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Development and performance evaluation of interlocking bricks using industrial waste materials

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ABSTRACT

Red brick is a basic building material used in the construction of buildings. In the ever-growing construction field, Civil Engineers are searching for new building materials based on economy, durability and efficiency. It should also be eco-friendly. This project aims to create low cost, eco-friendly, sustainable and durable system for the construction of load bearing walls using the Interlocking Bricks (IB). It is a mortar-less masonry system and cement is also not used in brick manufacturing. The interlocking brick is made using waste materials (i.e. fly ash & GGBS) and hydraulic lime as binder. Mix proportions are varied based on the proportion of waste materials. Comparison of interlocking brick and conventional brick on the basis of compressive strength & water absorption of the brick unit. It was found that interlocking brick composed of 55% of fly ash, 25% of GGBS and 20% of lime had the best results in all the tests. The compressive strength was 30% higher than the conventional red bricks. The interlocking brick wall panel was tested by applying axial compressive load and software analysis is carried out using ANSYS 2021 R1 to compare it with the experimental results to find the degree of accuracy between theoretical and experimental models. Cost analysis is done to compare the rate of construction with conventional red brick masonry and was found that it was almost 40% cheaper.

Keywords: *Fly Ash, GGBS, Lime, Compressive Strength, Interlocking Brick, Mortar-Less Masonry, ANSYS & Cost Analysis*

1. INTRODUCTION

Masonry brick is one of the construction materials which is used from ancient times as old as 7000BC. The conventional procedures of brick making were by mixing raw materials and then the bricks were moulded, dried and fired till they obtained a certain level of strength. This process was not energy efficient compared to the modern manufacturing processes [1]. The manufacturing process has been improved in recent times along with the introduction of several new types of bricks like Fly ash bricks, Aerocon bricks and hollow blocks [2-4]. But these bricks use cement in their manufacturing process and during the construction process in the form of mortar. But the cement manufacturing process is a major contributor to CO2 emissions. Hence, the aim of the project was to reduce the usage of cement in both manufacture and during the construction process. A large amount of industrial wastes like fly ash, GGBS are generated from industries every year. Fly ash is obtained from thermal power plants as a by-product. According to a Central Electricity Authority report (CEA, 2020), fly ash generation in India was 226.13 million tons in the year 2019–2020. Despite the continuous efforts to increase the utilization rate, the government still does not achieve 100% utilization [5]. With an identical chemical composition to Ordinary Portland Cement (OPC), GGBS is an industrial waste obtained by quenching molten iron blast-furnace slag in water or steam. According to US Geological survey, the global production of GGBS is in order of 170 to 250 million tons. In India, GGBS, with an annual production of about 15 million Tons, is mainly used in cement manufacturing plants and partial replacement of cement in concrete. However, this utilization rate for GGBS only amounts to 55%. So we must try to use these materials as a substitute for cement. Interlocking system is a new concept to make masonry construction more economical and faster compared to the conventional masonry construction which has mortar joints [6-9]. Interlocking bricks are unique in relation to conventional bricks since the absence of the mortar to be filled between the brick layers during the construction process. Curing and plastering are not needed in Interlocking Brick (IB) [10]. Interlocking brick is economical. Instead of using nominal brick, interlocking brick can be used as it saves cost in terms of cement, sand and water.

Interlocking bricks are subjected to less damage when compared with nominal brick during an earthquake [11]. The construction of building walls and partitions is faster. It requires less-skilled workers as the bricks are assembled dry and stacked on one another. In case of walls, the strength was higher than conventional masonry because of homogeneous layers which leads to effective load transfer.

2. MATERIALS USED

2.1 Fly ash

Fly ash is a waste product from the coal power plant that contains fine particles of burned coal that are driven out of boilers together with the gases. In modern coal-fired power plants, fly ash is generally captured by particle filtration equipment before the flue gases reach the chimneys. Fly ash includes substantial amounts of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and calcium oxide (CaO), the main mineral compounds in coal-bearing rocks. Fly ash required for the project was procured from a supplier near Mettur power plant. The Specific Gravity was 2.12. It was class F fly ash as it was pozzolanic & not cementitious.

