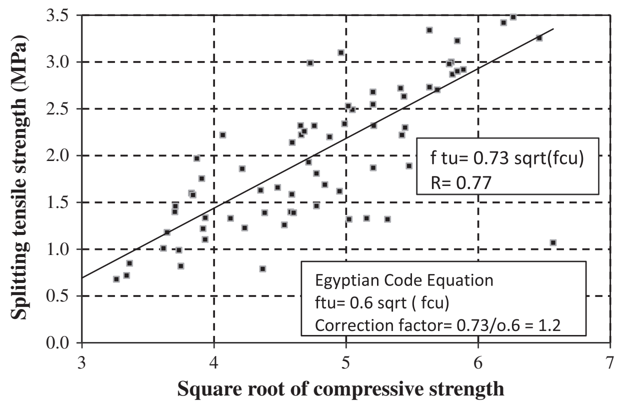


Figure 13 Relationship between splitting-tensile and compressive strengths.

clay brick aggregates as compared with that for natural aggregates. The findings reported herein are in good agreement with Debieb and Kenai [2] and Akhtaruzzaman and Hasnat [5]. It is of great interest to conclude that the well-known formulas given in most code provisions for estimating concrete elastic modulus for conventional concrete may not be applicable for concrete incorporating recycled aggregates.

3.2.3.4. Porosity (P) and ultrasonic pulse velocity. The porosity of crushed clay brick aggregates itself, in addition to cracks created during the crushing process, is reflected directly on the global porosity of concrete. Fig. 15 shows the effect of recycled aggregates content on concrete porosity. The figure clearly demonstrates that the increase in the content of crushed clay brick aggregates increases the concrete porosity. Replacement of the fine and coarse aggregates with recycled aggregates increases the concrete porosity by up to 63%.

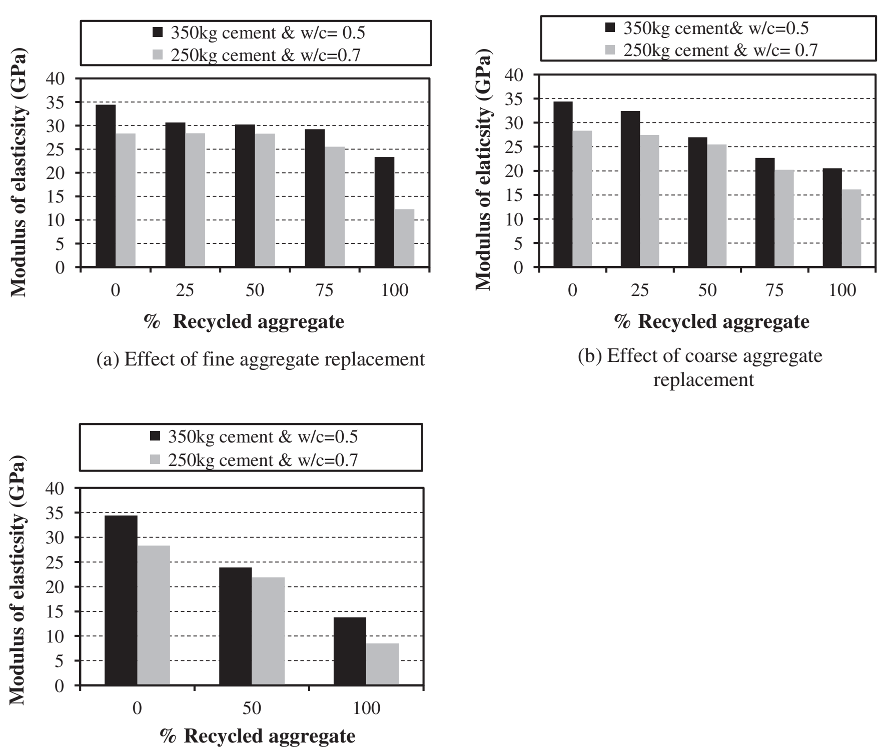
At this point, the ultrasonic pulse velocity test was introduced. Direct transmission technique was adopted to analyze the porous structure of concrete and to detect the internal defects (voids, cracks, etc.). The measured ultrasonic pulse velocity values against recycled aggregates substitution ratios are presented in Figs. 16–18. Again, replacement of the fine and coarse aggregates with recycled aggregates reduces the pulse speed by up to 67%. This result confirms the finding mentioned above. Results of porosity and ultrasonic pulse velocity for varied aggregates contents are tabulated in Table 7. It should be pointed out that the data obtained throughout the current program indicate the importance of the media porosity on the mechanical performance. The correlation between the compressive strength and porosity is presented in Fig. 19. The figure clearly demonstrates the critical effect of increased porosity on reducing concrete strength.

