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Article

Mechanical Properties of Cement-Clay Interlocking (CCI) Hollow Bricks

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Abstract. In this paper, an investigative study on mechanical properties of CCI hollow bricks, for example, compressive strength, modulus of rupture, splitting tensile strength, water absorption capacity and heat transfer is conducted. The experimental program is divided into two parts. In the 1st part, bricks from three different regions (A, B and C having different soil stratum) of Thailand were collected and their mechanical properties were investigated. The mechanical properties of CCI hollow bricks of region A were observed relatively very low as compared to other regions. The compressive strength values of region A bricks were found even below the standard values required by Thai Community Product Standards (TCPS). Then, in the 2nd part, change in three mix design ratios followed by sand, cement and fly ash for region A have been exercised to observe their effects on mechanical properties of bricks from said region. Results showed significant improvements as compared with previous results obtained in first part of the experimental program. Also, a cost-benefit analysis was performed to observe the effect of the manufacturing cost on the mechanical properties of CCI hollow bricks in Thailand. It has been investigated that the brick samples with more cement content (from region C, Mix – 2 & Mix – 3) are relatively expensive as compared with other brick samples with less cement content (from region A, region B & Mix – 1).

Keywords: Cement, clay, interlocking bricks, compressive strength, water absorption capacity, fly ash.

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1. Introduction

Bricks are one of the primary construction material which is widely used all around the world since decades [1]. Conventional fired clay-based bricks are usually produced by mixtures of clays and shale as raw materials, and which are then processed in different shaping, drying and firing procedures at high temperature. Fired clay bricks are main construction material which is used for the construction of buildings but in the same time, it suffers from the higher costs of energy with some other environment related problems such as high energy usage and emission of carbon dioxide [2]–[9]. Also, conventional fired clay bricks are very much vulnerable to weather, especially in rainy seasons in which soil material may lose cohesiveness, in particular with cement plaster [10]. In addition, the ever-increasing demand of building construction made it necessary to develop new ways to fulfil and solve construction related problems. However, an initiative to produce highly compressed stabilized cement-clay interlocking (CCI) hollow bricks (which are somehow similar to the LEGO blocks) as an alternative method in comparison of the conventional fired clay bricks, this method uses less or minimum mortar to fix the bricks together. These CCI hollow bricks are mainly produced by using appropriate different soil mixes (such as clay, sand and stone dust), with adequate compaction and stabilization using cement and admixtures, which ensures the increased density of the bricks, reduced water absorption capacity, increased frost resistance in extreme weathers and mainly enhanced compressive strength of CCI hollow bricks. This method of manufacturing unfired bricks has major advantage over conventional fired bricks as it produces around 80% less carbon dioxide in the atmosphere, giving it advantage with respect to environmental concerns, while using comparatively very low energy incurred in the manufacturing process [11]–[16]. A study by Walker (1995) [17] investigated the impacts of soil characteristics and cement content on the physical properties of stabilized soil blocks and suggested that the strength of the stabilized soil blocks in saturated conditions and durability can be enhanced by adding cement content as compared with clay contents. He suggested that the ideal soil-cement blocks must have a plasticity index in between of 5 to 15. The mixes having plasticity index more than 20-25 are not very suitable for stabilization in manual pressing method as it causes shrinkage due to excessive drying process, with inadequate durability and lower compressive strength values. Reddy and Gupta (2005) [18] used the sandy soils for investigating various characteristics of the soil-cement blocks and inferred that the compressive strength of the mixes increase 2.5 times if cement content is doubled with an increase from 6% to 12%. They also concluded that the saturated water content of the blocks is not very much sensitive to cement content, while moisture absorption greatly influenced by cement content. As cement content is increased, the pore size is decreased in cement-soil blocks. However, the surface porosity is not sensitive when adding cement content. In Thailand, cement-clay interlocking (CCI) hollow bricks are usually locally made with the available clay materials throughout the country for the construction of low rise residential buildings without following any standard procedure or guidelines. These bricks are manufactured locally in small factories located in different regions of Thailand. In Thailand, there are at least more than 700 brick manufacturing plants in Thailand [19]. Mostly, these plants are located in rural areas and these plants are owned by successful farmers or entrepreneurs who have gained experience through working with other brick plants. Most of the rural brick manufacturing plants owners use clay dug from their own land. According to the geological map of Thailand, the sedimentary and metamorphic rock distribution of Thailand is quite diverse, ranging from mudstone to sandstone and shale [20]. Many studies have reported that change in clay contents cause change in mechanical properties of bricks [14], [21] - [23]. In addition, there are no standard guidelines or reference codes of practice to manufacture CCI hollow bricks. However, some limits on compressive strength and water absorption capacity of interlocking blocks are defined by Thai Industrial Standards Institute, Bangkok [24]. In general, each CCI hollow brick manufacturing plant is using different mix designs. These mix designs are produced from locally available materials and existing knowledge and practice of the local manufacturing laborers. For example, some plants use only cement and clay to produce CCI hollow bricks whereas some plants also add stone dust or sand along with cement and clay to produce CCI hollow bricks. The change in mix design proportions directly affects the mechanical properties of CCI hollow bricks, for example, compressive strength, tensile strength and water absorption. Mechanical properties of bricks such as compressive strength, splitting tensile strength and modulus of rupture are very important engineering properties which are used to design masonry structures. In the past different methods such as non-destructive and destructive methods have been used to access the compressive strength of existing masonry construction [25]. In addition, compressive behavior of masonry triplets in wet and dry conditions have been also investigated under laboratory conditions [26].

As per author's information there are limited studies on the mechanical properties of CCI bricks [21] and there is no comprehensive research study conducted on the mechanical properties of clay-cement interlocking hollow bricks manufactured in different regions of Thailand. Hence there is a need to hasten the effort to determine the effects of locally available materials and mix design ratios on the mechanical properties of clay-cement interlocking bricks. In addition, Thailand has two major types of climate; i.e., dry season and rainy season. But, there is not much variation in temperature which ranges between 30-35^{0}C. In Thailand, the local residents favor in using interlocking hollow bricks because of obvious reasons of heat transfer and moisture content control, and no usage of mortar. Thus there is need to study the moisture absorption and heat transfer rate of CCI hollow bricks. To achieve this goal, an experimental program is planned to determine the mechanical properties such as compressive strength, modulus of rupture, splitting tensile strength, water absorption capacity and heat transformation. The experimental program is divided into two parts. In the 1st part, CCI hollow bricks from three different regions (A, B and C having different soil stratum) of Thailand were collected and their mechanical properties were investigated. The mechanical properties of CCI bricks were also compared with the recommendations of Thai community product standards [21]. The mechanical properties of CCI hollow bricks of region A were observed relatively very low as compared with other regions and compressive strength was found even below the standard values. As per author's information, in the past, limited studies have been conducted on the use of recycled and other waste materials to produce the solid clay bricks and CCI hollow bricks [27], [28]. Hu et al. 2014 investigated the mechanical properties of waste clay bricks from debris of buildings through lab tests. The test results of compaction property indicated that the cement treated aggregate which contains crushed clay brick had a lower maximum dry density and higher optimum moisture content [29]. Another study conducted on mechanical properties fired bricks with replacing clay by fly ash in high volume ratio reported that fly ash used as raw material replacing of clay to make fired bricks is an effectively measure of saving land and decreasing pollution [30]. Nazar and Sinha (2006) [31] studied the performance of brick masonry under cyclic compressive loading. The bricks masonry was built using interlocking grouted stabilized mud-fly ash bricks. In another study Nazar and Sinha (2007) [27] explored the fatigue behavior of inter-locking stabilized mud-fly ash brick masonry with grouts. Both studies have shown that fly ash can be effectively used to produce the interlocking bricks. Therefore, in the 2nd part, different mix design ratios of sand, cement, and fly ash were proposed and their effects on mechanical properties of CCI hollow bricks were investigated. The use of sand is basically adopted due to the ease in the availability and low cost. Fly ash was also used to replace the cement and to investigate the effectiveness of Fly ash to manufacture CCI bricks. Fly ash is one of the coal combustion products (CCPs) of coal burning power plants and it contains substantial amounts of potentially harmful constituents to the environment. The major difference between fly ash and Portland cement is the relative quantity of each of the different compounds. Portland cement is rich in lime (CaO) while fly ash is low. Fly ash is high in reactive silicates while Portland cement has smaller amounts. It was found that proposed mix ratios are very effective to alter the performance and mechanical properties of CCI hollow bricks as compared with original mixes (i.e., 1st Part).