Table-1: Chemical Composition of Fly Ash

Chemical	SiO_2	Al_2O_3	CaO	FeO	TiO_2	MgO	K_2O	Na_2O	SO_3
Proportion(%)	28.62	25.06	14.72	10.47	11.51	4.70	1.34	1.45	2.13

2.2 GGBS

Ground Granulated Blast Furnace Slag (GGBS) is a by-product from the blast furnaces used to make iron. GGBS comprises mainly of CaO, SiO_2, Al_2O_3, MgO. It has the same main chemical constituents as Ordinary Portland Cement but in different proportions. GGBS reacts like Portland cement when in contact with water. But as the rate of reaction is slower, an activator is necessary. The calcium hydroxide released when Portland cement or lime reacts with water serves to activate GGBS. GGBS procured for the project was commercially available JSW GGBS. The Specific Gravity was 2.9.

Table-2: Chemical Composition of GGBS

Chemical	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	Ir	SO_3	Sulphide
Proportion(%)	37.63	34.81	17.92	0.66	7.80	0.21	0.19	0.2	0.51

2.3 Hydraulic Lime

A hydraulic lime is made from limestone that either naturally contains or has artificially introduced some form of amorphous silica in the burning process. This amorphous or "free" silica fuses with some of the quicklime to form a clinker, a cementitious compound. That clinker is what makes the lime hydraulic, which means that it will set with the addition of a certain percentage of water. Hydraulic lime procured was from a locally available supplier.

Table-3: Chemical Composition of Hydraulic Lime

Chemical	CaO	SiO_2	MgO	K_2O	Al_2O_3	FeO	Na_2O	SO_3
Proportion(%)	91.80	3.22	2.08	1.02	1.32	0.32	0.16	0.08

3. SHAPE AND SIZE OF INTERLOCKING BRICK

We aimed to create a new system of interlocking to eliminate the disadvantages of failure in the key region. We should also eliminate the dimensional variation in the bricks due to complicated shapes. The system of interlocking introduced is the usage of chords for interlocking instead of keys.

The size of the IB is 300mm x 150mm x 150mm. The diameter of each hole is 30mm through which chords are introduced for interlocking. We have chosen the length and breadth as 300mm and 150mm respectively because the sides of the interlocking bricks produced is very smooth and do not require plastering. A chamfer is given in the top and bottom edges to facilitate pointing. The shape of the brick and hole positions are in such a way that we can use any type of bond like Stretcher bond, English bond and Flemish bond. We have used 1/3rd scaled model bricks of size 100mm x 50mm x 50 mm with a hole diameter of 10mm[12]. This was done for ease of testing the wall panel.

4. MIX PROPORTIONS OF IB

The IB consists of fly ash and GGBS. As both of the materials are pozzolanic in nature, we need to add hydraulic lime since these industrial wastes require chemical activation to trigger the cementation reactions. The hydraulic lime was used as it was both eco-friendly and cost-effective compared to cement. The 10 mix proportion were chosen for the project work is shown in Table 4 'L' represents the proportion of hydraulic lime while 'G' represents the proportion of GGBS in the mix and the numbers next to 'L' and 'G' represents the amount of proportion of hydraulic lime and GGBS in the mix respectively

Table 4: Mix Proportions of IB

S.No	**MIX ID**	**FLY ASH (%)**	**LIME (%)**	**GGBS (%)**
1	L10G10	80	10	10
2	L10G20	70	10	20
3	L20G10	70	20	10
4	L20G20	60	20	20
5	L30G10	60	30	10
6	L10G30	60	10	30
7	L15G25	60	15	25