4. Phase II: concrete masonry units

4.1. Experimental program

4.1.1. Materials

Portland cement CEM-I 42.5N (ASTM Type I) from one local source was used in all mixes (Table 1). Natural siliceous sand

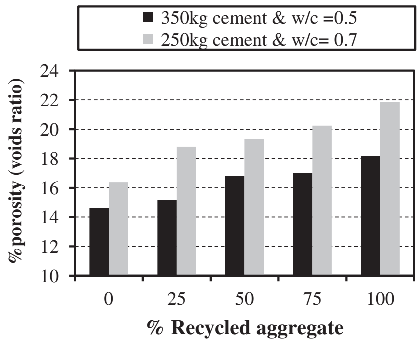


(a) Effect of fine aggregate replacement

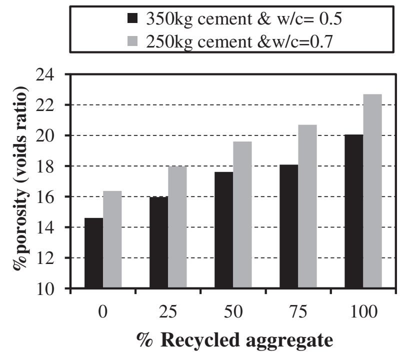
(b) Effect of coarse aggregate replacement

(c) Effect of coarse and fine aggregate replacement

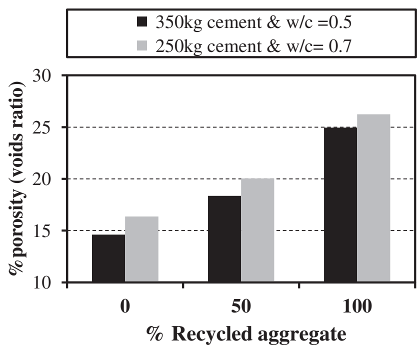
Figure 14 Effect of coarse and fine recycled aggregates content on concrete modulus of elasticity.



(a) Effect of fine aggregate replacement

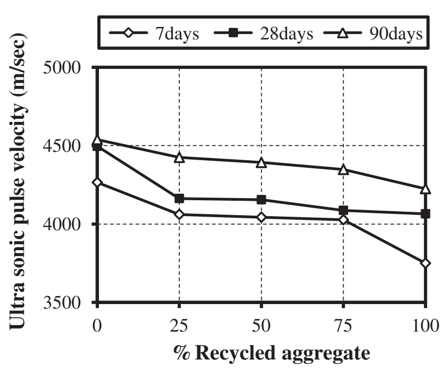


(b) Effect of coarse aggregate replacement

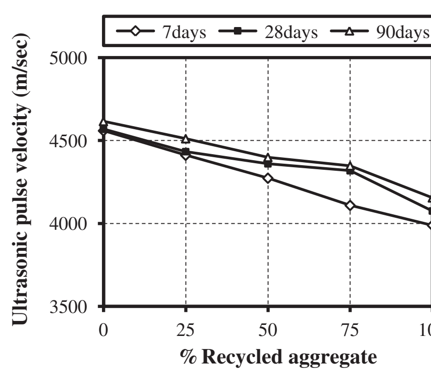


(c) Effect of coarse and fine aggregate replacement

Figure 15 Effect of coarse and fine recycled aggregates content on concrete porosity.

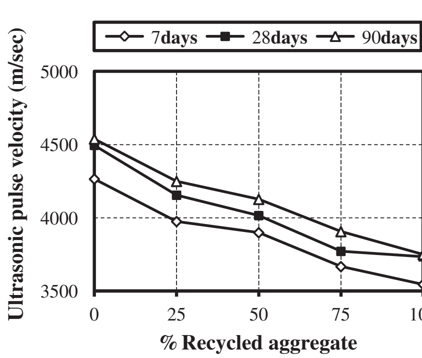


(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70

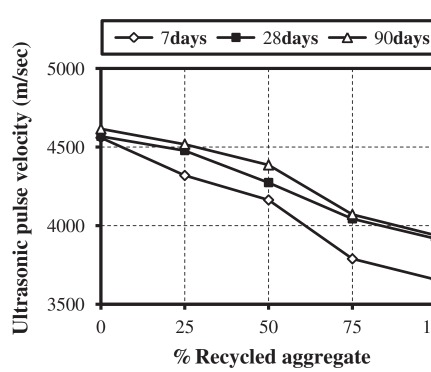


(b) Cement content = 350 kg/m^3 and w/c ratio = 0.5

Figure 16 Effect of fine recycled aggregates content on concrete ultrasonic pulse velocity.

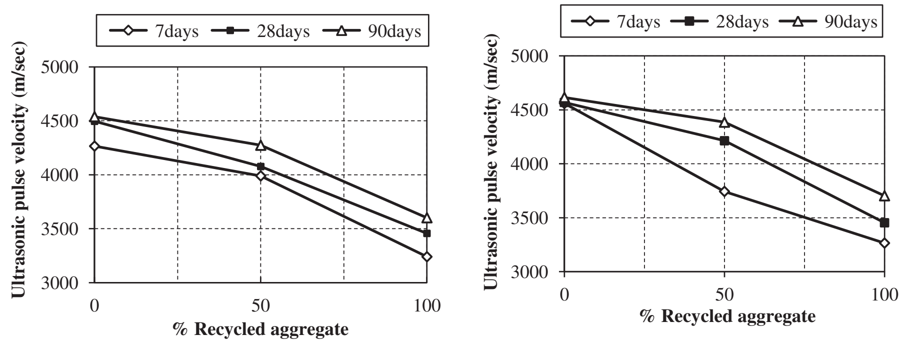


(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70



(b) Cement content = 350 kg/m^3 and w/c ratio = 0.5

Figure 17 Effect of coarse recycled aggregates content on concrete ultrasonic pulse velocity.



