Innovative use of brick wastes as coarse aggregate in concrete

Naraindas Bheel¹, K Rajesh Kumar²,², Ashok Kumar³, Rehana Bhagam⁸, Adeyemi Adesina⁴, ShankerLal Meghwar⁵ and Noor Ahmed Memon⁶

¹Department of Civil Engineering, Hyderabad College of Science & Technology Hyderabad, Pakistan.
²Centre for Construction Methods and Materials, SR Engineering College, Warangal, Telangana, India.
³Department of Civil Engineering, College of Engineering and Technology, University of Sargodha, Pakistan.
⁴Department of Civil and Environmental Engineering, University of Windsor, Canada.
⁵Department of Civil Engineering, Mehran University of Engineering & Technology, Jamshoro, Pakistan.
⁶Department of Civil Engineering, Quaid-e-Awam University of Engineering, Science & Technology, Pakistan.
⁷Department of Civil Engineering, SR University, Warangal, Telangana, India.
⁸Sumathi Reddy Institute of Technology for Women, Warangal, India.

Abstract. Coarse aggregates occupy the largest volume in concrete which is one of the most widely used construction material as per industry surveys. The depleting supply of coarse aggregate coupled with the high greenhouse gasses emissions from its processing and transportation has resulted in a need to find alternatives that can be utilized as coarse aggregate. Of such materials that are available in abundance locally in Pakistan are brick wastes that are generated from the construction and demolition processes. In order to evaluate the feasibility of using brick wastes as coarse aggregate in producing concrete, this study was undertaken. Six concrete mixtures were made by incorporating brick wastes as a replacement for the natural coarse aggregates and the corresponding properties evaluated. The properties evaluated are the slump, density, compressive strength and flexural strength. Results from this study indicated that the use of brick wastes as coarse aggregates in concrete resulted in a decrease in the slump and mechanical properties. However, concrete mixtures incorporating brick wastes up to 100% replacement of natural coarse aggregate exhibited flexural and compressive strength higher than 2 MPa and 10 MPa respectively. Nonetheless, the incorporation of brick wastes as coarse aggregate resulted in a decrease in density due to its lower bulk density in comparison to that of the natural coarse aggregate.

1 Introduction

Civil Engineering industry is one of the primary industries that support any nation’s growth, concerned with the developing nation this industry plays key role supporting economy in several ways. It is well known that the concrete is always most widely used construction material, and a larger volume of concrete is occupied by coarse aggregates[1]. Therefore, with the increasing use of concrete for various
construction purposes comes a corresponding higher consumption of coarse aggregates. The conventional aggregates used in concrete are obtained from crushing rocks which consumes very huge quantum of energy and produce a significant amount of greenhouse gases and release it in the environment. Also, the transportation of coarse aggregate from where they are sourced to construction sites has been found to result in significant carbon dioxide emission to the environment. The increasing use of concrete has also been found to result in extensive strain on the sources of these aggregates and a consequential deformation of the environment due to the excessive exploration. Certain parts of the world also do not have enough reserve of coarse aggregate to meet the future demand for concrete, but the construction activities in those regions are steadily gaining momentum. The production and usage of construction materials also grows at a rapid pace in those regions with large amount of natural resource consumption in place. There is a need to use alternate materials in those regions including several developing countries since they are also struggling to manage the natural resources that are available.