2. Research Significance

As bricks are widely used construction material in Asia. So, this study is aimed at designing a good mix of component materials for improved mechanical properties using locally available materials. Also, the performance of the mechanical properties of traditionally prepared bricks are compared with the new proposed mixes. This research study can be used as guidelines for the manufacturing of CCI hollow bricks with improved mechanical properties. This research study also highlights the effective use of locally available materials for the manufacturing of CCI hollow bricks.

3. Manufacturing Process of CCI Hollow Bricks

The Cement-Clay Interlocking (CCI) hollow bricks were prepared in three different steps. In the first step, the component materials were collected and the coarse particles of red-clay were broken down into fine particles for the purpose of easy mixing. The collection of the clay material was done very carefully so that none of the impurities were contained in the clay-material. For the sake of removing organic material and impurities from the pure clay-material, the un-soiling of the clay was done. In the un-soiling process, the top layers of the soil were removed off so that vegetation and stone pebbles should not be contained in the sample components. In this process, the unwanted particles were removed before the grinding process. The grinding process of the component materials were carried out with the help of mechanical mixing machine to get homogeneous mix of design components. In the second step, all of the designed component materials (such as cement, sand, red-clay, fly-ash and water etc.) were mixed in a concrete mixing machine. In this step, the blending of the component materials was done and each component material was added as per designed amounts. Different homogeneous mixes were prepared using designed amounts of component materials. In the third and last step, the prepared mixes were put into aluminum molds and were pressed either hydraulically or manually with machines. These prepared mixes were shaped into brick molds of specific dimensions, which were later burnt at certain degree of temperature for obtaining good quality bricks. These bricks were further tested in the lab to investigate the mechanical properties.

4. Experimental Program

The A large scale experimental program was planned to achieve the research objectives. The proposed experimental program is divided into two parts. In the 1st part, bricks from three different regions (A, B and C having different soil stratum) of Thailand were collected and their mechanical properties were investigated. These regions were selected to represent different kinds of sedimentary and metamorphic rocks. The names of the provinces are not revealed to avoid any kind of conflict. In the manufacturing process of these CCI hollow bricks, the plant owner's do not follow any specific mix design specifications and or recommendations. CCI hollow bricks were prepared based on their experience and knowledge. Mix components of these different regions are summarized in Table 1. The nominal dimensions of these CCI hollow bricks are shown in Fig. 1 and summarized in Table 2. While in the second part, specific mix designs were advised to be followed for manufacturing of CCI hollow bricks from region A. Three different mix designs were proposed by changing/adding the ratios of sand, cement and fly ash in the original conventional mix from region A. These mix designs were labelled as Mix–1, Mix–2 and Mix–3. Mix components are summarized in Table 3. The newly proposed mix designs were exercised at the manufacturing plant of CCI bricks of region A. The nominal size of these newly manufactured CCI bricks was similar to the CCI bricks of region A (Table 2). In the last step, the prepared mix is placed into the aluminum molds and pressed by either hydraulically or manually operated machines.

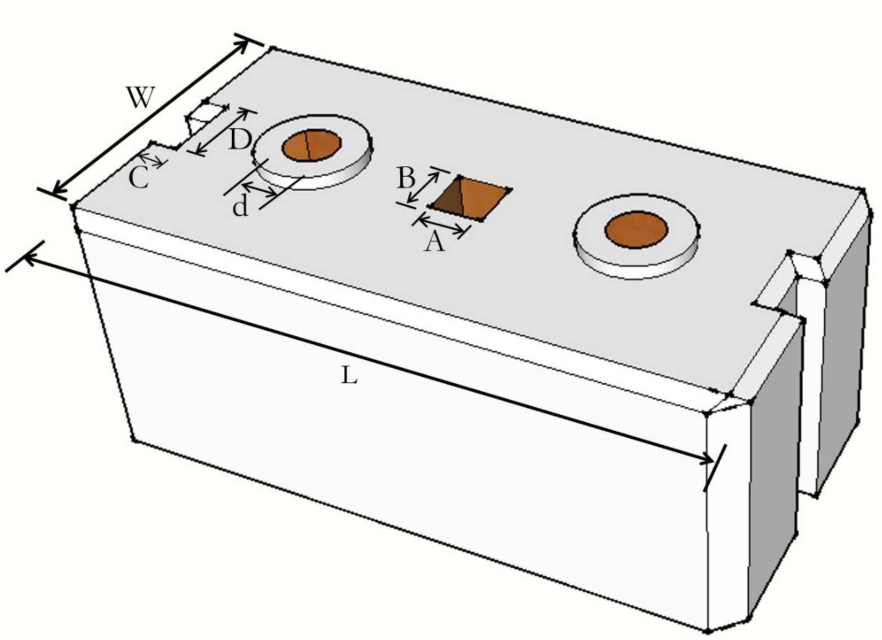

Fig. 1. Typical detailing of CCI hollow bricks.

Table 1. Mix components of different regions to prepare CCI hollow bricks.

Regions	**Mix components (kg/m³)**			
	Cement	**Sand**	**Stone dust**	**Red clay**
Region A	164.0	-	-	1636.0
Region B	660.0	570.0	380.0	190.0
Region C	534.0	380.0	126.0	760.0

Table 2. Dimensional details of CCI hollow bricks.

Dimensions (mm)	**Region A**	**Region B**	**Region C**
L	250	200	250
W	125	100	125
H (Height of brick)	100	100	100
d	35	20	30
A x B	20 x 20	30 x 25	25 x 25
C x D	10 x 20	10 x 25	10 x 25
Bearing Area (BA) (cm²)	285	181	287
Weight (kg)	4.95	3.02	5.01
Density (kg/m³)	1737	1669	1746

Table 3. Newly proposed mix proportions.