(a) Cement content = 250 kg/m^3 and w/c ratio = 0.70 (b) Cement content = 350 kg/m^3 and w/c ratio = 0.5

Figure 18 Effect of coarse and fine recycled aggregates content on concrete ultrasonic pulse velocity.

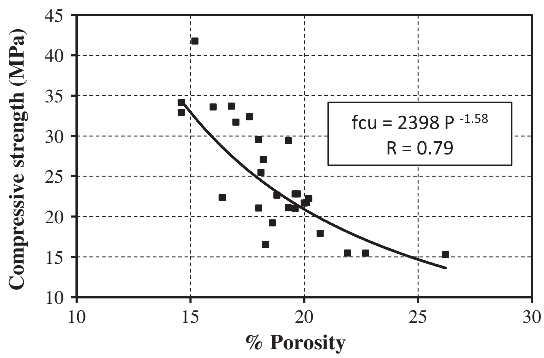


Figure 19 Compressive strength – porosity relationship.

Figure 20 Mixture appearance after mixing.

and limestone with 9.75 mm nominal maximum size were used as natural aggregates. Crushed clay brick wastes were prepared as mentioned earlier to comply sizes from 9.75 mm to 2.36 mm and from 4.75 mm to 0.15 mm for coarse and fine aggregate, respectively. Table 8 presents the physical properties and grading of the used aggregates.

4.1.2. Mix proportions

Natural fine/coarse aggregates or all-in aggregates were replaced with crushed clay brick aggregates. The substitution ratios of were 0%, 50% and 100% by volume. A total of 18

Table 8 Properties of the used aggregates.

Properties	Natural aggregates		Crushed clay brick aggregate		Limits	
	9.5 mm	Fine	9.5 mm	Fine		
Specific gravity (SSD)	2.59	2.63	2.06	2.08	–	
Water absorption (%)	0.8	1.3	16.2	18.3	⩽1.0[a] for coarse agg. and ⩽2.0[a] for fine agg.	
Fine materials%	1.32	1.54	2.2	5.9	⩽3.0[a]	
Fineness modulus	–	2.63	–	3.07	–	
Particle size distribution (mm)	Percent passing%				9.5 mm (Nominal size)	Fine
12.5 mm	100	–	100	–	100	–
9.5 mm	95.2	–	96.3	–	85–100	–
4.75 mm (No. 4)	13.7	99.0	25.8	100	10–30	95–100
2.36 mm (No. 8)	3.1	95.3	9.4	80.5	0–10	80–100
1.18 mm (No. 16)	0	81.1	1.2	51.2	0–5	50–85
600 μm (No. 30)	–	48.4	–	31.3	–	25–60
300 μm (No. 50)	–	9.8	–	20.3	–	5–30
150 μm (No. 100)	–	3.1	–	9.7	–	0–10

[a] According to ESS No. 1109/1971.

Table 9 Mix proportion of used concrete masonry units mixtures.

Mix no.	Replacement percentage		Recycled aggregates%	w/c	Mix proportions (kg/m^3)					
					C	W	Coarse aggregate		Fine Aggregate	
							Natural	Recycled	Natural	Recycled
1	Series(I)	Control	0%	0.5	350	175	1116	0	744	0
2		Fine agg. rep%	50%	0.5	350	175	1116	0	372	294
3			100%	0.5	350	175	1116	0	0	589
4		Coarse agg. rep%	50%	0.5	350	175	558	444	744	0
5			100%	0.5	350	175	0	888	744	0
6		Both agg. rep.%	50%	0.5	350	175	558	444	372	294
7			100%	0.5	350	175	0	888	0	589
8			100% F and 50% C	0.5	350	175	558	444	0	589
9			50% F and 100% C	0.5	350	175	0	888	372	294
10	Series(I I)	Control	0%	0.7	250	175	1166	0	777	0
11		Fine agg. rep%	50%	0.7	250	175	1166	0	389	307
12			100%	0.7	250	175	1166	0	0	615
13		Coarse agg. rep%	50%	0.7	250	175	583	464	777	0
14			100%	0.7	250	175	0	927	777	0
15		Both agg. repl%	50%	0.7	250	175	583	464	389	307
16			100%	0.7	250	175	0	927	0	615
17			100% F and 50% C	0.7	250	175	583	464	0	615
18			50% F and 100% C	0.7	250	175	0	927	389	307

F: Fine aggregate and C: Coarse aggregate.

concrete mixtures for masonry units were designed with various aggregate replacement ratios with almost zero slumps as usually suitable for brick press. The harsh mixtures appearance after mixing are presented in Fig. 20 while the concrete mix ingredients designed specially for concrete masonry units (hollow blocks) are given in Table 9.

