Optimum intensity of compaction in drained state consolidation of clay beams

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ABSTRACT

Unavailability of aggregates, in plains of Pakistan, has compelled to find alternative economical materials of building construction. Efforts are being made to introduce Reinforced Baked Clay (RBC) panels of beams as a substitute for Reinforced Cement Concrete (RCC) to build low cost houses. However, shrinkage and reduced compressive strength of baked clay beams is an obstacle. This paper presents optimum compactive pressure to be applied to clay beams during casting to reduce shrinkage and to achieve maximum possible compressive strength. For this purpose, clay beams were cast and compacted at 0 to 7 MPa in drained state. Shrinkage of beams and compressive strength of cubes was determined. The results show that (*i*) shrinkage of clay beams reduced from 8 to 1.25 % at compactive pressure of 2 MPa and 6 MPa, respectively, and (*ii*) the compressive strength of both the unbaked and baked clay increased by increasing compactive pressure on clay beams during casting. However, there was no significant difference in compressive strength of clay beams when compressed at pressure from 6 to 7 MPa. The compressive strength of baked clay obtained at optimum compactive pressure of 6 MPa was 35 MPa, which is about 1.7 times higher than that of M20 grade concrete.

Keywords: Compressive strength; Baked Clay; Compactive pressure; Shrinkage; Consolidation; Low cost housing.

INTRODUCTION

In plains of Pakistan, there is unavailability of aggregates, which are transported from remote hilly areas. As a result, the cost of houses has been increased. Therefore, it is unaffordable for low income people to have houses constructed of Reinforced Cement Concrete (RCC). Thus, to provide shelter for a common man at an affordable cost, it is necessary to use indigenous and low-cost materials of construction.

Clay and sand are the most abundant soils in the plains of the country. The suggested plan is to manufacture precast panels of beams, columns, and slabs, which can be baked, reinforced, and even prestressed. The coefficient of thermal expansion of clay is about $6 \times 10^{-6}/^{0}C$, which is comparable to that of steel (Douglas and Ransom, 2007). This implies that the reinforcement is compatible with baked clay.

These panels of Reinforced Baked Clay (RBC) could be used as a substitute for RCC to construct low cost houses. In this regard, it is desirable that the compressive strength of baked clay should be comparable to that of concrete of grade M20 having cube crushing strength of 20 MPa (BIS 10262,2009). Compressive strength of baked clay is associated with its density (Lakho and Zardari 2016a-d), which can be improved by application of compaction at the time of casting (Lakho and Zardari 2016e). Maximum compressive strength can be attained by compacting the clay specimen at Optimum Moisture Content (OMC).

The pioneering work on RBC was started by manufacturing panels of beams (Ansari, 2008; Ansari *et al*., 2013a-b). The beams were cast from moist mixture of clay and pit sand having water content of 20 %, which was needed for ease of moulding. The quantity of water mixed with the soil was more than its OMC that was 13%. The water content beyond OMC, required for workability, may cause high shrinkage, cracks, warping, and low compressive strength

of clay beams during drying process. Hence, it is necessary to drain some mixed water out of the clay beams so as to reach the OMC. The amount of the water that is required to be expelled from the moist clay beams during casting process depends upon both the intensity of compactive pressure and the time of loading. Therefore, it is essential to find an optimum intensity of compactive pressure necessary to drive off excess water content above OMC in order to reduce shrinkage and increase compressive strength of clay beams after drying and baking.

LITERATURE REVIEW

Clay is a low cost, environmental friendly and recyclable material of construction. Sun dried and baked clay bricks have been used as a walling material for thousands of years (Nidzam *et al.,* 2016; Lekshmi *et al.,* 2017 & Smeu *et al.,* 2014). Before invention of cement, clay and lime mortar were also used in masonry.