Proposed mix	Mix components (kg/m^3)				Density (kg/m^3)
	Cement	Sand	Fly ash	Red clay	
Mix-1	164.0	164.0	-	1472.0	1838
Mix-2	328.0	-	-	1472.0	1944
Mix-3	164.0	-	164.0	1472.0	1892

5. Mechanical Properties

The detailed methods to find and investigate the mechanical properties of cement–clay interlocking (CCI) hollow bricks such as compressive strength, modulus of rupture, splitting tensile strength, water absorption capacity and heat transfer are briefly discussed in this section. Standard testing guidelines according to ASTM standards [32]–[34] were followed in the experimental program to investigate the mechanical properties of CCI hollow bricks.

5.1. Compressive Strength

Standard testing procedure [32] was used to investigate the compressive strength of the CCI hollow bricks in each part of the study. The Universal Testing Machine (UTM) was used to carry out the testing procedure. During the testing period, load at a constant speed of 0.5 mm/minute was applied on each sample in the same manner. A typical loading setup for testing CCI hollow bricks is shown in Fig. 2. Prior to the load application, top surfaces of CCI bricks were grinded to remove the upward projects around circular openings and load was applied over the net area of CCI bricks. The following equation (equation 1) was used to determine the compressive strength (CS) of CCI hollow bricks.

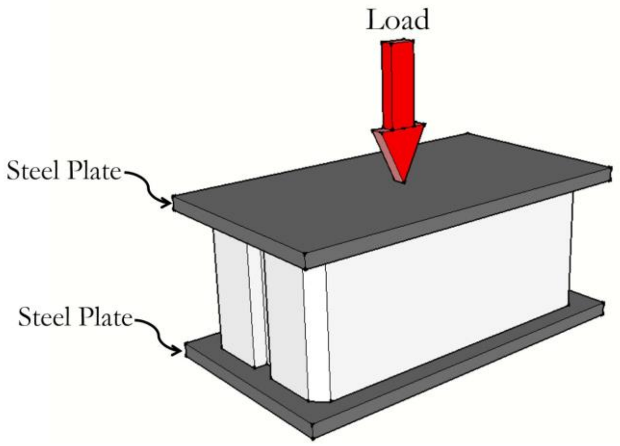

Fig. 2. Typical loading scheme for compressive strength test.

$$CS=\frac{P}{A} \quad (1)$$

where,

CS = Compressive strength (MPa)

P = Maximum load (N)

A = Net bearing area of CCI bricks (mm^2)

5.2. Modulus of Rupture

Modulus of rupture can be defined as "a material property in the form of stress in the material just before it yields in a flexural test. Standard sampling and testing procedure [33] was used to investigate the flexural strength of three samples in each part of the study. The UTM was used to carry out the testing procedure. During the testing period, load at a constant speed of 0.5 mm/minute was applied on each sample in the same manner. A typical loading setup for testing of CCI hollow bricks is shown in Fig. 3. The following equation (equation 2) was used to determine the modulus of rupture of CCI hollow bricks.

$$R=\frac{3P(0.50L_1-x)}{WH^2} \quad (2)$$

where;

R = Modulus of rupture (MPa)

L_1 = Distance between the supports (mm) = L – 50, where L is length of CCI brick

W = Net width (face to face distance minus voids) at the plane of failure (mm)

H = Depth (bed surface to bed surface distance) at the plane of failure (mm)

X = Average distance from mid-span of specimen to plane of failure in the direction of span along center-line of the bed surface subject to tension (mm)

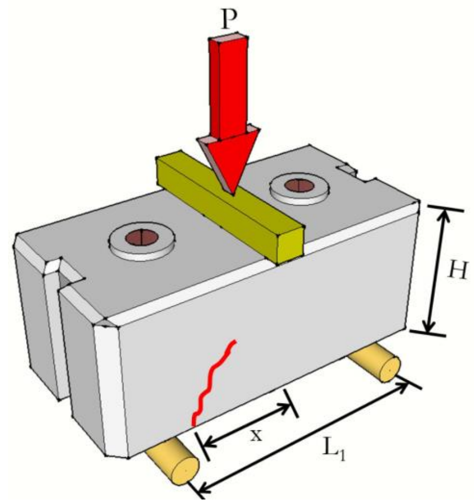

Fig. 3. Typical loading scheme for modulus of rupture test.

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5.3. Splitting Tensile Strength

Standard sampling and testing procedure [34] for masonry units was used to investigate the splitting tensile strength of CCI hollow brick samples. The UTM was used to carry out the testing procedure. During the testing period, load at a constant speed of 0.5 mm/minute was applied on each sample in the same manner. A typical loading setup for testing of CCI hollow bricks is shown in Fig. 4. The following equation (equation 3) was used to determine the splitting tensile strength of CCI hollow bricks.

$$T=\frac{2P}{WH} \quad (3)$$

where;
T = Splitting tensile strength (MPa)
W = Split length (mm) (Gross width minus the length of any voids along failure plane of the bearing rods)
H = Distance between rods (mm) = height of CCI brick (see Table 2)

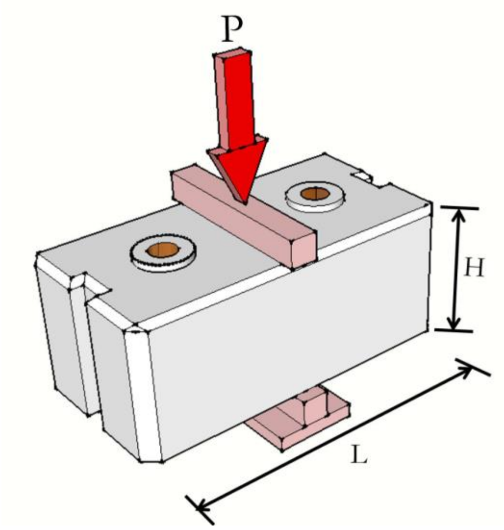

Fig. 4. Typical loading scheme for splitting tensile strength test.

5.4. Water Absorption Capacity

Standard testing procedure [32] of masonry units was used to find the water absorption capacity of CCI hollow brick samples. In each part of this study, three brick samples of each region or mix were tested to determine the average water absorption capacity of CCI bricks. In order to determine the water absorption capacity of CCI hollow bricks, the brick samples were oven dried and placed in water for 24 hours. Following equation (equation 4) was used to find the water absorption capacity of CCI hollow bricks.

$$A=\frac{W_s-W_d}{W_d}x100 \quad (4)$$

where;
A = Water absorption capacity (%)
W_d = Weight of oven dried bricks (kg)
Ws = Weight of saturated bricks (kg)

5.5. Heat Transfer

Heat transfer through the CCI hollow bricks was measured by inducing a high temperature (up to 350oC) by using hot plate (electric heater). Actually, the temperature was induced on one side (side A) and transformation of temperature on the other side (side B) was noted during the heat transfer test. Thermocouple wires were used to record temperature on both sides of brick samples (i.e., side A and side B) through data logger and computer. During the heat transfer test the initial temperature, variation of temperate, highest temperature and time to reach highest temperature on both sides of CCI hollow brick samples were observed and recorded. A typical test setup of heat transfer test for CCI hollow bricks is shown in Fig. 5.