8	L15G20	65	15	20
9	L25G20	55	25	20
10	L20G25	55	20	25

5. CASTING OF INTERLOCKING BRICKS

The casting of IB was done using H-frame hydraulic press. We produced scaled model bricks of dimension 100mm x 50mm x 50mm. The density of the brick was around 1400 kg/m³ so we can classify it as low-density brick. The bricks produced were machine moulded and had better shape and higher production rate compared to ground and table moulded bricks. The materials (Fly ash, GGBS and Hydraulic Lime) were weighed and taken in the pan according to the proportion and dry mixed until the material was uniformly mixed. Then potable water was added according to OMC which was 17% and was wet mixed until we got a uniform paste. Then we weighed the amount of material required for one brick and placed them into the mould with the help of a hopper. After placing the material, closing with top plate and using the hydraulic press, a pressure of 750-1000 psi was applied. Care was taken to maintain the height of the brick to prevent dimensional variation. The top plate was removed and the brick was ejected by pressing down the lever in the mould. This is shown in Fig. 1 The brick was then removed from the mould and was allowed to air dry for 24 hours and then normal curing was done for 28 days under room temperature.

(a) Mixing of material **(b)** Placing in mould **(c)** Operating Hydraulic Press **(d)** Ejecting from the mould

Fig. 1(a)-(d): Casting process of Interlocking Brick

6. EXPERIMENTAL WORK

6.1 Compressive Strength Test

The test was carried according to IS 3495:1992-Part 1 [13]. The rate of loading was14 N/mm² per min i.e.,) 1.167 kN/sec for the model brick. An average value of 3 specimens was taken. The specimen was immersed in water at room temperature for 24 hours. The specimen was removed from water and any surplus water was drained out. No mortar was filled in perforations and no mortar capping was provided. The perforated faces of the brick were placed between two 3-ply plywood sheets each of 3 mm thickness and carefully centered between the plates of the testing machine as shown in fig 2. The load was applied axially at uniform rate mentioned above till the failure occurs and the maximum load was noted at failure. The failure load was the maximum load at which the specimen failed to produce any further increase in the indicator reading on the testing machine. The average of results was reported.

$$\text{Compressive strength in N/mm}^2 = \frac{\text{Maximum load at failure in N}}{\text{Average net area of two faces under compression in mm2}}$$

Fig. 2: Compressive Strength test

6.2 Water Absorption Test

The test was carried according to IS 3495:1992-Part 2 [14]. Water absorption test on bricks was conducted to determine the durability property of bricks such as quality and behavior of bricks in weathering. The specimen was dried in an oven at a temperature of 105 °C to 115°C till it attains constant mass. Then specimen was cooled to room temperature and obtain its weight (M_1). This specimen was completely immersed in water at a temperature of 27±2°C. After 24 hours the specimen was removed from the water and wiped out of any traces of water with a cloth and was weighed (M_2). Water absorption, % by mass, after 24 hours immersion in cold water was given by the formula, $W=\{(M_2-M_1)/M_1\} \times 100$

6.3 Test on Wall Panel

The test was carried out according to IS 1905-1987 [15]. Tests were conducted by applying axial compression load. Based on the journal study the dimension of the wall panel was taken as 1.2m x 1.2m [For scaled model brick, size is reduced according to scale = 1.2/3=0.4 m] [12]. The wall panel was cured for 7 days after construction. We used steel rods for the interlocking mechanism of IB but they were paced in such a way that the load applied is taken completely by the wall panel. The dial gauge was placed at L/2 and L/3 distances to measure the deflection of the wall panel as shown in fig 3. Vertical compression load was applied to the top without any eccentricity and was uniformly distributed throughout the panel.

(a) Test setup **(b)** Dial Gauge placement for Wall Panel Test

Fig. 3 Axial compression Test on Wall Panel

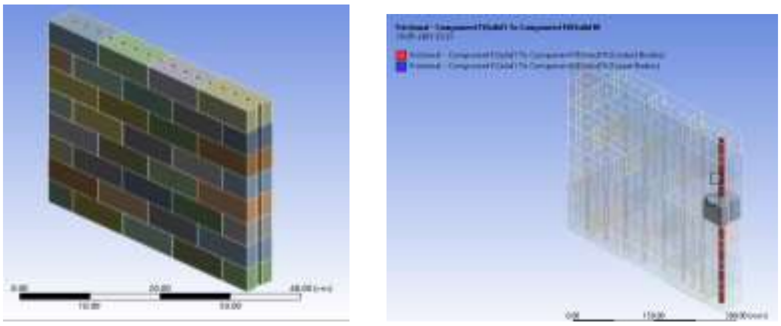
6.4 Rate Analysis of Brickwork Masonry

Rate analysis for brickwork comprises of the following:
1) Quantity and cost of material
2) Labour - mason and helper cost.