4.1.3. Mixing and curing

The experiments have been conducted at a local factory specialized in the manufacturer of hollow block concrete masonry units. The manufactured specimens are with dimensions of 90 mm × 190 mm × 390 mm with 20 mm web thickness. The total mixing time was about 3 min. Special mixing process was followed. Firstly, cement was placed in the mixer along with water and mixed for 1 min. Then, fine aggregates were added and mixed for 1 min, and finally, coarse aggregates were added and mixed for 1 min. This procedure was followed to ensure good adherence among the cement particles and the used aggregates as recommended by Sadek [6]. After mixing, the fresh concrete mixtures were pressed under pressure by means of mechanical press as presented in Fig. 21. Subsequently, and after consolidation, the manufactured hollow blocks were water-cured twice a day up to the age of 28 days.

Figure 21 The used press.

4.1.4. Testing

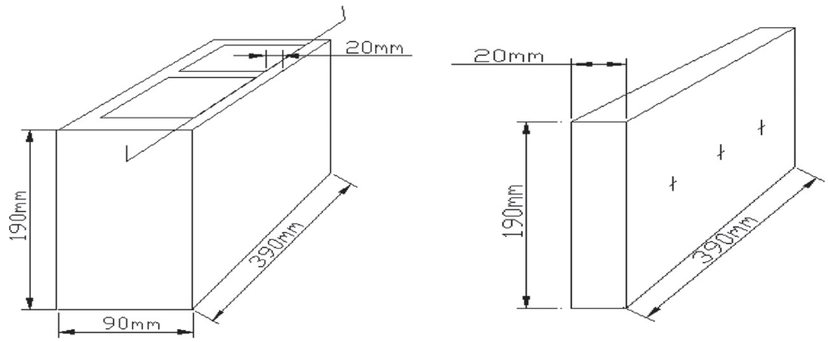
All concrete masonry blocks were tested under compression where the compressive force was applied to the sample's face with dimensions of 390 × 90 mm. Each result is the average of five concrete masonry units. The results were checked for compliance with ES 1292/2 [16] for non-load bearing units.

For unit weight assessment, the manufactured concrete masonry units were dried in an oven at 110 °C for 24 h, then removed from the oven and left to cool at room temperature and weighed. The unit weight of concrete hollow block was calculated by dividing the dry weight of each sample by its overall volume including cavitations. Afterward, the samples were immersed in water for 24 h, and then were taken out of the tank and the visible surface water was removed with a damp cloth and then reweighed to get the saturated weight. Then, water absorption was determined in accordance with ASTM C 140-03 [17].

Thermal resistance of concrete masonry units was individually established in accordance with IS EN ISO 6946. The followed methodology can be summarized as follows. Firstly, all blocks were prepared by saw cut as illustrated in Fig. 22. Then, thermal conductivity of concrete was determined by means of guarded hot plate method as accordance to British Standard [18]. The thermal conductivity, k, was calculated based on the following equation:

$$k = (\emptyset) \cdot (d/A) \cdot (1)/(T_1 - T_2) \quad (1)$$

where $\emptyset$ is the average power supplied to the metering section of the heating unit, d is the average specimen thickness, A is the metering area, T_1 is the average temperature at the hot side of



(a) 3D view of the manufactured CMU (b) The prepared specimens after cutting

Figure 22 Specimen preparation for thermal conductivity test.

the specimen, and T_2 is the average temperature at the cool side of the specimen.

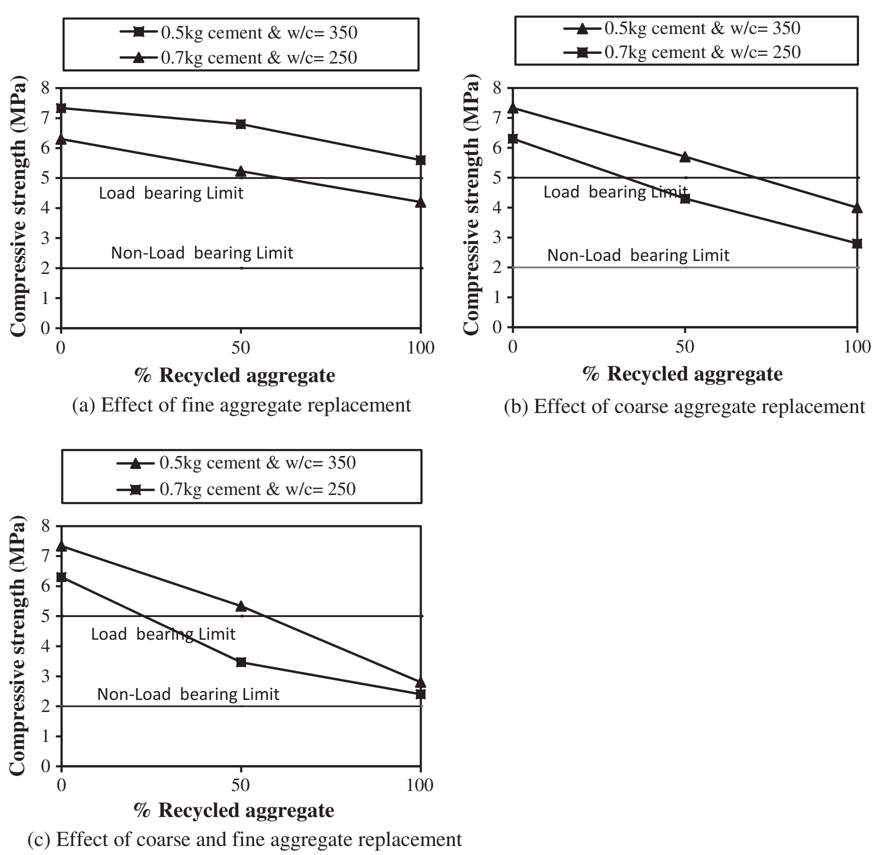
As a final point, the authors initially calculate thermal resistance of each concrete masonry block by means of thermal conductivity and dimensions of concrete masonry units using the 'Combined Method' as per IS EN ISO 6946 [19].