Several research works concluded that conversely, various solid wastes can be reused in concrete as coarse aggregate and some of them are highly successful in developing the concrete with the addition of those materials. Awareness creation related to sustainability in the concrete production and materials supplying industry seen the utilization of various solid wastes such as plastics\cite{2}, crumb rubber\cite{3,4}, recycled concrete\cite{5–7}, etc., as aggregates in concrete. The use of these wastes to partial and totally replace aggregates in concrete has also been found to make concrete mixtures more sustainable\cite{8,9}. Another waste that which can be effectively utilised as concrete coarse aggregate is brick wastes (BW). BW are construction and demolition wastes obtained from the repair and construction of buildings made with brick. In contrast to other construction and demolition wastes such as concrete, there exist limited application and study of brick wastes in concrete \cite{10,11}. Yet, brick production is huge across the globe and its being used widely for construction purpose for any type of structures due to its versatility. Because of this brick production, therefore, in areas where the brick wastes are generated in large quantities, they are a viable alternative to supplement the demand for natural coarse aggregates. There is huge potential for using this brick waste for several purposes but only few opportunities such as surki based lime mortar with brick bats, pavement construction is being explored and other viable chances of utilising it is not explored. Considering this there is good scope for using the brick bats for construction purpose including using it as an aggregate for concrete production. Concrete is a versatile construction material which can engulf waste material without altering its nature and can produce good strength unless the added material reacts with it. Hence, any reaction neutral material can be used as additive in concrete without altering its strength and durability \cite{25-26}. Many developing countries are trying several methods to produce concrete by using the alternate materials and also by reusing the waste materials as aggregates, pozzolana etc. Among this technologies, addition of waste materials for the aggregate purpose is one good measure which will be more effective than adding pozzolana \cite{16}, \cite{27-30}. This is not only cost effective but also can reduce waste material dumping because of no proper usage availability. Brick is made naturally from earth and it has natural pozzolanic property due to the calcination of clay, hence it can be effectively used as an additive in concrete without effect in its strength and durability.

Asian countries and the people of ASEAN countries mostly use brick for construction purpose due to the nature of society and the willingness they have to use it. Several countries including India, Pakistan, and Sri Lanka use brick for construction due to its strength, durability and nature to withhold in any environment, cooling nature, adaptability with any mortar etc. Pakistan which is the third-largest producer of bricks in South-Asia and produces over 40 billion of bricks annually for building construction from its 19000 kilns\cite{12}. However, with this high production of virgin bricks to replace old ones comes a large generation of construction and demolition wastes in the form of bricks. Daily generation of bricks for construction purpose also is drastically increasing due to unavailability of alternate sources to replace bricks. Using this bricks for alternate purpose is the primary issue producers are facing since they don’t possess any market value for selling except for few rare usage including agriculture and for filler purpose. Brick kilns are increasing day by day.
due to the trend in increased construction activities in Pakistan due to surging demand in housing and industrial buildings. Yet, the technologies that are available through research is not reaching the end users due to the failure in dissemination systems or adapting related issues prevailing. Recycling of waste materials is gaining impetus across the world, multiple waste materials is being used in construction materials development. Replacement of aggregates by waste materials is an area where researchers are working on for last two decades and many established protocols were derived. Also, waste material generation is raising due to several activities such as demolition of buildings, etc, brick kilns also produce lot of unusable brick bats that are simply disposed without productive usage. Therefore, recycling these wastes as coarse aggregate in concrete will create an efficient way to manage these wastes while conserving the natural coarse aggregate deposits. In addition to the BW serving as an alternative coarse aggregate in concrete, it will result in cost reduction of recycling these wastes and a corresponding reduction in the overall cost and embodied energy of concrete. Mostly brick is burnt, the full strength will be attained and they are discarded only because of size related issues, hence they can be used as aggregated without any issue. However, it is essential to ensure that concrete incorporating these alternative waste materials still possess minimum strength and durability requirements for construction applications. Addition of materials should not generate any voids and also should not alter the natural characteristics of concrete, should give aesthetic look too. Hence, this study aims to utilize BW by replacing it for coarse aggregate in concrete up to 100% replacement. Six concrete mixtures were made and BW was used to replace 20%, 40%, 60%, 80% and 100% natural coarse aggregate. The mixture made with only natural coarse aggregate was used as the control mixture. The corresponding effects of the incorporation of various dosages of the BW on the properties of concrete were evaluated. The properties evaluated are the slump, density, compressive strength and flexural strength. A correlation between some of the properties was also carried out. Results from this preliminary study are presented herein.