6. Test Results and Discussions

The experimental results of both parts (i.e., part 1 and part 2) in terms of compressive strength (CS), modulus of rupture (MR), splitting tensile strength (STS) and water absorption (WA) capacity of CCI hollow bricks are summarized in Tables 4-9. Experimental results are also shown graphically in Figs. 6-9. A detail discussion of experimental results is provided in the following sections.

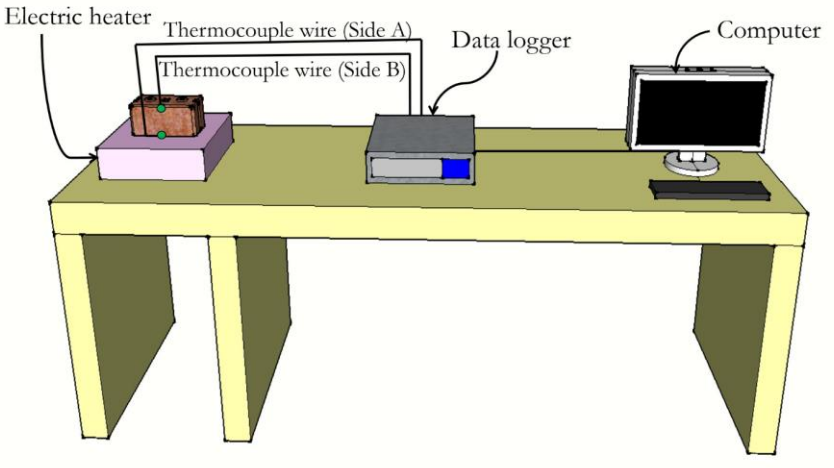

Fig. 5. Typical setup for heat transformation.

Table 4. Experimental results of CCI hollow bricks (Part-1).

Bricks	CS (MPa)	MR (MPa)	STS (MPa)	WA (%)	WA (kg/m³)
1A	5.23	0.77	0.25	15.15	265.0
2A	2.84	0.72	0.18	14.50	253.0
3A	4.59	1.06	0.22	9.340	160.0
Average	4.22	0.85	0.22	13.00	226.0
Standard error	0.583	0.087	0.017	1.501	27.092
1B	18.52	1.73	0.24	9.830	167.0
2B	14.78	1.98	0.32	10.39	171.0
3B	16.08	1.67	0.31	9.840	164.0
Average	16.46	1.80	0.29	10.00	167.0
Standard error	0.895	0.078	0.021	0.151	1.656
1C	7.41	2.06	0.23	10.02	174.0
2C	11.60	1.56	0.25	10.34	179.0
3C	8.48	2.20	0.20	10.07	178.0
Average	9.16	1.94	0.23	10.10	177.0
Standard error	1.026	0.159	0.012	0.081	1.247

Table 5. Experimental results of newly manufactured CCI hollow bricks (Part-2).

Bricks	CS (MPa)	MR (MPa)	STS (MPa)	WA (%)	WA (kg/m³)
M1-1	4.73	1.90	0.12	12.73	229.0
M1-2	6.49	0.62	0.16	9.280	172.0
M1-3	6.38	1.10	0.17	9.860	184.0
Average	5.87	1.21	0.15	10.60	194.6
Standard error	0.465	0.305	0.012	0.871	14.166
M2-1	12.32	2.05	0.28	13.32	329.0
M2-2	11.88	1.41	0.41	10.58	303.0
M2-3	15.39	2.09	0.39	9.880	331.0
Average	13.20	1.85	0.45	11.30	321.0
Standard error	0.901	0.180	0.033	0.857	7.364
M3-1	12.30	1.78	0.49	8.620	161.0
M3-2	6.03	2.21	0.41	9.130	168.0
M3-3	6.77	2.26	0.34	8.780	169.0
Average	8.37	2.08	0.41	8.800	166.1
Standard error	1.615	0.124	0.035	0.123	2.055

Table 6. Comparison of compressive strength values of newly manufactured CCI bricks.

Bricks	Average CS (MPa)	Percentage increase in average CS
Region A	4.22	-
Mix-1	5.87	39.00
Mix-2	13.20	213.00
Mix-3	8.37	98.30

Table 7. Comparison of modulus of rupture values of newly manufactured CCI bricks.

Bricks	Average MR (MPa)	Percentage increase in average MR
Region A	0.85	-
Mix-1	1.21	42.35
Mix-2	1.85	117.64
Mix-3	2.08	144.70

Table 8. Comparison of splitting tensile strength values of newly manufactured CCI bricks.

Bricks	Average STS (MPa)	Percentage increase in average STS
Region A	0.22	-
Mix-1	0.15	-
Mix-2	0.45	104.54
Mix-3	0.41	86.36

Table 9. Comparison of water absorption capacity of newly manufactured CCI bricks.

Bricks	Average WA (%)	Percentage reduction in average WA
Region A	13.00	-
Mix-1	10.60	18.46
Mix-2	11.30	13.07
Mix-3	8.800	32.31

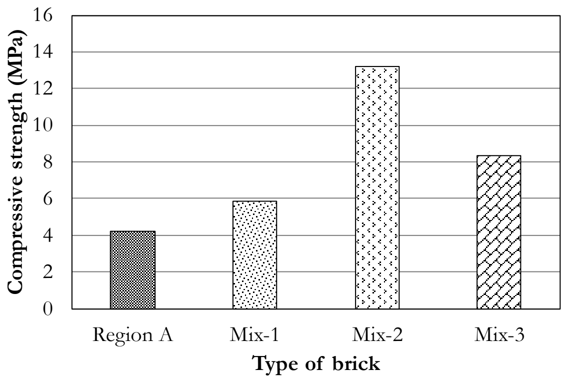

Fig. 6. Comparison of average CS values.

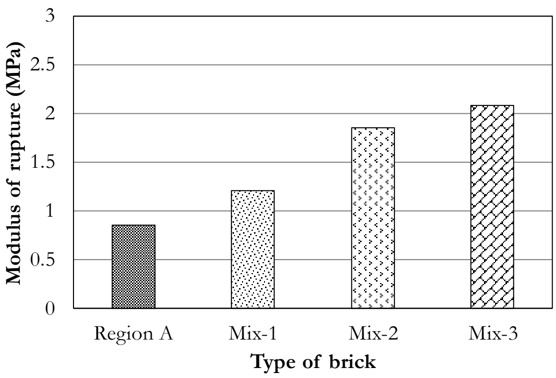

Fig. 7. Comparison of average MR values.

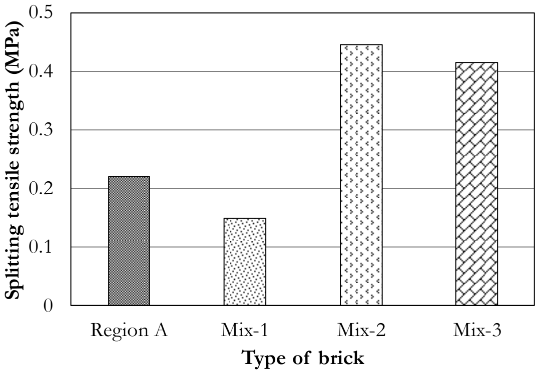

Fig. 8. Comparison of average STS values.