4.2. Results and discussion

4.2.1. Compressive strength

The compressive strength of the subject concrete masonry units is plotted against the percentage of recycled aggregates for different cement contents in Fig. 23. The compressive strength values vary from 7.33 to 2.80 N/mm^2. The figure clearly demonstrates that the higher the rate of substitution, the lower the concrete compressive strength. Actually, the control concrete units exhibit the largest compressive strength among the group.

Results indicate that whenever fine aggregate is totally replaced with recycled aggregate the mixture achieves acceptable results. Concrete masonry units containing 350 kg cement per m^3 and 100% recycled aggregates meet the requirements of Egyptian specifications of load and non-load bearing units. On the other hand, the reduction in compressive strength is significant whenever coarse aggregate is totally replaced with recycled aggregate. Up to 62% reduction is recorded; however, it is still appropriate for producing non-load bearing masonry units. Actually, for producing load bearing concrete masonry

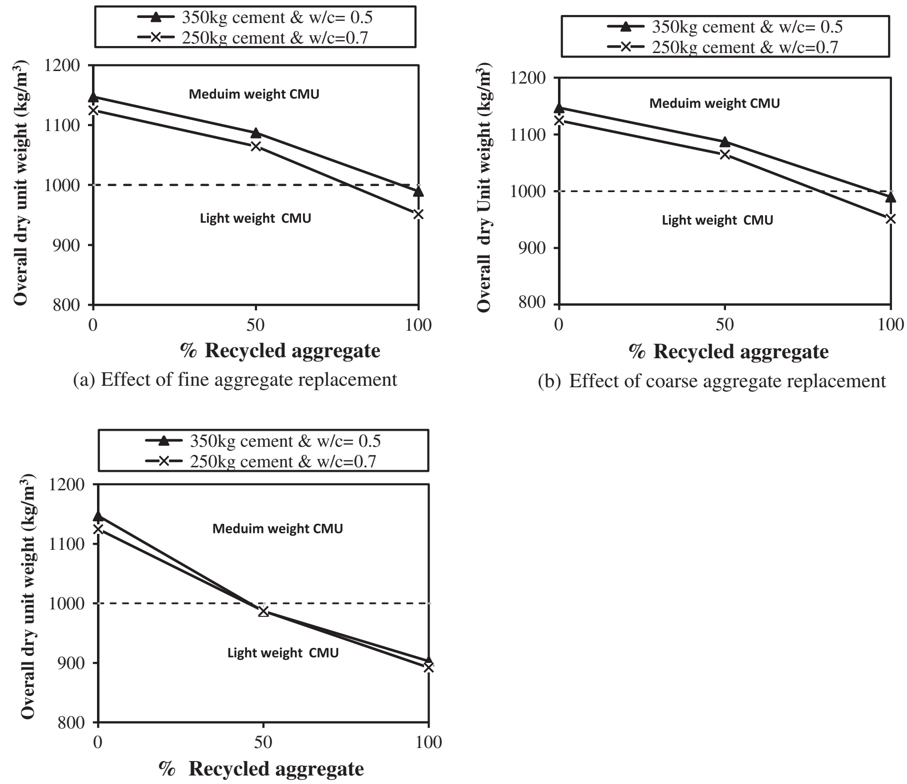


(a) Effect of fine aggregate replacement

(b) Effect of coarse aggregate replacement

(c) Effect of coarse and fine aggregate replacement

Figure 23 Effect of coarse and fine recycled aggregates content on compressive strength.



(a) Effect of fine aggregate replacement

(b) Effect of coarse aggregate replacement

(c) Effect of coarse and fine aggregate replacement

Figure 24 Effect of coarse and fine recycled aggregates content on dry unit weight.

units, it is strongly recommended that the substitution level of coarse aggregate should not exceed 50% especially for lower cement content blocks in order to meet the requirements of Egyptian specifications. In addition, concrete masonry units are still in agreement with Egyptian specifications limitations for non-load bearing units even if both fine and coarse aggregates are totally substituted with recycled aggregates.