Clay in plastic state can be moulded into a desired shape by pressing it. Generally, 14-35% water is mixed with clay to develop sufficient plasticity (Andrade, 2011). Drying shrinkage of clay may cause cracking and warping. Moist clay may shrink up to 15% (Umana *et al.*, 2016; Lakho *et al.,* 2015a; Phonphuak *et al.,* 2016; Walker, 1995; Abdi *et al*., 2008 & Fatahi *et al.*, 2013). Drying shrinkage depends on both type of clay and water content. Drying shrinkage is more in plastic clays and less in sandy clays. Excessive shrinkage reduces compressive strength of clay. To reduce shrinkage and increase compressive strength of clay specimens, it is desirable to add non-clay materials like pit-sand as high as 40% (Dixon *et al.,* 1985). The use of non-plastic soils in clay produces large voids, which facilitate quick evaporation of water through the surface (Boivin *et al*., 2004; Omidi *et al.,* 1996 & Fatahi *et al*., 2013).

Chemically combined water in clay starts to drive off when fired above 350^0C (Rhodes, 2015). Due to dehydration of water at 500^0C, clay loses its plasticity and becomes friable (Rhodes, 2015). At about 573^0C, quartz crystals present in clay may cause slight increase in volume (Rhodes, 2015). Generally, clays vitrify at 1000^0C and become sufficiently hard (Rhodes, 2015).

MATERIALS AND METHODS

Mixing of clay and sand

Both clay and pit sand were obtained locally near Hala, District Matiari, Sindh, Pakistan. Clay as obtained from site was in lumped form (Fig. 1); therefore, it was pulverized using grinding machine (Fig. 2). The ratio of clay to pit sand in the mixture was seventy to thirty by weight. Fine powder of clay and pit sand are shown in Figures 3 and 4, respectively. The beams manufactured using above mentioned proportions experience less shrinkage and more compressive strength (Ansari, 2008). Twenty percentage potable water was mixed to the clay-pit sand mixture. The mixing process was carried out in pan mixer for 15 minutes. The moist mixture was stored for 24 hours in an airtight plastic sheet to develop sufficient workability. The natural moisture content and plasticity index of clay was 12% and 22%, respectively. The pit sand is non-plastic having natural moisture content and bulk unit weight of 8% and 20 kN/m³, respectively.

Casting of clay beams

The moist mixture was laid on steel mould in five layers of equal depths (Fig. 5). Each layer was tamped down with a wooden pad. A slight spray of water was applied between the layers. The beams were compacted and consolidated using a Mechanized System (Fig. 6) whose detailed working procedure is described elsewhere by the authors (Lakho *et al*., 2015b). The beams were compressed using wooden plunger, which was connected to hydraulic jacks (Fig. 6). The length, width, and depth of the mould were, respectively, 1980 mm, 150 mm, and 400 mm. The mould was filled with moist clay up to 400 mm. The steel mould was railed into the compacting chamber of the Mechanized System to compact the beams under drained condition. The effect of intensity of compaction on shrinkage and compressive strength of clay beams during drained state was investigated. For this purpose, the compactive pressure applied to the beams was varied from 0 to 7 MPa.

Fig. 1. Clay after being quarried from site.

Fig. 2. Grinding machine being utilized to pulverize clay.

Fig. 3. Clay in fine powder form after grinding process.
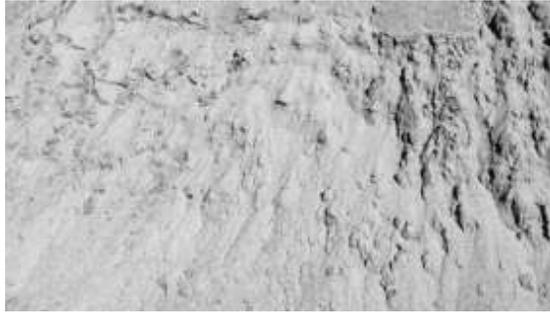
Fig. 4. Pit sand used to prepare mixture for casting beams.
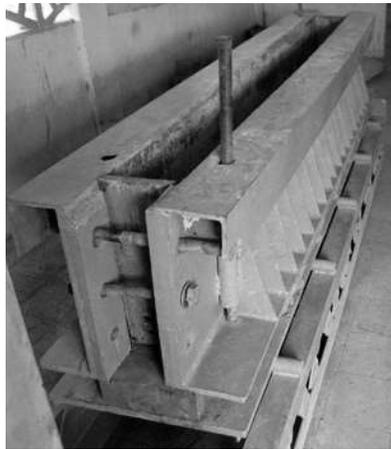