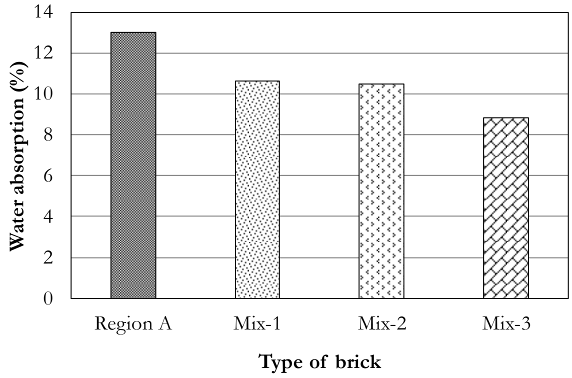

Fig. 9. Comparison of water absorption capacity.

6.1. Compressive Strength

Axial compressive load under static loading was applied to determine the compressive strength of the CCI hollow bricks (Fig. 2). The compressive strength values obtained from the first part of experimental study are summarized in Table 4. As it can be seen (Table 4) there is large variation in compressive strength values of CCI bricks collected from different regions of Thailand. On average, the lowest compressive strength (i.e., 4.22 MPa) is recorded for the CCI bricks collected from the region A. Also, it is evident from the results that CCI bricks from region B showed the highest compressive strength with an average value of 16.46 MPa. While, CCI bricks from region C shows moderate value of compressive strength of 9.16 MPa. The lowest compressive strength of CCI bricks collected from region A can be associated with the least amount of cement in the mix design of region A as compared with regions B and C as shown in Table 1. According to the Thai community product standards [24], the recommended lowest compressive strength of masonry bricks base on net area is 14.0 MPa and base on gross area is 7.0 MPa. Therefore, the CCI bricks collected from region A can be considered as un-acceptable for masonry structures in Thailand. In the second part of this experimental study, use of sand, cement and fly ash was adopted to alter and or to enhance the compressive strength of the CCI bricks of region A. Three new mix designs were proposed and used to manufacture CCI bricks at region A. The experimental results (part-2) are summarized in Table 5. A comparison between newly manufactured CCI bricks and CCI bricks of region A is also summarized in Table 6. As it can be seen (Table 6 and Fig. 6), the highest average compressive strength (i.e., 13.20 MPa) was observed for CCI bricks manufactured using Mix–2 which is quite closer the lowest compressive strength of masonry bricks in Thailand. The least value of compressive strength (i.e., 5.87 MPa) was shown by Mix-1. Mix–3 showed moderate results of compressive strength with an average value (i.e., 8.37 MPa). By comparing experimental results of newly manufactured CCI bricks with CCI bricks of region A, it can be seen (Table 6), that compressive strength of newly manufactured CCI bricks is significantly enhanced. The newly manufactured CCI bricks of Mix–1, Mix–2 and Mix–3 were resulted into 39.09%, 213.0% and 98.30% higher average compressive strength values, as compared with CCI bricks of region A, respectively (Table 6). It is evident from the experimental results that use of cement and fly ash is found very effective to alter the performance of CCI hollow bricks and average compressive strength values are found higher than the lowest values recommended by Thai community product standards. However, the use of sand is not found significantly effective to alter the compressive strength of CCI bricks. Further, this is well known fact that the compressive strength of compressed clay bricks is much lower than the fired clay bricks. A previous study on fired bricks with replacing clay by fly ash in high volume ratio reported compressive strength of 14.70 MPa for fired bricks which is very close to the compressive strength CCI bricks manufactured using Mix–2. This is an indication that the mix design of the CCI bricks can be further modified to produce bricks of sufficient compressive strength. Further, CCI bricks can be used as alternative to the fired clay bricks to reduce environmental pollution and to enhance sustainability.

6.2. Modulus of Rupture

Three-point bending loading setup was used to determine modulus of rupture of CCI bricks (Fig. 3). The test results of modulus of rupture of CCI hollow bricks obtained from first part of experimental study are summarized in Table 4. As it can be seen, there is large variation in modulus of rupture of CCI bricks collected from different regions of Thailand. The highest average value of modulus of rupture (i.e., 1.94 MPa) was observed for CCI bricks collected from region C. While, CCI bricks collected from region A showed the least value of modulus of rupture with an average value of 0.85 MPa and CCI bricks from region B shows moderate value of modulus of rupture i.e., 1.80 MPa. Similar to the compressive strength, the modulus of rupture of CCI bricks collected from region A was found lowest as compared with CCI brick of regions B and C. In the second part of this experimental study, the use of sand, cement and fly ash was adopted to alter or enhance the modulus of rupture of CCI bricks of region A. Three new mix designs were proposed and used to manufacture new CCI bricks at region A. The experimental results (part-2) are summarized in Table 5. A comparison between newly manufactured CCI bricks and CCI bricks of region A is also summarized in Table 7. Once again, there is found, large variation in the results as shown in Fig. 7. The highest average modulus of rupture was recorded for CCI bricks of Mix-3, lowest average modulus of rupture was recorded for CCI bricks of Mix-1, and moderate average modulus of rupture was recorded for CCI bricks of Mix-2. Overall, the modulus of rupture of newly manufactured CCI bricks is found higher as compared with CCI bricks of region A (Table 7). The modulus of rupture of newly manufactured CCI bricks i.e., Mix-1, Mix-2, and Mix-3 were found to be 42.35%, 117.64% and 144.70% higher than CCI bricks of region A, respectively (Table 7). This higher value of modulus of rupture of Mix-3 as compared with Mix-2 can be associated with the use of fly ash.

6.3. Splitting Tensile Strength (STS)

Standard sampling and testing procedure for masonry units was used to investigate the splitting tensile strength of CCI hollow brick samples. The experimental results of splitting tensile strength obtained from the first part are summarized in Table 4. As compared with compressive strength and modulus of rupture, the experimental results of splitting tensile strength are less scattered (Table 4). Further, by comparing average splitting tensile strength values among each region, it can be seen that trend of experimental results is almost similar to the compressive strength results i.e., the lowest average STS is observed for CCI bricks of region A, moderate average values of STS are recorded for CCI bricks of region C and highest average STS is found for region B. The lowest compressive strength of CCI bricks collected from region A can be associated with the least amount of cement in the mix design of region A as compared with regions B and C as shown in Table 1. In the second part of this experimental study, use of sand, cement and fly ash was adopted to alter or enhance the splitting tensile strength of the CCI bricks of region A. Three new mix designs were proposed and used to manufacture new CCI bricks at region A. The experimental test results (part-2) are summarized in Table 5. A comparison between newly manufactured CCI bricks and CCI bricks of region A is also summarized in Table 8 and Fig. 8. As it can be seen (Table 8), the highest average splitting tensile strength (i.e., 0.45 MPa) was observed for CCI bricks manufactured using Mix–2. The least average value of splitting tensile strength (i.e., 0.15 MPa) was shown by Mix-1. Mix–3 showed moderate results of splitting tensile strength with an average value of 0.41 MPa. By comparing experimental results of newly manufactured CCI bricks with CCI bricks of region A, it can be seen (Table 8), that use of cement and fly ash is resulted into higher average splitting tensile strength of newly manufactured CCI bricks as compared with CCI bricks of region A. However, the use of sand is sand is resulted into lower average splitting tensile strength of newly manufactured CCI bricks as compared with CCI bricks of region A. Based on experimental results, it can be concluded that the use of cement and fly ash is very effective to alter the splitting tensile strength of CCI bricks and the use of sand is not effective to alter the splitting tensile strength of CCI bricks. Further detailed studies should carry out to understand this phenomenon.