Based on experimental evidences, it can be said that at full replacement of sand with recycled aggregates, the higher cement content in concrete masonry units is not promising. This may be attributed to the porous nature of crushed clay brick which significantly reduce the mechanical properties of concrete masonry units.

4.2.2. Overall dry unit weight

Results of unit weights for concrete masonry units are illustrated in Fig. 24. It is clear that the use of crushed clay brick aggregates as alternative aggregates linearly reduces the unit weight of the units. Based on experimental evidences, it can be stated that the totally replacement of fine and coarse aggregate with recycled aggregate reduces the dry unit weight of concrete masonry units by about 25%. The comparison between the obtained unit weight and limits of the Egyptian standard of light-weight bricks indicates that full replacement of coarse aggregate inserts the resulting bricks in the light-weight bricks category.

In fact, the dry unit weight of concrete masonry unit has a direct effect on its mechanical properties indicating the importance of unit weight on mechanical performance. Analysis of obtained data presented in Fig. 25 through the current program yields the following expression:

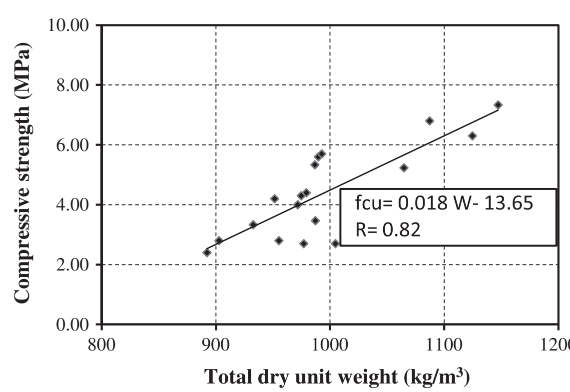


Figure 25 Compressive strength – dry unit weight relationship for mansonary units.

$$f_c = 0.018W - 13.65 \quad (2)$$

where W is the dry unit weight of concrete masonry block in kg/m^3, and f_c is compressive strength in MPa.

4.2.3. Absorption

Results of water absorption tests for concrete masonry units are demonstrated in Fig. 26. It can be observed that the water absorption of concrete masonry unit increases with the reduction in cement content and the increase in crushed clay brick aggregates content. The totally replacement of fine and coarse aggregate with recycled aggregate increases the dry unit weight of concrete masonry units by about five times. This may be attributed to the highly porous nature of crushed brick aggre-

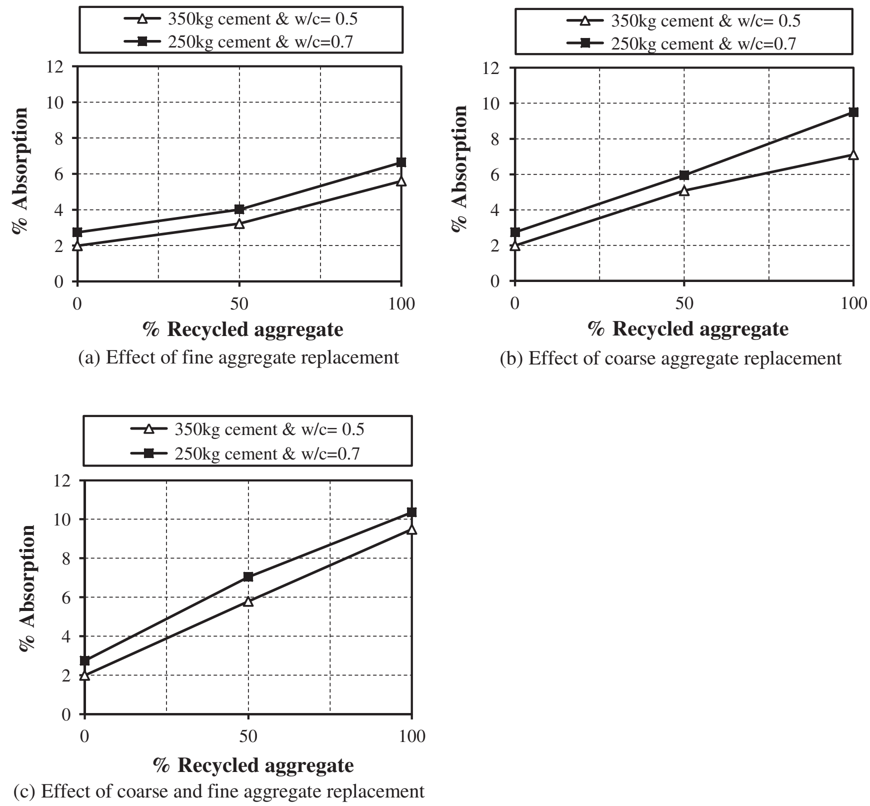


Figure 26 Effect of coarse and fine recycled aggregates content on water absorption.