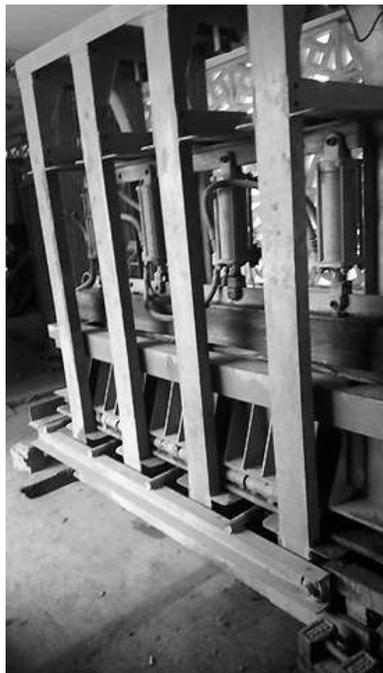**Fig. 5.** Steel mould for casting clay beams.

Fig. 6. Mechanized System for casting and compacting of clay beams.

Drained state consolidation of clay beams

Initially, to achieve maximum density, it was tried to cast clay beams using moist mixture of clay and pit sand mixed with optimum moisture content of 13%. Due to less degree of plasticity, insufficient bond was developed between clay particles, which resulted in cracks in beams immediately after demoulding. Therefore, to attain adequate plasticity of the mix, water was increased to 20%. Although workability of clay beams was increased, yet shrinkage increased and density decreased. To resolve this problem, a technique of drained state consolidation was utilized.

To increase the density of the clay beams, the excess water must be drained off. For this purpose, a porous fabric sheet was wrapped around the clay beams. The beams were pressed with wooden plunger. Compactive pressure on the beams was gradually increased from 0 to 7 MPa (each increment of 1 MPa) and the same was maintained for 24 hours. As a result, the water drained off from the beams. After casting, the beams were de-moulded (Fig. 7) and dried in shade (Fig. 8). The beams were covered with plastic sheet to control rate of evaporation and to restrict cracks during drying. On average, the clay beams took 150 days for shade drying at a temperature ranging from 20^0C to 40^0C. It is remarked that the shade drying process of clay beams is effective but time consuming.

With the help of a platform lift (Fig. 9), the shade dried beams were shifted from laboratory to kiln (Fig. 10). The beams were fired in the kiln at 1000^0C. The firing temperature of the beams is in accordance with the ASTM C62 that is used for baking of clay bricks. A view of a fired clay beam is shown in Fig. 11.

Fig. 7. Clay beams are demoulded from steel mould.

Fig 8. Clay beams dried in shade.

Fig. 9. Dried clay beams are being transported to kiln using platform lift.

Fig. 10. Kiln located in laboratory premises for firing of clay beams.

Fig 11. Clay beam after firing in kiln.

Testing program

Cubes of 150 mm size were sawed both from unfired and fired clay beams. The cubes were sawed using cutter machine as shown in Fig. 12. The cubes were tested for compressive strength using Universal Testing Machine (Fig. 13) in accordance with British Standards (BS EN 12390-3:2002).

Fig. 12. A view of cutter machine to saw cubes from baked clay beams.

Fig. 13. Baked clay cube tested for compressive strength in Universal Testing Machine.

RESULTS

Expulsion of water from clay beams using compactive pressure during casting

Moist mixture of clay and pit sand, filled in the mould, was subjected to compression using wooden plunger of the Mechanized System (cf. Fig. 6). The beams were compacted at pressure of 0, 1, 2, 3, 4, 5, 6, and 7 MPa, respectively. Three beams were cast at each increment of compactive pressure that was maintained for 24 hours.