6.4. Water Absorption Capacity

Immersion method was used to find out the water absorption capacity of CCI bricks. Oven dried CCI hollow bricks were immersed in water for a period of one day (i.e., 24 hours) to find the saturated weight. The experimental results (part-1) are summarized in Table 4. In the first part of the study, the highest value of water absorption (i.e., 13.0% and 226.0 kg/m^3) was observed for CCI hollow bricks of region A. The soils which have smaller particle size (i.e., silt and clay) absorb more water as compared to sand with larger particle size and small surface area [14]. Therefore, the highest water absorption of brick samples collected from region A can be associated with large amount of clay contents in the mix design of region A as compared with region B and C. The least water absorption (i.e., 10.00% and 167.0 kg/m^3) was observed for CCI hollow bricks collected from region B. The CCI hollow bricks collected from region C showed a moderate value of water absorption (i.e., 10.10% and 166.10 kg/m^3). According to the Thai community product standard [24], the recommended highest values of water absorption of masonry bricks is 288 kg/m^3. Therefore, the CCI hollow bricks collected from region A can be considered as vulnerable against heavy rainfall. In the second part of this experimental study, use of sand, cement and fly ash was adopted to alter or reduce the water absorption of the CCI hollow bricks of region A. Three new mix designs were proposed and used to manufacture new CCI bricks at region A. The experimental results (part-2) are summarized in Table 5. A comparison between newly manufactured CCI hollow bricks and CCI hollow bricks of region A is also summarized in Table 9 and shown in Fig. 9. All newly manufactured CCI bricks of proposed mixes showed a significant reduction in water absorption capacity as compared with traditional CCI bricks from region A. The water absorption capacity of CCI bricks of Mix-1, Mix-2 and Mix-3 is found 18.46%, 13.07% and 32.31% lower, respectively, as compared with CCI hollow bricks of region A. In this case use of fly ash is resulted into highest reduction in the water absorption capacity of CCI hollow bricks.

6.5. Density of CCI Hollow Bricks

Density of CCI hollow bricks is given in Tables 2 and 3 for different regions and newly mixed design proportions. It can be seen that the density of newly prepared CCI hollow bricks is significantly higher than the traditional CCI bricks of different regions. According to the Thai community product standards [24], the recommended density of masonry bricks is 1349 kg/m^3. The density of both traditional and newly prepared CCI hollow bricks is observed higher than the Thai community product standards

6.6. Heat Transfer Through CCI Hollow Bricks

Heat transfer through CCI hollow bricks was determined by inducing a high temperature of 360 ^oC by using an electrical hot plate (Fig. 5). Thermocouple wires were used to measure temperature on both sides of the CCI hollow bricks (side A and side B). The experimental results in terms of average initial temperate on both sides, the average highest temperature on both sides, average time to teach at high temperature and average heat transfer through CCI hollow bricks are summarized in Tables 10 and 11. A comparison of average heat transfer among newly manufactured CCI bricks and CCI bricks of region A is given in Table 12 and graphically shown in Fig. 10. In first part of the study, highest average heat transfer (i.e., 33.67^oC) through the CCI hollow bricks of region B was observed (Table 10). This is primarily because of these reasons; 1) well compaction of the CCI hollow bricks of region B (this assumption can be verified by highest value of average compressive strength of CCI hollow bricks of region B), 2) the small value of the width of CCI hollow bricks of region B (Table 2) as compared with CCI hollow bricks of regions A and C. The CCI hollow bricks collected from region C showed a moderate average heat transfer i.e., (i.e., 23.50 ^oC) and the CCI hollow bricks samples collected from region A showed a lowest heat transfer of 13.32 ^oC as compared with other regions. The lowest average heat transfers through CCI hollow bricks of region A can be associated with the presence of more air voids in the CCI hollow bricks of region A as compared with regions B and C. Lowest compressive strength is also an indication of large air voids in the CCI bricks of region A (Table 4). In the second part of this experimental study, use of sand, cement and fly ash was adopted to alter the mechanical properties of CCI hollow bricks. Here, the highest average heat transfer (i.e., 19.60 ^oC) was observed in the CCI hollow bricks of Mix–2 (Table 11). The highest average heat transfer through the CCI hollow bricks of Mix-2 could be associated with the large amount of presence of cement contents in the Mix-2 as compared with the Mix1 and Mix-3 (Table 3). The CCI hollow bricks manufactured using fly ash (Mix-3) showed a lowest average heat transfer of 8.63 ^oC. The use of sand is resulted into a moderate average heat transfer (13.74 ^oC) through CCI hollow bricks as compared with cement and fly ash. By comparing experimental results of average heat transfer through the newly manufactured CCI hollow bricks with region A (Table 12), it can be seen that the use of fly ash is resulted to reduce the average heat transfer through by 35.0% and use of both sand and cement is not found effective to reduce the heat transfer through the CCI hollow bricks.

Heat flux can be defined as the amount/quantity of heat which is transferred per unit area in unit time from or to a brick surface. Heat flux could be calculated by assuming one-dimensional conduction in the steady state condition and using following equation;

$$Q_x = \frac{kd_t}{d_x} \tag{5}$$

where;
Q_x = Heat flux (W/m^2)
d_t = T_1-T_2, T_1 is temperature at side A (^oC), T_2 is temperature at side B (^oC)
d_x = Length of heat transfer region (m)
k = Thermal conductivity (W/m.K), thermal conductivity for bricks was taken equal to 0.60 as described in details in previous work [35].

The calculated average values of heat flux are summarized in Table 13. In case of traditional bricks i.e., region A to region C bricks, the highest amount of heat flux is recorded for CCI bricks of region A. Whereas, in case of newly manufactured CCI hollow bricks, the highest amount of heat flux is observed for CCI hollow bricks of Mix-3.

Table 10. Heat transfer test results of CCI hollow bricks (Part-1)

Mix components	Region A	Region B	Region C
Average initial temperature at side A (^oC)	31.00	30.50	31.00
Average initial temperature at side B (^oC)	31.20	31.20	31.20
Average highest temperature at side A (^oC)	360.0	360.0	360.0
Average highest temperature at side B (^oC)	44.52	64.87	54.70
Average time to reach at highest temperature (min)	55	40	35
Average heat transfer through bricks (^oC)	13.32	33.67	23.50

Table 11. Heat transfer test results of CCI hollow bricks (Part-2)

Mix components	Mix-1	Mix-2	Mix-3
Average initial temperature at side A (°C)	35.50	31.80	40.70
Average initial temperature at side B (°C)	36.30	34.20	33.10
Average highest temperature at side A (°C)	360.0	360.0	360.0
Average highest temperature at side B (°C)	50.04	51.10	41.73
Average time to reach at highest temperature (min)	94.25	65.00	65.50
Average heat transfer through bricks (°C)	13.74	16.90	8.63

Table 12. Comparison of average heat transfer through newly manufactured CCI hollow bricks.