2 Research program

2.1 Materials
Type 1 Portland cement (PC) was used as the only binder in all the concrete mixtures. The specific gravity and fineness value of the PC is 3.15 and 8.6% respectively. Natural coarse aggregate (NCA) and natural fine aggregate (NFA) with a maximum size of 19 mm and 4.75 mm, respectively were used as the primary aggregates. Brick wastes (BW) can be utilised as replacement materials of the NCA in the concrete mixtures. The BW were obtained from a local construction firm in Nawabshah, Pakistan. The obtained BW was crushed and those with sizes between the 4.75 mm and 19 mm were used to replace the NCA. The physical properties and particle distribution of the aggregates are presented in Table 1 and Figure 1 respectively. It shows the the brick aggregate possess similar properties like that of coarse aggregate used in this study including fineness modulus but it has more water absorption since its made up of clay, hence slight modification is required in w/c ratio during mix design. Also pre-soaking of brick aggregates in water for 24 hours before using in concrete is a technique that will reduce the water absorption in initial mixing stage of concrete.

| Property            | NFA | NCA | BW  |
|---------------------|-----|-----|-----|
| Fineness Modulus    | 2.46| 6.95| 6.10|
| Specific Gravity    | 2.62| 2.67| 2.26|
| Absorption (%)      | 1.78| 0.58| 14.36|
| Bulk density (kg/m³)| 1720| 1672| 1250|
| Maximum size (mm)   | 4.85| 19  | 19  |
2.2 Mixture design

The main aim of the work done focused to investigate the influence of BW on concrete properties for which the brick aggregates were added in the mix using standardised procedures. Therefore, BW was used to replace the NCA up to 100% in concrete mixtures. A detailed composition of the six mixtures investigated in this study is presented in Table 2. The mix ID utilized in Table 2 represents the percentage of NCA replaced with BW.

Table 2. Concrete mixtures (kg/m³)

| Mixture ID | PC   | Water | NFA | NCA   | BW  |
|------------|------|-------|-----|-------|-----|
| 0BW        | 330  | 170   | 620 | 1240  | 0   |
| 20BW       | 330  | 170   | 620 | 990   | 210 |
| 40BW       | 330  | 170   | 620 | 500   | 420 |
| 60BW       | 330  | 170   | 620 | 745   | 630 |
| 80BW       | 330  | 170   | 620 | 250   | 840 |
| 100BW      | 330  | 170   | 620 | 0     | 1050|

2.3 Sample preparation and curing

For preparing the concrete specimens thorough mixing of aggregates is done for two minutes in dry condition, after which water is added as per water-cement ratio defined, mixed additionally for extra five minutes. After a homogenous mixture has been achieved, the slump was evaluated, and the mixture was poured in moulds for the other tests to be carried out. Figure 2 shows the placing of the concrete in the moulds for the mechanical tests to be carried out. Mould were prepared after proper cleaning so that no addition of materials happen, neatly oiled with waste oil so that the concrete edges were not damaged. Concrete is placed in the mould immediately after mixing and vibrated properly using needle vibrator. Care is taken to avoid segregation and bleeding during vibrating. Once the concrete is placed the specimens were moved to a dry, clean and plain surface and the surface is closed with polythene sheets to avoid moisture escape. Twenty four hours after initial casting, the samples were demoulded from the mould and cured underwater for 28 days before testing. Water used for curing is free from any adulterant and have neutral pH to avoid any reaction with the binder. Full immersion is done to avoid exposing of surface and drying of the surface. Also the water surface is not exposed to direct sunlight to avoid water evaporation or heating, the temperature of water is maintained as atmospheric temperature for full curing period. After the curing period the specimens were taken out and painted in white colour to note the visible cracks before testing, also the specimens were dried for two hours before application of load.
2.4 Slump
The slump of each mixture was performed once the mixing is fully completed as per the procedures mentioned in BS EN 12350 – 1 [13]. Test procedure entails filling a cone in three layers and rodding each layer 25 times. After the third layer has been finished, the cone was removed and the length between the top of the concrete and top of the cone measured as the slump.