As mentioned earlier, the clay pit sand mixture consisted of 20% water. As the compactive pressure was increased, water was gradually forced to drain off from the beams that were enveloped in porous propylene fabric sheet. Fig. 14 presents expulsion of water from beams that were subjected to compactive pressure varying from 0 to 7 MPa. It can be observed that water started to drain away from the beams at compactive pressure of 2 MPa and this process continued till the pressure reached 7 MPa.

When compactive pressure was increased from 0 to 6 MPa, 33% of added water was expelled from the beams, whereas only 2.5% of added water was expelled from the beams subjected to compactive pressure from 6 to 7 MPa. This shows that the rate of expulsion of added water from the beams was slow when the intensity of compaction increased from 6 to 7 MPa. This implies that if the compactive pressure is increased beyond 6 MPa, there could be very less increase in dry density and compressive strength. This is because both the dry density and compressive strength are associated with decrease in water content of clay beams. Hence, it is uneconomical to compact clay beams above 6 MPa.
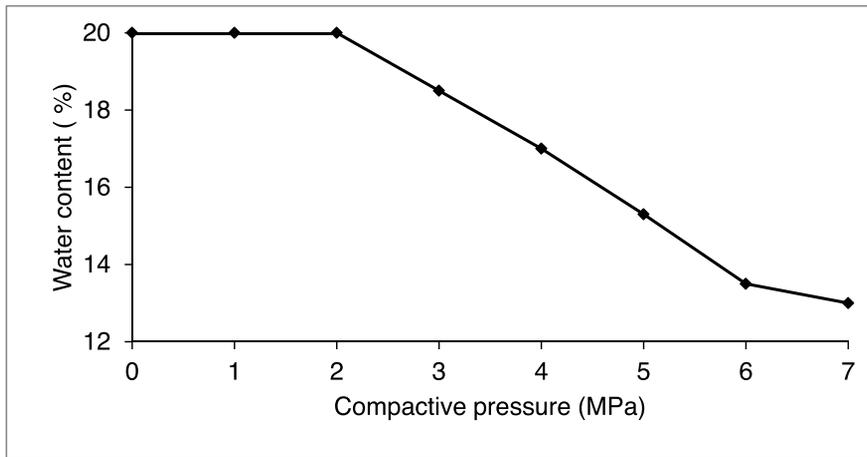
Fig 14. Amount of water expelled from clay beams when subjected to varying intensity of compactive pressure that was maintained for 24 hours.

Shrinkage of clay beams

Fig 15 shows effect of compactive pressure on shrinkage of clay beams. As expected, drying shrinkage of about 8% was observed in clay beams, which were subjected to compactive pressure varying from 0 to 2 MPa. This is because the compactive pressure of 0 to 2 MPa was not high enough to cause water to expel from the clay beams. The beams, which were compacted below 2 MPa, showed non-uniform shrinkage.

When the compactive pressure on clay beams was increased from 2 to 6 MPa, shrinkage was decreased from 8 to 1.25%. At this stage, the shrinkage of clay beams was uniformly distributed, whereas there was no significant reduction in shrinkage when the compactive pressure was increased from 6 to 7 MPa.
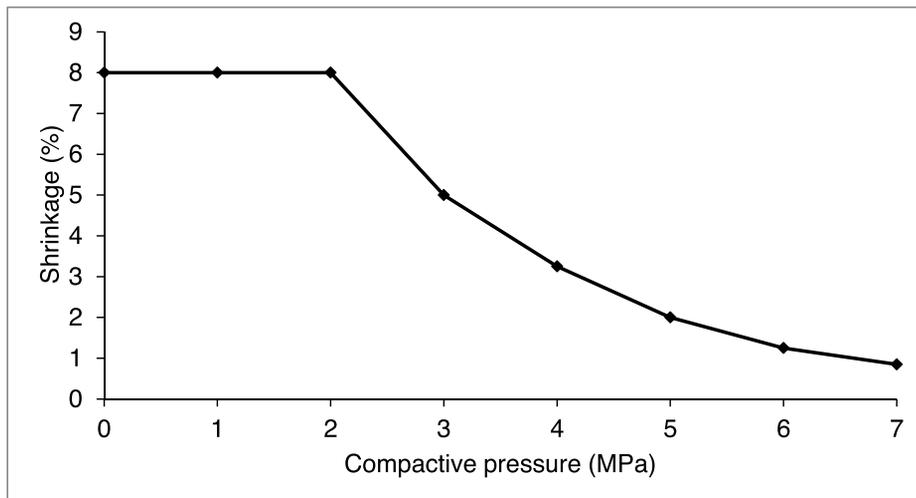