Bricks	Heat transfer through CCI hollow bricks (°C)	Percentage reduction (-) or increase (+) in heat transfer
Region A	13.32	-
Mix-1	13.74	+3.000
Mix-2	16.90	+27.00
Mix-3	8.630	-35.00

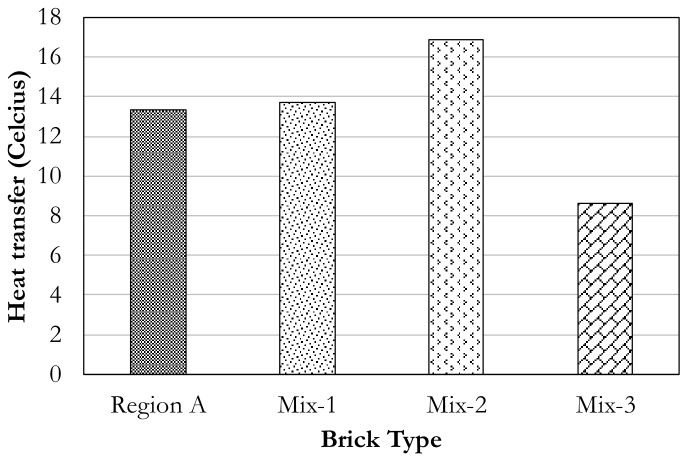

Fig. 10. Comparison of average heat transfer through CCI hollow bricks.

Table 13. Heat flux of CCI hollow bricks.

Bricks	Heat flux of CCI bricks (W/m²)	Percentage reduction (-) or increase (+) in heat transfer as compared with region A
Region A	1858	-
Region B	1733	-6.7
Region C	1838	-1.1
Mix-1	1817	-2.2
Mix-2	1857	-0.1
Mix-3	1867	0.5

7. Failure Modes

Almost all of the CCI hollow brick samples investigated in this study showed a similar pattern of failure in each type of testing such as compressive strength, flexural strength and splitting tensile strength as shown in Figs. 11 and 12. In the compression test, CCI bricks failed mainly in crushing manner as shown in Figs. 11(a) and 12(a). While in case of modulus of rupture test, an inclined crack in the middle region of CCI hollow bricks was observed (Figs. 11(b) and 12(b)). This can be associated with the fact that in three-point bending loading scheme, bricks tend to bend after the application of load. Prior to the final inclined rupture of the CCI hollow bricks, minor flexural cracks at the tension face of CCI hollow bricks were also observed. In splitting tensile strength tests, a straight-line crack was observed in the middle region of CCI hollow bricks as shown in Figs. 11(c) and 12(c).

(a) Compression test (Part-1)

(b)

(b) Flexure test (Part-1)

(c) Splitting tensile test (Part-1)

Fig. 11. Typical failure modes of CCI hollow bricks (Part-1).

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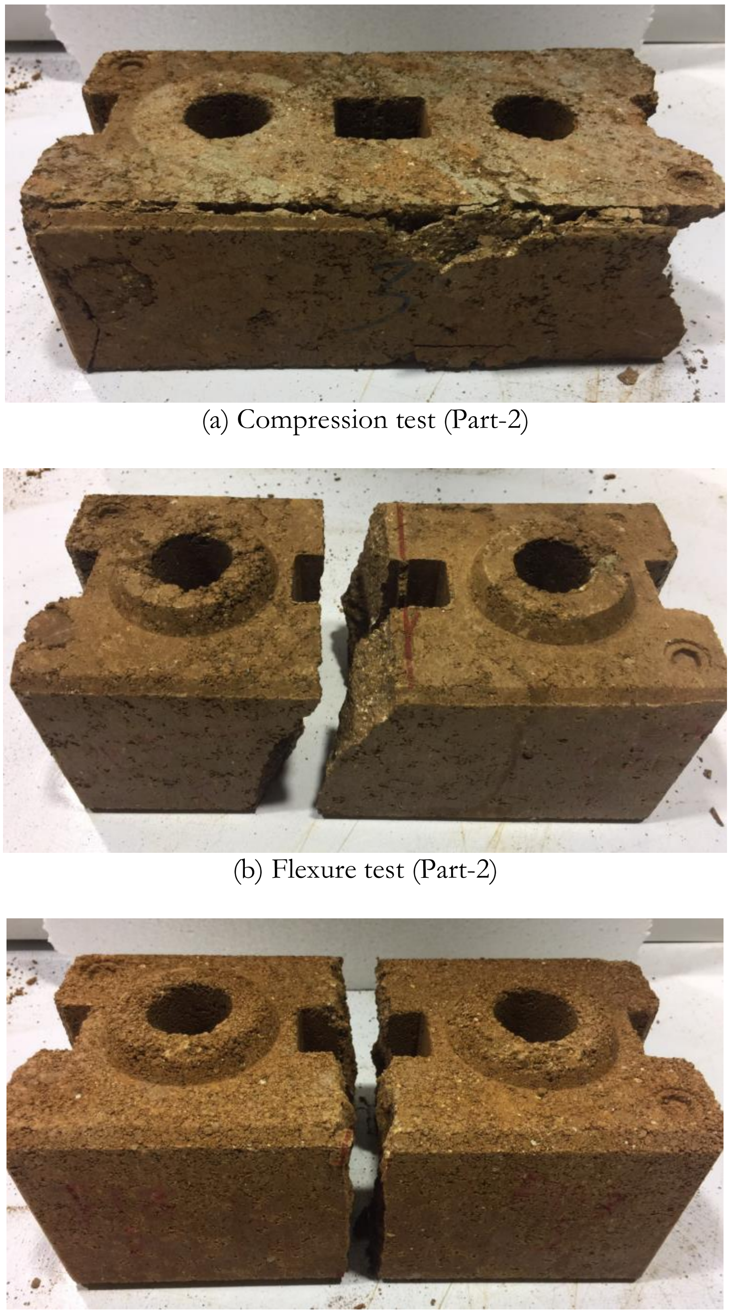

(a) Compression test (Part-2)

(b) Flexure test (Part-2)

(c) splitting tensile test (Part-2)

Fig. 12. Typical failure modes of newly manufactured CCI hollow bricks (Part-2).

8. Cost-benefit Analysis

The production cost of the CCI bricks is mainly dependent upon availability of materials, workmanship and weather conditions. The exact cost details of CCI hollow bricks collected from different regions of Thailand and newly manufactured CCI hollow bricks are summarized in Table 14. The production cost of the CCI bricks in Thailand is in the range of 10-14 Thai Baht (0.30-0.45 US Dollar). The production cost of the CCI bricks collected from region A and B is similar and lower than region C. Since the cement is most expensive material in the production of CCI bricks, therefore lower price of the CCI hollow bricks of region A is associated with the least amount of cement in the mix design of region A as compared with region B and C (Table 1). Although the amount of cement in the mix design of region B is highest as compared with region A and C, but the lower price of the CCI bricks collected from region B is mainly due to its small size as shown in Table 2. As it can be seen (Table 14), the cost of CCI hollow bricks collected from region C is highest; this is because the manufacturer was getting the clay material from a bit far distance from the manufacturing plant. A cost-benefit analysis of the CCI hollow bricks collected from different regions of Thailand is graphically shown in Fig. 13.