Quantity and cost of material includes the number of bricks, cement and sand quantity required for 10 cubic meters of brickwork. For installing brick work masons and helpers are required. So, the labour rate per m^3 for brickwork was calculated.

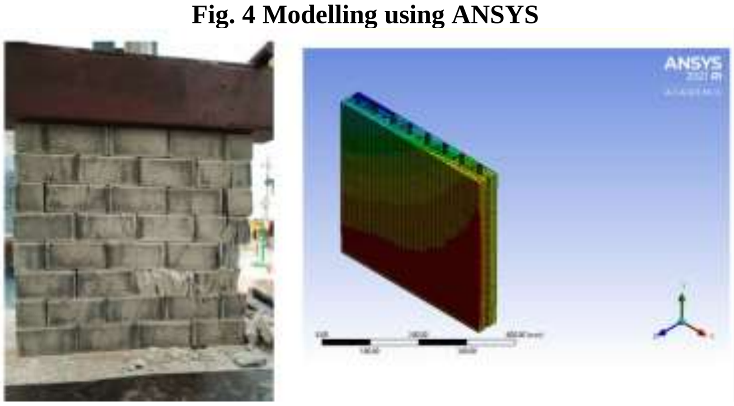
7. ANALYTICAL WORK

The software used in our project work is ANSYS 2021 R1 student version. In our project work, we applied a load to find the displacement of the wall panel and the result obtained was compared experimental results. Modelling was done with the help of SpaceClaim, a 3D modelling module in the software. The dimension of the model was the same as the experimental model in order to compare the accuracy of the simulated model to a real-life model. The model was created to simulate the experiment hence the load applied is completely taken by the IB. This was achieved by reducing the length of the steel rod so that it does not reach the top layer. Since it is an interlocking wall panel the connections are frictional connection as shown in Fig.4. On brick to brick connection, the contact body and target bodied are assigned based on top to bottom basis and left to right. In case of contact between the steel rod and brick, the contact body is steel rod and the target body is the brick. The meshing was done to 1:10 ratio of the element. For example, the length of the brick was 100 mm was the length of the mesh was 10 mm and so on. Static structural analysis was done to find the deformation as the load applied is an axial compression load which varies slowly with time. The wall was simply supported same as the experimental condition. We applied a load by selecting the load area and intensity of the load & analysed it to get the theoretical deformation. The probe option was used to find the deformation at required lengths L/2 and L/3. It was repeated for every load as in the experiment at 5 KN intervals approximately. Fig.5 shows that the deformation during the failure load was similar to the failure profile of the experimental specimen hence we can say that the behaviour of the models is similar. The range of variation of results experimental and analytical model will be discussed in the next section.



(a) Analytical Model **(b)** Application of frictional connection between brick & steel rod

Fig. 4 Modelling using ANSYS



(a)Experimental Specimen **(b) Analytical Model**

Fig. 5 Deformation at failure load

8. RESULTS AND DISCUSSION

8.1 Compressive Strength

The compressive strength is a very important parameter of the brick. The results obtained were an average of 3 specimens. The compressive strength of the mix proportions on 7 days, 14 days & 28 days as shown in table 5.