Fig 15. Reduction of shrinkage due to application of compactive pressure maintained for 24 hours.

Compressive strength of unfired clay

After the beams were dried in shade, cubes of 150 mm were cut. The compressive strength of the cubes cut from beams that were subjected to compactive pressure of 0 to 7 MPa (each increment of 1 MPa) was determined. The compressive strength of unfired clay cubes versus compactive pressure on clay beams during casting is presented in

Fig. 16. The coefficient of correlation for compactive pressure applied during casting and the resulting compressive strength of the unbaked cubes was calculated to be 0.93. It can be observed that the cube crushing strength of unfired clay is unaltered; even the compactive pressure was increased from 0 to 2 MPa. The possible reason for the constant compressive strength of unfired clay is that the added water did not expel from clay beams when they were pressed up to 2 MPa. The cube crushing strength of clay increased by increasing compactive pressure from 2 to 7 MPa. On the other hand, the compressive strengths of clay cubes that were sawed from beams compacted at a pressure of 6 and 7 MPa were almost the same. This is because less quantity of water was expelled from clay beams when the compactive pressure was increased from 6 to 7 MPa.
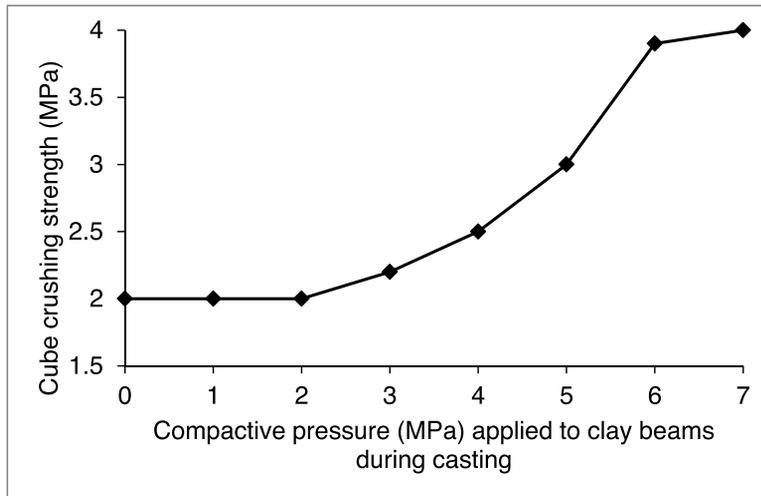

Fig. 16. Compressive strength of unbaked clay cubes that were obtained from clay beams pressed at various intensities of compactive pressure during casting.

Compressive strength of baked clay

Fig. 17 illustrates compressive strength of baked clay cubes that were sawed from beams manufactured at compactive pressure of 0 to 7 MPa. The correlation coefficient of 0.96 was determined for the effect of compaction during casting on cube crushing strength of baked clay. As expected, the compressive strength of baked clay cubes, fired at 1000^0C, was higher than that of corresponding unfired clay cubes (cf. Fig. 16). This is because clay contains many sand-like particles called silica. When clay is fired at elevated temperature, silica melts. On lowering the temperature, silica causes the clay to become hard like a rock.

