Comparative Study On Load Resistance of Eco-Friendly Interlocking Blocks For Sustainable Construction

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Research Article

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Abstract

The rapid growth of contemporary construction industry has driven engineers to explore new construction techniques for sustainable development. Interlocking block wall construction reduces time, labour and enhances construction efficiency compared to conventional masonry wall construction. The interlocking pattern has been applied to the top and bottom surface of block to withstand gravity and lateral loads whereas current interlocking blocks only serve the purpose of easy alignment. In this study, eco-friendly blocks have been developed with industrial waste such as fly ash, quarry dust and geopolymer as binder. Tests to evaluate the compressive strength, water absorption and efflorescence have been carried out on both traditional and geopolymer interlocking blocks. Later, on two blocks joint, in-plane vertical load has been applied and the same model is generated to validate the failure. Using numerical modelling, horizontal and vertical load resistance of interlocking block wall and traditional brick wall was compared. The experimental results show that, relative to traditional clay brick, the compressive strength of the geopolymer interlocking block was high but the absorption of water was low. The vertical load resistance is identical but horizontal load resistance was high in interlocking block wall. The interlocking geopolymer block was the best approach for environmental sustainability.

Introduction

Bricks are one of the fundamental components and play a significant role in the field of construction. Bricks have been used for building infinite structures over many thousands of years (Shu et al. 2017). Clay brick was the most common type of bricks and it was defined as solid masonry unit of clay, shale or natural earthy materials subjected to heat treatment or high temperature firing procedure (Gencel et al. 2020). But these days, emulating the high temperature into environment has raised concerns due to emissions of greenhouse gases and high energy consumption (Muñoz et al. 2020). Moreover, the topsoil needs to be cleared to procure clay for brick production, thereby damaging natural terrain such as forests and subsequently depleting natural resources (Muheise-Araalia and Pavia 2021). Concrete was also a popular alternative for brick manufacturing and has been widely used in the construction of buildings (Dawood and Mahmood 2021). The concrete masonry brick consists of cement, water, aggregates. As an example, one tonne manufacturing of cement consumes 1.7 tons of raw materials and emits 0.8 tons of CO_2 into atmosphere (“Investigating the Economic and Environmental Effect of Integrating Sugarcane Bagasse (SCB) Fibers in Cement Bricks” 2021). To ensure environmental safety, the process of recycling and recovering industrial waste has become vital as these arises environment issues.

Recycling the industrial waste into useful construction materials was considered as an realistic option for eliminating certain pollution-related environmental concerns (Torres-Carrasco and Puertas 2015). Many experiments have been performed to reduce the consumption of cement in brick industry and the geo-polymerization being one of them (Mohammed et al. 2018). Geopolymers are alkaline aluminosilicate binders which can be used as a substitute for construction material (cement). Studies demonstrated to achieve compressive strength of mortar up to 50 MPa after 7 days of curing at 65°C by optimizing the concentration and type of the alkaline activator (Reig et al. 2013). Fly ash was proven to be one of the strongest activated materials, and it can be applied to the geopolymer composition to enhance compressive strength and other mechanical properties. (Öz et al. 2021).

In traditional masonry construction, bricks are connected together by a layer of mortar or cementitious material (Bui et al. 2017). Since, the mortar has a low strength, failure in traditional masonry structures often begins either at the brick to mortar interface or in the mortar layer (Chewe Ngapeya, Waldmann, and Scholzen 2018). Traditional masonry structures have inadequate structural performance, especially when subjected to extreme loading conditions, for instance earthquakes, damage, and blast loads (Uzoegbo 2019). Meanwhile, many old and historical structures built with mortar and bricks exhibits considerable loss of structural performances because of chemical, physical, and mechanical degradation of the mortar layer (Thanoon et al. 2004). Furthermore, the competence and experience of laying of bricks have a significant impact on the construction proficiency and structure quality (Lee, Shek, and Mohammad 2017). Owing to the overwhelming need for masonry to compete with other structural materials such as steel and concrete, major developments have arisen in masonry design over the past few decades (Jeba Jeslin and Padmanaban 2020). To enhance construction efficiency and quality, several types of interlocking bricks have been developed over the past few years. The interlocking patterns can be provided in either vertical, horizontal or both directions.