Table 5: Compressive strength of mix proportions

S.No	MIX ID	AVG. COMPRESSIVE STRENGTH IN MPa		
		7 DAYS	14DAYS	28DAYS
1	L10G10	1.69	4.65	7.97
2	L10G20	3.46	6.10	10.07
3	L20G10	2.55	4.76	9.84
4	L20G20	4.60	6.46	10.53
5	L30G10	4.10	6.20	8.25
6	L10G30	4.21	5.23	9.75
7	L15G25	4.91	6.72	10.70
8	L15G20	5.13	6.56	10.15
9	L25G20	4.37	6.47	10.92
10	L20G25	5.40	8.93	11.20

Strength of Conventional Red Brick =8.78 MPa

It can be seen from the results that the bricks gain about 45% to 50 % of the average compressive strength in 7 days and about 65% to 75 % of the average compressive strength in 14 days. It can also be seen that the mix L20G25 gains the same strength as a conventional red brick in 14 days itself. On average the strength of the interlocking bricks is about 20% to 30% more than red bricks as shown in fig. 6. It can be seen that the strength increased with an increase in lime and GGBS content.

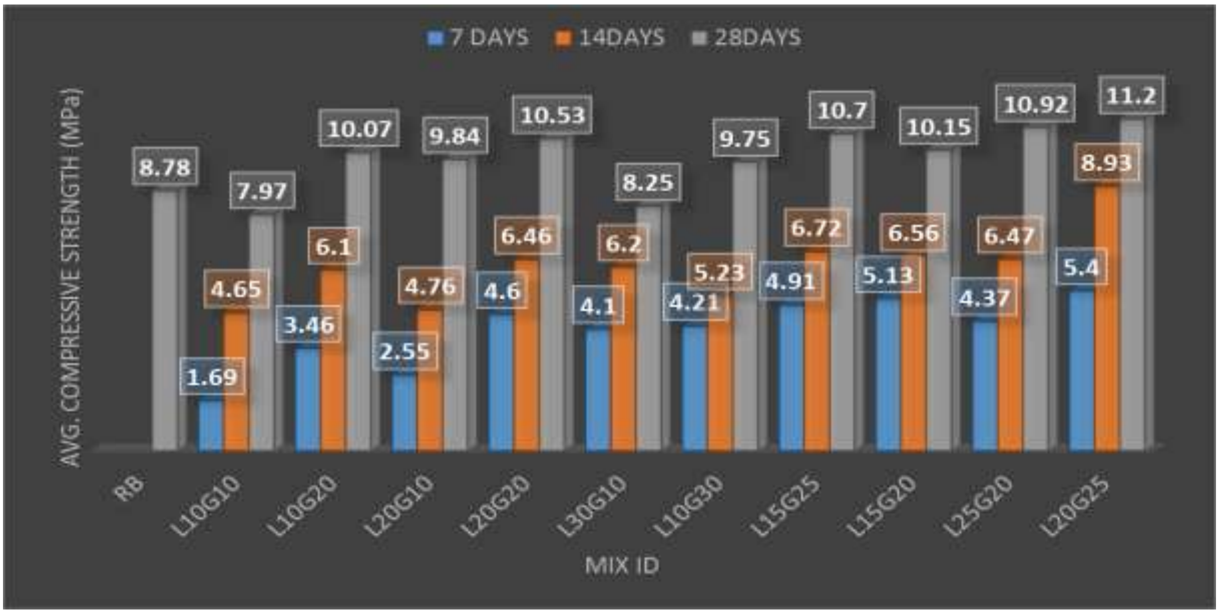


Fig. 6: Compressive strength of mix proportions

From the test results, the mixes with the strength above 10MPa i.e.) class 10 bricks and a lime content below 20% was chosen for further tests. They were L10G20, L15G20, L15G25, L20G20 and L20G25.

8.2 Water Absorption

The results of average water absorption of 3 specimens as shown in table 6.

Table 6: Average Water absorption (%)

Mix ID	1min	10mins	30mins	1hr	1day
RB	9.13	10.57	11.54	11.54	15.87
L10G20	4.53	8.23	11.32	15.64	21.19
L20G20	5.87	8.30	14.58	16.80	19.84
L15G25	3.03	7.07	12.12	16.16	20.61
L15G20	6.01	9.22	11.82	15.63	20.64
L20G25	3.82	8.24	12.05	15.46	19.08

It was seen that around 20% of the total water absorption takes place in the first minute, about 40% in 10 minutes, about 60% in 30 minutes, about 80% in 1 hour. From this, we can infer that the rate of water absorption gradually reduces after the pores are filled with water. Water absorption should be within 20% after 24 hours and higher values in the test were due to the low density of bricks as shown in Fig. 7. But with the present results, we can see that mixes L20G20 & L20G25 were within the limit although the water absorption was higher than the red bricks. This can be reduced by increasing the density of the brick. The dimension of the brick can be maintained despite increasing the amount of materials by applying more pressure during the casting process to compress the brick to the required dimensions.