The baked clay cubes, cut from beams pressed with compactive pressure of 0 to 2 MPa, showed constant compressive strength of 14 MPa. This is because the compactive pressure of 0 to 2 MPa was not high enough to cause added water to expel from moist beams during casting. Thus, the water content of the beams remained unchanged, which resulted in constant drying shrinkage and compressive strength. As expected, the compactive pressure of 0 to 6 MPa applied to clay beams during casting played a key role in increasing compressive strength of baked clay cubes. The baked clay cubes that were sawed from beams compacted at pressure of 2 MPa and 6 MPa, respectively, showed compressive strength of 14 MPa and 35 MPa. However, the compactive pressure above 6 MPa applied to clay beams during casting has negligible influence on compressive strength of baked clay cubes. This is because the rate of expulsion of water from clay beams was lower when compacted at pressure of 6 to 7 MPa.

It is pertinent to compare the compressive strength of baked clay, presented in this paper, with that of concrete of grade M20 having compressive strength of 20 MPa (BIS, 2009). It can be observed that the compressive strength of baked clay was 1.7 times higher than that of normal concrete. This implies that baked clay could be used as an alternative to normal concrete for construction of low cost houses.
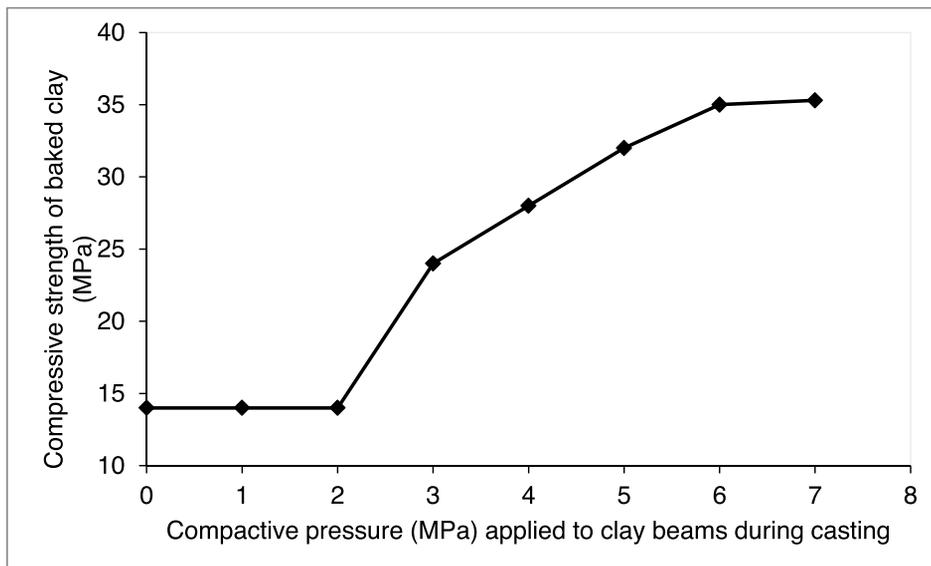
Fig 17. Compressive strength of baked clay cubes sawed from beams subjected to different intensities of compaction during manufacturing.

DISCUSSION

When the compactive pressure was increased to 7 MPa, the outer layer of the beams was harder than the interior ones. The reason is that the surface layers of the beams dried faster than the interior. Thus, a semi solid shell was developed around the moist central part of the beams. Therefore, moisture was entrapped in interior of the beams. Due to more compaction of outer layers, the rate of evaporation of entrapped moisture in interior of the beams was decreased. The outer semi-solid surface of clay beams experienced very small shrinkage as compared to central part. Therefore, further evaporation of the entrapped moisture with time caused small interior cracks in clay beams after drying.

After baking, these internal cracks (about 200 mm long and 5 mm wide) were visible at the outer surface. Since the cracks in a beam may cause reduced compressive strength, which is not desirable, therefore, it is suggested that these types of moist clay beams should be compacted below 7 MPa.

Future studies

As mentioned earlier, the shade drying of clay beams took much time. In this regard, future studies may be conducted to reduce drying time of clay beams using appropriate methods.