2.5 Compressive strength
Specimens compressive strength was calculated from the samples casted of size of 150mm x 150 mm x 150 mm as per BS EN 206 [14]. Testing is done in electric operated Compressive strength testing machine which is pre calibrated as per industrial norms. The compressive strength of the samples was obtained by calculating the ratio between the peak load and the cross-sectional area of the sample. The compressive strength presented represents the average compressive strength of the six samples tested and the specimens which failed quickly during the study is discarded. Figure 3a shows the test set up for the compressive strength.

2.6 Flexural strength
Prism samples with a dimension of 100 mm x 100 mm x 500 mm were used to investigate the flexural strength of the mixtures as per BS EN 12390 – 5 [15]. For each mixture, a total of four samples are tested and the flexural strength presented represents the average flexural strength of the four samples. A picture of the test setup is presented in Figure 3b.
3 Results and Discussion

3.1 Slump

Figure 4 represent the slump values obtained for the concrete prepared. It can be seen that the slump reduced with higher content of BW. The slump of concrete mixtures incorporating 40%, 80% and 100% BW as replacement of the NCA is 20%, 48% and 62%, respectively in comparison to the control (i.e. 0BW). We found that there is a decrease in slump value with increasing content of BW as coarse aggregate can be associated with it the high porosity and absorption which results in the reduction of the water available in the mixture. This observation is in agreement to that of Bazaz and Khayari[17] found that there is decrease in slump value with recycled aggregates was reported. For workability improvement of concrete mixtures incorporating BW as coarse aggregate, the BW can be used at a saturated surface dry state or high range water reducing admixtures can be utilized.

![Test setup for Compressive strength](image1)

![Test setup for Flexural strength](image2)

**Figure 3.** Set up for the mechanical property tests

![Slump of concrete mixtures](image3)

**Figure 4.** Slump of concrete mixtures
3.2 Density
Density of concrete plays predominant role in determining its durability, higher dense concrete will have more strength and also will have more endurance. Figure 5 represents the effect on density due to the incorporation of BW as a coarse aggregated in concrete which shows a clear decrease in density with the increasing BW content. It can be seen from the figure that the incorporation of BW into the concrete mixtures resulted in a decrease in the density. The density of 20BW, 40BW, 60BW, 80BW and 100BW is 2%, 7%, 8%, 9% and 13% lower than that of 0BW. The lower density of the concrete mixtures incorporating BW can be associated with its lower bulk density which results in a corresponding reduction in the density of the concrete. These results show that BW can be incorporated as a coarse aggregate where there is a need to reduce the deadload of concrete structures.

![Figure 5. Density of concrete mixtures](image)

3.3 Compressive strength
Compressive strength is an important characteristic of concrete concerned with durability of the structure, figure 6 shows the values obtained through this study with incorporation of BW as replacement for NCA. Results clearly shows that the addition of BW in concrete reduces its strength and a lower compressive strength value is obtained. It is found that the strength reduction incorporating 40% and 80% BW as replacement of NCA is 20% and 34% lower than that of the concrete mixtures made with only NCA as aggregate. Higher water absorption of BW may be major cause for the lowering of strength concerned with high BW added concrete. The higher porosity of the BW compared to that of NCA can also be related with the lower compressive strength observed in concrete mixtures incorporating BW as coarse aggregate. Nonetheless, as the compressive strength of all the concrete mixture evaluated is greater than 17MPa, they are suitable for structural construction applications [18]. These observations correlate with similar studies where construction and demolition wastes were used as coarse aggregate [19–22][27-30].

Figure 7 depicts the correlation between density and the strength for various mixtures. Correlation between these two properties is highly visible from this study. These correlations showed that the lower bulk density of the BW plays a role in the lower compressive strength observed.
3.4 Flexural strength

Flexural strength studies were conducted using single point load method using modified flexure setup in compression testing machine which is pre-calibrated. Flexural strength of concrete for various proportions of BW as replacement of NCA is presented in Figure 8. It can also be viewed that addition of BW into the concrete mixtures resulted in a reduction in the flexural strength which can be attributed to the absorption of the BW which results in limited water supply for the hydration process. Yet, the results are to be further verified with sorptivity test which is beyond scope of this work. Similar observations have been made when recycled concrete was used as aggregate in concrete mixtures [22–24],[32-34]. Figure 9 presents the correlation between the flexural strength and the compressive strength.
Conclusions