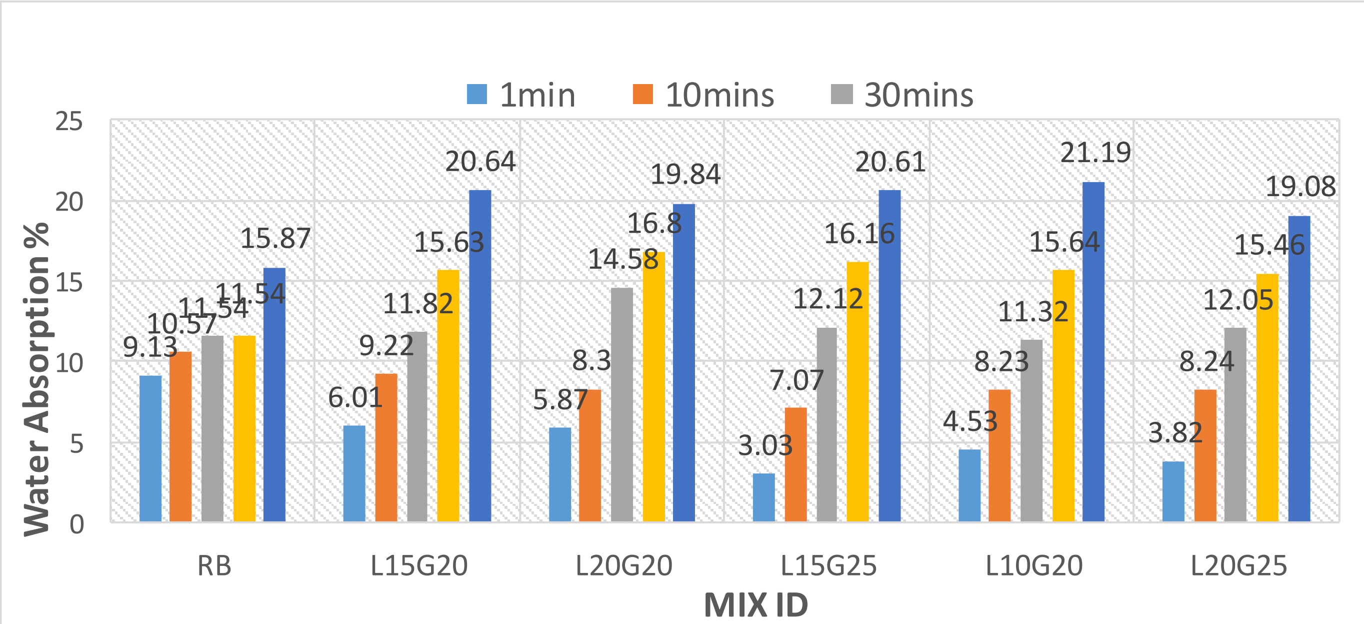


Fig. 7: Average Water Absorption of the mixes

Based on the compressive strength the highest value of 11.2MPa was attained by the mix L20G25. It also satisfied the conditions in water absorption test as it was below 20%. Hence L20G25 containing 55% Fly ash, 25% GGBS & 20% Lime was taken as optimum mix and the test on wall panel was done.