CONCLUSIONS

This paper presented results of an experimental study to investigate optimum compressive pressure to reduce shrinkage and achieve more compressive strength of baked clay in comparison to normal concrete having cube crushing strength of 20 MPa. Main conclusions drawn from this study are as follows:

1. It is necessary to remove extra water beyond optimum moisture content to reduce shrinkage and increase compressive strength of clay beams.

2. Removal of excess water was dependent on intensity of compressive pressure applied to clay beams in drained condition.

3. Shrinkage of clay beams was significantly reduced and the compressive strength was improved at optimum compressive pressure of 6 MPa applied during casting.

4. The beams compacted at 6 MPa showed cube crushing strength of 35 MPa, which is about 1.7 times more than that of M20 grade concrete.

5. Interior cracks in clay beams were observed at compressive pressure of 7 MPa due to presence of entrapped moisture.

6. The compaction of clay beams above 6 MPa during casting is uneconomical.

7. Future studies might be carried out to investigate suitable methods to reduce drying time of clay beams.

8. The findings of this study support the idea to utilize RBC as an alternative to RCC for construction of houses.

REFERENCES

Abdi, M.R., Parsapajouh, A. & Arjomand, M.A. 2008. Effects of random fiber inclusion on consolidation, hydraulic conductivity, swelling, shrinkage limit and desiccation cracking of clays. International Journal of Civil Engineering, **6**(4):284-292.

Andrade, F.A., Al-Qureshi, H.A. & Hotza, D. 2011. Measuring the plasticity of clays: a review. Applied Clay Science, **51**(1):1-7.

Ansari, A.A. & Lakho, N.A. 2013a. Determination of structural properties of baked clay as replacement of RCC. International Journal of Emerging Technology and Advanced Engineering, **3**(2):17-25.

Ansari, A.A., Bhatti, N.K. & Bhutto, A. 2013b. Suitability of pre-perforated post-reinforced baked clay beam panels for low cost housing. American Journal of Civil Engineering, **1**(1):6-15.

Ansari, A.A. 2008. Experimental study of the behaviour of pre-perforated post-reinforced baked clay panels of beams, Ph.D. Thesis, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah.

ASTM C62-13a. 2013. Standard specification for building brick (solid masonry units made from clay or shale). ASTM International, West Conshohocken.

BIS 10262. 2009. Indian standard concrete mix proportioning - Guidelines (First revision). Bureau of India Standard, New Delhi, India.

Boivin, P., Garnier, P. & Tessier, D. 2004. Relationship between clay content, clay type, and shrinkage properties of soil samples. Soil Science Society of America Journal, **68**(4):1145-1153.

BS EN 12390-3:2002. Testing hardened concrete - Part 3: Compressive strength of test specimens.

Dixon, D.A., Gray, M.N. & Thomas, A.W. 1985. A study of the compaction properties of potential clay—sand buffer mixtures for use in nuclear fuel waste disposal. Engineering geology, **21**(3-4):247-255.

Douglas, J. & Ransom, B. 2007. Understanding Building Failures. Taylor & Francis.

Fatahi, B., Le, T.M., Fatahi, B. & Khabbaz, H. 2013. Shrinkage properties of soft clay treated with cement and geofibers. Geotechnical and Geological Engineering, **31**(5):1421-1435.

Lakho, N.A. & Zardari, M.A. 2016a. Comparison of Compressive and Tensile Strength of Baked Clay with Those of Normal Concrete. Engineering, **8**:301-307.

Lakho, N.A. & Zardari, M.A. 2016b. Flexural Behaviour of Reinforced Baked Clay Beams. Engineering, **8**, 403-409.

Lakho, N.A. & Zardari, M.A. 2016c. Experimental Study of Flexural Behaviour of Reinforced Baked Clay Beams under Impact Loading. Engineering, **8**:347-352.

Lakho, N.A. & Zardari, M.A. 2016d. Suitability of Large Sized Compacted Baked Clay Blocks as a Walling Material. Engineering, **8**:669-675.