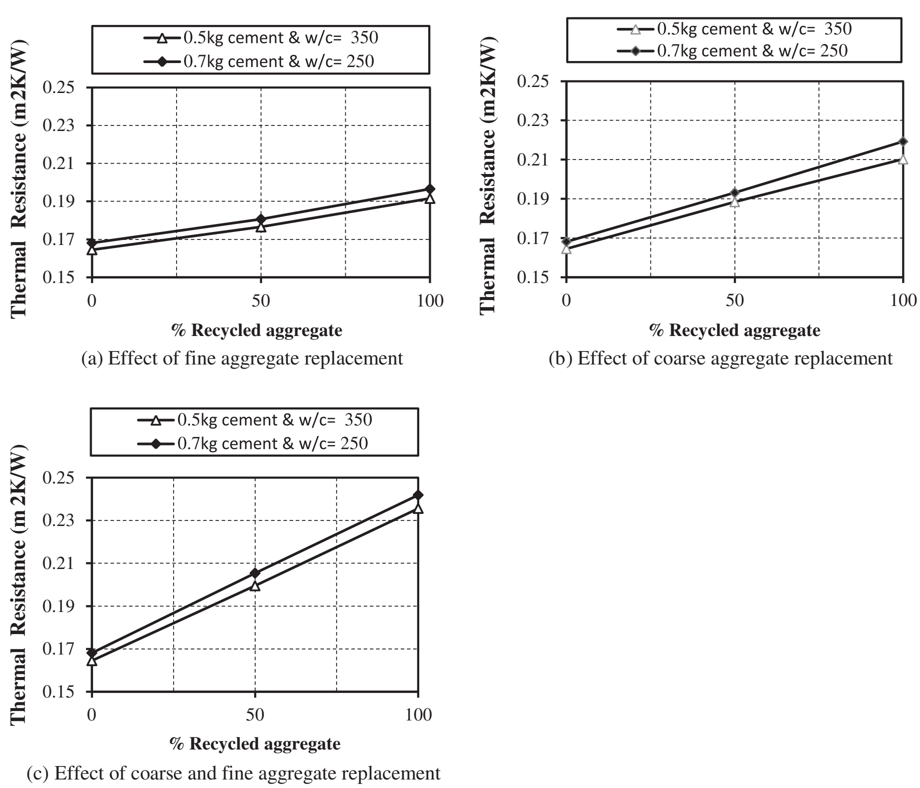


Figure 27 Effect of recycled aggregates content on thermal resistance of concrete masonry units.

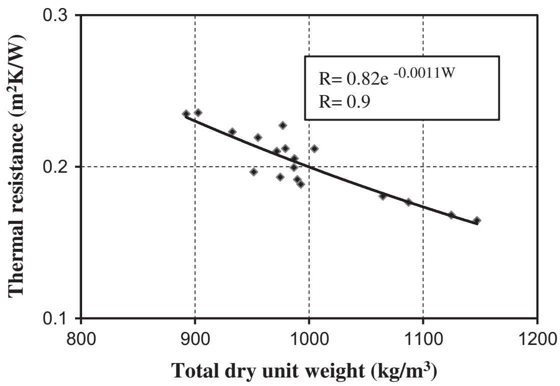


Figure 28 Thermal resistance – overall dry unit weight relationship.

gate and lower cement content concrete and confirm the finding reported earlier. This trend agrees with Sadek [6].

4.2.4. Thermal resistance

The thermal resistance of the manufactured concrete masonry units as a function of the replacement percentage of natural aggregates and cement content is shown in Fig. 27. It is evident from the figure that the use of crushed clay brick aggregates generally has a positive effect on thermal resistivity. This finding is valid for either fine, coarse or total aggregates, which are replaced by recycled aggregates. The effect of incorporating coarse recycled aggregate is more pronounced in increasing the thermal resistance of concrete masonry units.

In fact, the reduction in unit weight of concrete masonry units that is associated with the use of recycled aggregate made of crushed clay brick greatly affect the thermal resistivity of the units. The correlation between unit weight and thermal resistivity of masonry units is presented in Fig. 28 and can be expressed as:

$$R = 0.82e^{(-0.00141W)} \quad (3)$$

where R is the thermal resistance in m^2 K/W, and W is the dry unit weight in kg/m^3.

It should be mentioned herein that above expression is similar in the format with that reported by ACI 122R, where thermal conductivity is expressed as a function of oven dry density as follows:

$$K_c = 0.072e^{(0.00125d)} \quad (4)$$

where d is the oven-dry density in kg/m^3, and K_c is the thermal conductivity in W/m K.

5. Conclusions

A comprehensive experimental program for recycled aggregates and powder (CBP) produced from clay brick demolition wastes is presented. A total of 44 mixtures was utilized throughout the program. The main conclusions obtained from this study under the described battery of tests may be divided in two scopes:

5.1. Scope (I): cement paste, mortar and concrete

1. Specimens of paste, mortar and concrete incorporating recycled aggregates were examined. Three mixtures of cement pastes were prepared with various CBP ratios as a partial cement replacement; 0%, 15% and 25% by weight. Mortar mix proportions were selected in accordance with ASTM C109 where CBP was used as cement replacement and addition; 0%, 5%, 10%, 15%, 20% and 25% by cement weight. Also, twenty-six concrete mixtures were explored with various replacement ratios of fine and coarse aggregates with recycled aggregates.