8.3 Test on wall panel and comparison with analytical model

In case of the IB wall panel, the first crack appeared on 32.609 kN and the ultimate load carrying capacity of the wall was 48.91 kN. The homogeneous layers in the IB wall panel lead to effective load transfer which increases the load carrying capacity. The compressive strength of the wall panel was given by the formula (Ultimate Load)/ (Surface area of the plane of loading) which was 2.445 MPa. The first crack and crack pattern of the wall panel is shown in Fig.8. The maximum crack width was 3mm. The maximum displacement was 1.77mm at the L/2 position and 0.99mm at the L/3 position. Comparison of deformation is shown in Tables 7& 8. From these results it was found that the difference in solution between the experimental and analytical investigation work is around the range of 16% to 22%. The variation in displacement between analytical and theoretical models was due to differences in the experimental setup like a slight change in support condition, inefficiencies in load transfer and so on.

(a) Test setup **(b) First crack** **(c)After failure**

Fig. 8: Test on IB wall panel

Table 7: Comparison of analytical & experimental results at L/2

Load (KN)	Displacement L/2(mm)		% of difference in displacement
	Experimental	ANSYS	
4.347	0.41	0.352	16.43
10.87	1.09	0.924	17.84
15.217	1.32	1.107	19.26
21.739	1.47	1.214	21.04

26.087	1.57	1.327	18.28
30.435	1.65	1.372	20.24
34.783	1.71	1.428	19.71
39.13	1.77	1.45	22.06

Table 8: Comparison of analytical & experimental results at L/3

Load (KN)	Displacement L/3(mm)		% of difference in displacement
	Experimental	ANSYS	
4.347	0.22	0.188	16.87
10.87	0.48	0.4096	17.16
15.217	0.55	0.4628	18.84
21.739	0.65	0.54	20.39
26.087	0.72	0.601	19.67
30.435	0.81	0.6659	21.63
34.783	0.87	0.7218	20.53
39.13	0.92	0.7581	21.35

8.4 Rate Analysis of Brickwork Masonry

Rate analysis for 10m^3 of conventional red brickwork masonry:

Volume of brickwork = 10 m^3; Size of conventional red brick = 0.19 x 0.09 x 0.09 m; Thickness of mortar = 10mm (0.01m)

Quantity of Bricks:

No. of bricks = Volume of brickwork/ Volume of 1 brick with mortar

Volume of 1 Brick with mortar = 0.20 × 0.10 × 0.10 = 0.002 m^3 ∴ No. of bricks = 10 /0.002 = 5000 No’s

Quantity of Cement:

Volume of bricks = (0.19 × 0.09 × 0.09) x 5000 = 0.001539 x 5000 = 7.695 m^3

Quantity of mortar = Quantity of brickwork – Volume of bricks = 10 – 7.695 = 2.305 m^3

Add 5% wastage = 2.305 x 5 / 100 = 0.11525 m^3 ∴ Quantity of mortar = 2.305 + 0.11525 = 2.42 m^3

Adopt Mix Ratio – 1:4

Dry volume of mortar = Wet volume x 1.33 = 2.42 m^3 x 1.33 = 3.22 m^3

Quantity of Cement = {(Dry Volume of mortar x Cement ratio) / (Sum of the ratio)} = (3.22 x 1) / (1+4) = 0.644 m^3

Density of Cement = 1440 kg/m^3 ∴ Weight of Cement = 1440 x 0.644 = 927.36 Kg

1 bag of cement contains 50 kg of cement ∴ Number of bags = 927.36 Kg / 50 kg = 18.55 No’s

Quantity of Sand:

Quantity of Sand = Quantity of Cement x 4 ∴ Quantity of Sand = 0.644 m^3 x 4 = 2.576 m^3

Labours required:

For constructing 100 cft (2.83 m^3) first class Brickwork with 1:4 cement mortar in super-structure requires 2.5 Masons, 4.5 Mazdoor, and 0.5 Bhishti per day.

Therefore for constructing 10 m^3 first class Brickwork requires 8.83 Masons, 15.9 Mazdoor, and 1.77 Bhishti.