Lakho, N.A. & Zardari, M.A. 2016e. Effect of intensity of compaction on crushing strength of indigenous baked clay. Journal of Engineering Research, **4**(2):17-28.

Lakho, N.A., Zardari, M.A. & Memon, N.A. 2015a. Reduction of Cracking and Shrinkage in Compressed Clay Beams during Drying. Mehran University Research Journal of Engineering and Technology, **35**:395-400.

Lakho, N.A., Zardari, M.A., Memon, M. & Saand, A. 2015b. Design and fabrication of a mechanized system for casting and compacting laboratory-size clay beams. Scientia Iranica. Transaction A, Civil Engineering, **22**(6), 2046-2051.

Lekshmi, M.S., Vishnudas, S. & Nair, D.G. 2017. An investigation on the potential of mud as sustainable building material in the context of Kerala. International Journal of Energy Technology and Policy, **13**(1-2):107-122.

Nidzam, R.M., Norsalisma, I. & Kinuthia, J.M. 2016. Strength and environmental evaluation of stabilised Clay-PFA eco-friendly bricks. Construction and Building Materials, **125**:964-973.

Omidi, G.H., Thomas, J.C. & Brown, K.W. 1996. Effect of desiccation cracking on the hydraulic conductivity of a compacted clay liner. Water, Air, & Soil Pollution, **89**(1):91-103.

Phonphuak, N., Kanyakam, S. & Chindaprasirt, P. 2016. Utilization of waste glass to enhance physical–mechanical properties of fired clay brick. Journal of Cleaner production, **112**:3057-3062.

Rhodes, D. 2015. Clay and glazes for the potter. Martino Fine Books.

Smeu, S., Gal, A. & Badea, C. 2014. Environmental friendly building materials: Unfired Clay Bricks. Journal of Environment, **3**(3):47-50.

Umana, U.E., Davie, C.T. & Eminue, O. O. 2016. Investigation of the Effect of Multiple Wetting and Drying Cycles on the Shrinkage and Cracking of Engineered Clay Soil. International Journal of Engineering, **5**(11): 24-35.

Walker, P.J. 1995. Strength, durability and shrinkage characteristics of cement stabilised soil blocks. Cement and Concrete Composites, **17**(4):301-310.

شدة الضغط الأمثل لألواح الطين المتصلبة الجافة

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الخلاصة

إن عدم توفر الركام في سهول باكستان أدى إلى البحث عن مواد اقتصادية بديلة لتشييد المباني. تم بذل جهود كثيرة لتقديم ألواح من عجينة الطين المحمص (RBC) المُعزز كبديل عن الخرسانة المسلحة الأسمنتية لبناء منازل منخفضة التكلفة. ومع ذلك، فإن إنكماش وانخفاض قوة الضغط لتلك الألواح يعتبر عقبة. يقدم هذا البحث الضغط الأمثل ليتم تطبيقه على ألواح الطين أثناء الصب لتقليل الانكماش ولتحقيق أقصى قدر من مقامة الضغط الممكنة. ولهذا الغرض، تم صب وضغط ألواح الطين عند درجة من 0 إلى 7 ميجا باسكال. تم تحديد انكماش الألواح ومقاومة ضغط المكعبات. أظهرت النتائج أن (1) انكماش ألواح الطين انخفض من 8 إلى 1.25% عند ضغط قدره 2 ميجا باسكال و 6 ميجا باسكال على التوالي، و(2) مقاومة الضغط لكل من الطين غير المحمص والطين المحمص ارتفعت بزيادة الضغط على ألواح الطين أثناء الصب. في حين أنه لم يكن هناك اختلاف كبير في مقاومة ألواح الطين عند ضغطها عند درجة من 6 إلى 7 ميجا باسكال. كانت مقاومة ضغط الطين المحمص الذي تم الحصول عليه عند ضغط مثالي قدره 6 ميجا باسكال تبلغ 35 ميجا باسكال، وهو أعلى بحوالي 1.7 مرة من الخرسانة من الدرجة M20.