2. Tests performed throughout the program are X-ray diffraction (XRD), thermo-gravimetric analysis (TGA), and micro-structural analysis (MSA). Other properties such as compressive and splitting-tensile strengths, static elastic modulus, ultrasonic pulse velocity and porosity are also determined.

3. The X-ray diffraction tests performed on paste samples indicates the presence of portlandite, ettringite, calcite, quartz and C–S–H in all tested samples regardless the presence of CBP. Actually, comparable X-ray patterns are observed. It can be therefore concluded that the presence of CBS in the paste (up to 25% replacement) has a minimal effect on mineral compositions of the matrix.

4. Results of thermo-gravimetric analysis (TGA) demonstrate that the incorporation of CBP (at 25% cement replacement) reduces the weight loss of cement paste under high temperature of 600 °C by up to 35% which may lead to higher fire resistance.

5. Crushed clay brick powder improves cement paste structure. It reduces the volumes and numbers of pores. It is evident from the micro-structural analysis that the paste sample containing 25% CBP has the smallest pore size and the best pore structure. Actually, microscopic examination confirms that the additional hydrates produced by pozzolanic reactivity of CBP increase the density of the matrix and refine the pore structure. This finding is very promising in the area of construction engineering.

6. Reduction in the 28-day compressive strength of mortar is noticeable due to the incorporation of CBP. Up to 25.2% strength reduction is associated with 25% cement replacement by CBP. Contradictorily, slightly beneficial effect in compressive strength is noticeable when CBP is incorporated as an additive.

7. The use of clay brick powder as a cement addition improves mortar compressive strength.

8. Results of concrete specimens confirm that the increase in the recycled aggregates content decreases the concrete compressive strength except for fine aggregates replacement where strength remains comparable or slightly improved. This may be attributed to the good grading of the crushed clay brick aggregate and the pozzolanic reactivity of super fine portion of crushed brick aggregate.

9. The presence of high content of crushed clay brick aggregates decreases concrete modulus of elasticity, concrete splitting-tensile strength, and increases concrete porosity. The higher the cement content the more detrimental performance.

10. The approach of strength activity index specified by ASTM C618 and outlined in ASTM C311 implies that the used clay brick powder has pozzolanic properties.

11. From general prospective, the use of crushed clay brick as alternate aggregates has relatively negative effects on concrete porosity and mechanical properties which limits the use of these aggregates in many structural applications; however, it has other positive effects. It reduces concrete density, which leads to lower transportation cost and lower dead load, and it may be promising as a fire-resistant concrete.

12. Based on experimental evidences, it can be stated that the Egyptian code's formula for predicting the splitting-tensile strength from the compressive strength of concrete is underestimated by about 20% for concrete incorporated crushed clay brick aggregates.

13. To avoid strength reduction, it is strongly recommended to limit the percentage of coarse aggregate replacement by recycled aggregate to 25% and 50% for concrete containing 350 and 250 kg/m^3, respectively, of cement content. Actually, the reduction in compressive strength associated with higher replacement levels is pronounced.

5.2. Scope (II): concrete masonry units

14. The use of recycled aggregates reduces the overall unit weight of concrete masonry units. In fact, the overall unit weight of the subject units gradually decreased by increasing the content of crushed brick aggregates. Based on experimental evidences, it can be stated that the totally replacement of fine and coarse aggregate with recycled aggregate reduces the dry unit weight of concrete masonry units by up to 25%.

15. The thermal resistance of masonry concrete blocks is remarkably improved with increasing the content of crushed clay brick aggregates. Therefore, it can be stated that modified concrete masonry units have better thermal properties than traditional units made with natural aggregates.

16. The compressive strength of the subject masonry units is proportional to its total dry unit weight; the lower the unit weight, the lower the compressive strength. However, all units incorporating recycled aggregates meet the requirements of national specifications for non-load bearing units.

17. The reduction in compressive strength is significant whenever coarse aggregate is totally replaced with recycled aggregate. Up to 62% reduction is recorded; however, it is still appropriate for producing non-load bearing masonry units. In fact, concrete masonry units are in agreement with Egyptian specifications limitations for non-load bearing units even if both fine and coarse aggregates are totally replaced with recycled aggregates.

18. It is feasible to make use of crushed clay brick aggregates in producing load bearing units but it depends on the contents of crushed brick aggregates and cement in the mixture.

19. For producing load bearing concrete masonry units, it is strongly recommended that the substitution level of coarse aggregate should not exceed 50% especially for lower cement content blocks in order to meet the requirements of relevant standards.

20. From general prospective, it can be concluded that the use of recycled aggregate and dust made of clay brick is promising in many applications where the thermal resistance, cost and environmental aspects are imperative.

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