Rate analysis for 10m^3 of interlocking brickwork masonry:

Volume of brickwork = 10 m^3; Size of conventional red brick = 0.30 x 0.15 x 0.15 m

Quantity of Bricks:

No. of bricks = Volume of brickwork/ Volume of 1 brick

Volume of 1 Brick = 0.30 × 0.15 × 0.15 = 0.00675 m^3 ∴ No. of bricks = 10 /0.00675 = 1482 No’s

Manufacturing cost of Interlocking bricks:

Optimum mix L20G25 i.e., Flyash = 55%, Lime = 20%, GGBS = 25%

Weight of 1 brick = Density x Volume of brick

Weight of 1 brick = 1420 x {(0.3 x 0.15 x 0.15) – (4 x π x 0.0302 /4 x 0.15)} = 8.98kg

∴Weight of materials Fly ash = 4.94kg, Lime = 1.8kg, GGBS = 2.25kg.

Market rate of materials Fly ash = Rs.1.1/kg, Lime = Rs.4/kg, GGBS = Rs.3/kg

Cost of 1 brick = (4.94 x 1.10) + (1.8 x 4) + (2.25 x 3) = Rs.19.38.

Approximately Labour charges = Rs.5/Brick, Machinery charges = Rs.3/Brick.

Manufacturing cost of Interlocking brick = Rs.27.38

Quantity of Steel:

Length of wall = Quantity of brick work / (Width of wall x Height of wall) Length of wall = 10 / (0.15 x 1) = 66.67m

Wkt 6m length of 8mm dia bars required for 0.9m length of wall.

Length of steel = 66.67 x 6 / 0.9 = 444.47m

Quantity of steel = D^2 x L / 162 = 82 x 444.47 / 162 = 175.59 kg

Labours required:
For constructing 200 cft (5.66 m^3) Interlocking Brickwork in super-structure requires
2.5 Masons, 4.5 Mazdoor, 0.5 Bhishti per day.

Therefore for constructing 10 m^3 first class Brickwork requires 4.42 Masons, 7.95 Mazdoor and 0.885 Bhishti.

Table 9: Comparison of cost analysis between red brick and interlocking brickwork

S.No	Description	Conventional Red Brick				Interlocking Brick			
		Quantity	Unit	Rate	Cost	Quantity	Unit	Rate	Cost
		Brickwork with first class bricks in super-structure in cement mortar 1:4				Brickwork with Interlocking brick in super-structure			
A	**Labour charges**								
1	Mason	8.83	Nos.	900	7947	4.42	Nos.	900	3978
2	Mazdoor	15.90	Nos.	700	11130	7.95	Nos.	700	5565
3	Bhishti	1.77	Nos.	450	797	0.885	Nos.	450	399
B	**Material**								
1	Brick	5000	Nos.	11	55000	1482	Nos.	27.38	40578
	Wastage	5%			2750	5%			2029
2	Cement	18.55	Bag	400	7420				
3	Sand	2.576	m^3	1362	3509				
4	Steel					175.59	kg	55	9658
C	**Scaffolding 1% extra**	1%			660	1%			503
D	**Transportation cost 1% extra**	1%			660	1%			503
E	**Other charges 2% extra**	2%			1320	2%			1006
F	**Add for water charges @1%**	1%			660	1%			503
		Cost of 10 cu.m.			**91853**	**Cost of 10 cu.m.**			**64722**
		Cost of 1 cu.m.			**9185**	**Cost of 1 cu.m.**			**6472**
		Round off cu.m.			**9200**	**Round off cu.m.**			**6500**

Thus based on rate analysis, it was observed that the interlocking brickwork was around 40% cheaper than conventional red brickwork.

9. CONCLUSIONS

- Based on compressive strength the highest value was 11.2 MPa for the mix L20G25 which was 30% higher than red brick.
- The compressive strength of the IB increased with an increase in lime and GGBS content.
- Water absorption was also within the required limits of 20%.
- The mix L20G25 containing 55% Fly ash, 25% GGBS & 20% Lime was the optimum mix.
- The Range of variation of deformation between the experimental and analytical investigation work was around the range of 16% to 22%.
- Based on rate analysis the interlocking brick masonry was around 40% cheaper than conventional red brick masonry.

Hence it can be concluded that the Interlocking Brick proposed as low-cost, eco-friendly, sustainable and durable alternative to the conventional red bricks.

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