This study is part of a comprehensive study been undertaken to investigate the feasibility of using brick wastes as coarse aggregates in concrete mixtures. Brick wastes were used as coarse aggregate to replace the natural coarse aggregate up to 100% and the corresponding slump, density, compressive strength and flexural strength of the mixtures evaluated. The following conclusions can be made:

1. The lower bulk density of brick wastes compared to those of natural coarse aggregate makes it a good alternative to reduce the density of concrete mixtures. The density of concrete reduced up to 13% when brick wastes were used as the only coarse aggregate in concrete mixtures. This reduction in density of the concrete will result in a significant reduction in the dead load and cost of concrete.

2. Incorporating brick wastes as coarse aggregates in concrete resulted in a decrease in the slump due to the higher absorption of the brick wastes which led to a reduction in the limited supply of water for workability. Where higher workability is desired, high range water reducing admixtures can be used or/and incorporating the brick wastes in a saturated surface dry state.

3. The incorporation of brick wastes as aggregate in concrete mixtures resulted in a decrease in the compressive and flexural strength of the mixtures. However, as the compressive and flexural strength of concrete mixtures incorporating only brick wastes as aggregate greater than 17MPa and 2MPa; they can be used for structural application.

Figure 8. Flexural strength of concrete mixtures

Figure 9. Relationship between the flexural and compressive strength

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5. References

[1] A. Neville 2012 Properties of Concrete- 5th Edition.

[2] P.O. Awoyera, A. Adesina 2020, Plastic wastes to construction products: Status, limitations and future perspective, Case Stud. Constr. Mater. 12. https://doi.org/10.1016/j.cscm.2020.e00330.

[3] A. Adesina, O.D. Atoyebi 2020 Effect of crumb rubber aggregate on the performance of cementitious composites: A review, IOP Conf. Ser. Earth Environ. Sci. https://doi.org/10.1088/1755-1315/445/1/012032.

[4] B.S. Thomas, R. Chandra Gupta 2016 Properties of high strength concrete containing scrap tire rubber, J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.11.019.

[5] P.O. Awoyera, A. Adesina, R. Gobinath 2019 Role of recycling fine materials as filler for improving performance of concrete - a review, Aust. J. Civ. Eng. https://doi.org/10.1080/14488353.2019.1626692.

[6] A. Adesina 2019 Properties of Alkali Activated Slag Concrete Incorporating Waste Materials as Aggregate: A Review, Mater. Sci. Forum. https://doi.org/10.4028/www.scientific.net/msf.967.214.

[7] N. Bheel, S.L. Meghwar, S. Sohu, A.R. Khoso, A. Kumar, Z.H. Shaikh 2018 Experimental Study on Recycled Concrete Aggregates with Rice Husk Ash as Partial Cement Replacement, Civ. Eng. J. 2305. https://doi.org/10.28991/ccej-03091160.

[8] A. Sivakrishna, A. Adesina, P.O. Awoyera, K. Rajesh Kumar 2019 Green concrete: A review of recent developments, Mater. Today Proc. https://doi.org/10.1016/j.matpr.2019.08.202.

[9] A. Adesina 2018, Concrete Sustainability Issues, in: 38th Cem. Concr. Sci. Conf. UK, London.

[10] J. Yang, W.M. Shaban, K. Elbaz, B.S. Thomas, J. Xie, L. Li 2020 Properties of concrete containing strengthened crushed brick aggregate by pozzolan slurry, Constr. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2020.118612.

[11] X. Yuan, Y. Tang, Y. Li, Q. Wang, J. Zuo, Z. Song 2018 Environmental and economic impacts assessment of concrete pavement brick and permeable brick production process - A case study in China, J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.10.037.

[12] Pakistan third largest brick- producing country in South Asia – Business Recorder, (n.d.). https://fp.brecorder.com/2017/05/20170504175630/.

[13] BS EN 12350-1:2009, Testing fresh concrete. Slump-test, Eur. Norms.