Benefit only in terms of mechanical properties such as compressive strength, splitting tensile strength and water absorption were considered in the cost benefit analysis. It can be seen that the manufacturing cost of CCI bricks collected from region A and region B is same however the region B has better mechanical properties as compared with region A. On the other hand, the CCI bricks with the highest cost (i.e., region C) is showing moderate values of compressive strength, splitting tensile strength and water apportion capacity as compared with region A and B. Based on cost-benefit analysis it can be said that CCI bricks collected from region B are most suitable as compared with region A and C. In the second part of this experimental study, the use of sand, cement and fly ash were adopted to alter the mechanical properties of CCI hollow bricks. The use of additional materials in the newly proposed mix designs (Mix-1, Mix-2, and Mix-3) led to higher manufacturing costs of CCI hollow bricks as compared with CCI bricks of region A as shown in Table 14. In this case, lowest manufacturing cost is observed for the CCI hollow bricks of Mix-1 due to sand which is low price and easily available material. Further, it can be seen that the cost of the Mix–3 is more as compared of other new proposed mixes. The reason of the higher cost is fly ash. Although, fly ash is a waste product, but its availability and higher transportation costs yield in more expensive bricks. The use of cement resulted in moderate production cost of CCI hollow bricks as compared with Mix-1 and Mix-3. A cost-benefit analysis for newly manufactured CCI hollow bricks is presented in Fig. 14. It can be seen that the manufacturing cost of CCI bricks of Mix–1 and Mix–2 is almost similar, however the mechanical properties of CCI bricks of Mix-2 are better than the mechanical properties of CCI bricks of Mix-1. Further, it can be noted (Table 14 and Fig. 14) that CCI bricks manufactured using Mix-3 resulted in higher manufacturing cost and their mechanical properties such as compressive strength, splitting tensile strength and water absorption capacity are found moderate as compared with CCI bricks of Mix-1 and Mix-2. Since the compressive strength is the main mechanical property which defines the quality of bricks according to Thai community product standards [24]. Therefore, among newly proposed mix designs, Mix-2 can be considered as the most suitable as compared with other mix designs (Mix-1 and Mix-3).

Table 14. Production cost details of CCI hollow bricks.

Bricks	Production cost of CCI bricks in Thai Baht (US Dollar)	Percent increase in production cost of newly manufactured CCI hollow bricks
Region A	10.0 (0.30)	-
Region B	10.0 (0.30)	-
Region C	12.0 (0.36)	-
Mix – 1	11.0 (0.33)	10.0
Mix – 2	12.0 (0.36)	20.0
Mix – 3	14.0 (0.42)	40.0

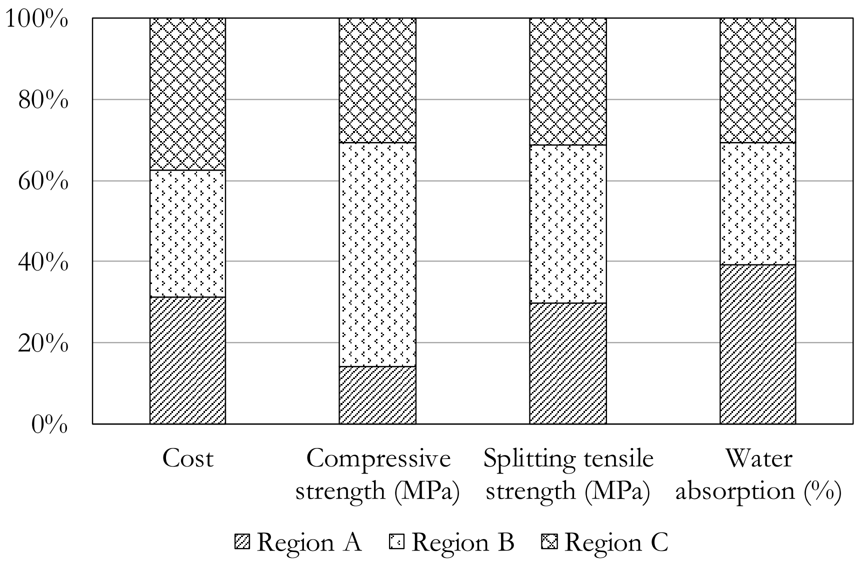

Fig. 13. Cost-benefit analysis of CCI hollow bricks (Part-1).

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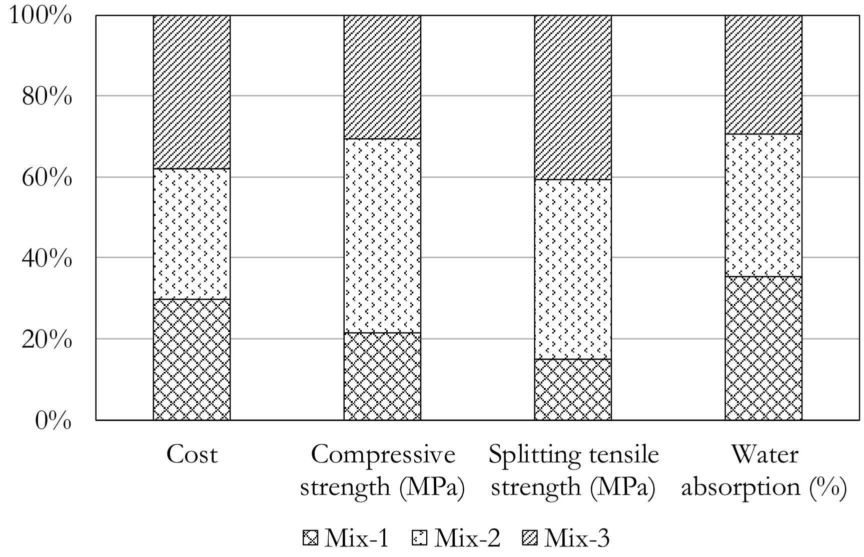

Fig. 14. Cost-benefit analysis of CCI hollow bricks (Part-2).

9. Conclusion

In this paper, an investigative study on mechanical properties of CCI hollow bricks such as compressive strength, modulus of rupture, splitting tensile strength, water absorption and heat transfer is conducted. The experimental program is divided into two parts. In the 1st part, bricks from three different regions (A, B and, C having different soil stratum) of Thailand were collected and their mechanical properties were investigated. In the 2nd part, change in mix design ratios followed by sand, cement and fly ash for region A have been exercised to observe their effects on mechanical properties of bricks from said region. Based on the experimental results, the following observations are concluded;

1. Uses of locally available materials and different mix designs have significant effect on the mechanical pro perties of CCI hollow bricks. A large variation in the investigated mechanical properties was observed fo r CCI hollow bricks collected from different regions.
2. Overall, CCI bricks from region B have superior me chanical properties as compared with traditional CC I bricks from region A and C. Only modulus of rupt ure of region B is observed slightly lower than regio n C.
3. CCI bricks from region A do not satisfy compressiv e strength and water absorption values recommende d by Thai community product standards.
4. Newly proposed mixes (use of sand, cement and fly ash) to manufacture CCI hollow bricks are found qu ite effective to improve and or alter the mechanical properties of CCI hollow bricks.
5. The use of cement in the manufacturing of CCI bric ks is found to be most effective and suitable as com pared with sand and fly ash.

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