[14] BS En 206:2013:, BSI Standards Publication Concrete — Specification , performance , production and conformity, Br. Stand.

[15] Testing hardened concrete - Part 5: 2009 Flexural strength of test specimens, BS En 12390-52009. British Standard.

[16] K.Rajesh Kumar , Shyamala G, Awoyera P O, Vedhasakthi K and Olalusi O B 2020 Cleaner production of self-compacting concrete with selected industrial rejects-an overview Silicon.

[17] J. Bolouri Bazaz, M. Khayat 2012 Properties and Performance of Concrete Made with Recycled Low-Quality Crushed Brick, J. Mater. Civ. Eng. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000385.

[18] A.M.M. Neville, J.J.J. Brooks 2010, Concrete Technology Second Edition. https://doi.org/10.1016/0360-1323(76)90009-3.

[19] V. Corinaldesi 2010 Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates, Constr. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2010.02.031.

[20] A. Adesina, P. Awoyera 2019 Overview of trends in the application of waste materials in self-compacting concrete production, SN Appl. Sci. https://doi.org/10.1007/s42452-019-1012-4.

[21] H. Sasanipour, F. Aslani 2020 Durability properties evaluation of self-compacting concrete prepared with waste fine and coarse recycled concrete aggregates, Constr. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2019.117540.
[22] H. Gurdián, E. García-Alcocel, F. Baeza-Brotons, P. Garcés, E. Zornoza 2014 Corrosion behavior of steel reinforcement in concrete with recycled aggregates, fly ash and spent cracking catalyst, Materials (Basel). https://doi.org/10.3390/ma7043176.

[23] R. Sato, I. Maruyama, T. Sogabe, M. Sogo 2007 Flexural behavior of reinforced recycled concrete beams J. Adv. Concr. Technol. https://doi.org/10.3151/jact.5.43.

[24] W.C. Choi, H. Do Yun 2013 Long-term deflection and flexural behavior of reinforced concrete beams with recycled aggregate, Mater. Des. https://doi.org/10.1016/j.matdes.2013.04.044.

[25] Murthi P, Poongodi K and Awoyera P O 2019 Enhancing the Strength Properties of High-Performance Concrete Using Ternary Blended Cement: OPC, Nano-Silica, Bagasse Ash Silicon.

[26] Shyamala G, Kumarasamy K, Ramesh S, Kalaivani M and Pillalamarri S P 2020 Influence of nano-silica in beam-column joint flexural properties IOP Conf. Ser. Mater. Sci. Eng. 872 012169.

[27] Adesina A, Awoyera P O, Sivakrishna A, Kumar K R and Gobinath R 2020 Phase change materials in concrete: An overview of properties Mater. Today Proc. 27 391–5.

[28] Awoyera P O, Adesina A, Sivakrishna A, Gobinath R, Kumar K R and Srinivas A 2020 Alkali activated binders: Challenges and opportunities Mater. Today Proc. 27 40–3.

[29] K. Rajesh Kumar and Mahendran N 2013 Experimental Studies On Strength, Durability And Behaviour Of Beam Using S.C.C. With E-Glass Fiber Strands Int. J. Eng. Res. Technol. 2-10

[30] R. Abiraami and K. Rajesh Kumar N M 2015 Mechanical and Microstructural Characteristics of Int. J. Appl. Eng. Res. 10 1–6.

[31] K. Rajesh Kumar, Ramamohan R and Murthi P 2019 Shear Resistance of portal Frame Reinforced with Bamboo and Steel Rebar: Experimental and Numerical Evaluation Int. J. Recent Technol. Eng. 8 445–52.

[32] K. Rajesh Kumar and Mahendran N 2016 Structural behaviour of deep beam using S.C.C. with chopped strands and polypropylene fibre J. Intell. Fuzzy Syst. 30 1219–29.

[33] Swamy Yadav Golla, K. Rajesh Kumar, Khan M I, Rahul C and Pruthvi Raj K 2020 Structural performance of exterior beam-column joint using biochar impregnated pond ash concrete Mater. Today Proc. doi. https://doi.org/10.1016/j.matpr.2020.07.722.