Researchers investigated the mechanical properties of bricks having various interconnections. Some researchers discovered that interlocking bricks have a poor axial loading ability due to the comparatively limited contact area caused by joint imperfection. (Fundi, Kaluli, and Kinuthia 2018). Due to lateral expansion and stress concentration, a crack and failure of a stacked pier with interlocking bricks began from the bond of the connection (Shi et al. 2021). Studies on the flexural bending capacity of interlocking bricks were rare because dry stacked (mortarless) interlocking bricks cannot offer bending resistance without axial pre-compression (Al-Fakih, Mohammed, et al. 2020). Regardless of these advantages, the geometric imperfection of the blocks caused by contact surface imperfection has a major effect on the mechanical performance of dry stacking masonry structures (Al-Fakih, Wahab, et al. 2020). Scientists discovered that the interaction behaviour of dry-stacked masonry at block to block interface was affected by surface roughness and it has huge impact on the joint behaviour of two rough blocks moving over each other. (Casapulla, Mousavian, and Zarghani 2019) Shaking tables experiments on a full-scale unreinforced brick masonry vault (arch roof) revealed that the interfaces between mortar and brick were the weakest section of the vault, where cracks opened and closed. (Giamundo et al. 2016)

The aim of this research was to develop eco-friendly interlocking blocks (IB) and to propose a technique for constructing masonry units without consuming mortar (dry stacked wall). To produce blocks that not only reduce environmental damage and encourage sustainability, but also to enhance their properties. The elimination of mortar reduces the cost of materials, time, skilled labour and improves construction efficiency and sustainability. The industrial waste (quarry dust) was collected from aggregate industry and used as a filler for geopolymer matrix. Five different proportions of geopolymer mix having fly ash and quarry dust were developed. The mechanical properties of eco-friendly IB and a comparative analysis between traditional brick wall (TBW) and interlocking block wall (IBW) using numerical simulation was presented.

Materials

3.1 Alkali activated solutions:

In this study, the alkaline activator was formed by blending different proportions of NaOH and Na_2SiO_3. The NaOH pallet was dissolved in distilled water to achieve the required NaOH solution concentrations. Sodium silicate is composed of 27% SiO_2, 8% Na_2O, and 65% H_2O (by mass). NaOH with a purity of 98% was supplied in solid capsules forms.

3.2 Fly Ash

Fly ash is a by-product of the coal combustion in thermal power generation and consists mainly of SiO_2, Al_2O_3, Fe_2O_3, CaO, and some impurities. In this study, Class F fly ash was used, and it contains low content of CaO and exhibit pozzolanic properties.

3.3 Quarry Dust

Quarry dust, a by-product of the stone crushing process produced during quarrying operations. This has recently gained popularity as a concreting aggregate in several applications including cement mortar, building blocks, and concrete.

3.4 Mix Proportion

Fly ash and quarry dust were used as cementitious and filler materials to evaluate the properties of Geo-polymer interlocking blocks. The amount of fly ash was gradually reduced, while the amount of quarry dust was increased in five different proportions, the sodium hydroxide and sodium silicate remained constant. The molarity of NaOH and Na_2SiO_3 maintained at 12M as well as ratio at 2.5. The mix proportions are tabulated in [Table 1]. The dry ingredients were mixed in a pan mixer till appearance of homogeneity in mixture, then solutions were added to dry ingredients and mixed until uniform blending was achieved. The specimens were placed into mould and vibrated in a table vibrator before being left to cure for 24 hours in the ambient environment. Specimens were exposed to ambient temperature till curing age after removing from mould.

Table 1
Mix Proportion of Blocks

Mix ID	Fly Ash (Kg/m^3)	Quarry Dust (Kg/m^3)	Sodium Silicate (Kg/m^3)	Sodium Hydroxide (Kg/m^3)
FDQ01	450	1316	200	80
FDQ02	420	1352	200	80
FDQ03	378	1404	200	80
FDQ04	336	1456	200	80
FDQ05	294	1508	200	80

Interlocking Block

Bricks are primary elements used for construction of various structures from 1st century AD (Radivojević and Kurtović-Folić 2006). Geometrical modifications have been made over the years and several unique bricks forms were developed. The major drawbacks of these TB were that they require lot of material in preparation, require skilled labour for alignment over each other and entails lot of time for construction (Chunduri and Khed 2021). The eco-friendly IB was developed for construction of building wall rapidly. The interlocking building block includes two square projection and depression parallelly along the length of block on bottom and top surface. The projections and depressions were designed in a predefined manner that no two projections or depressions meet side by side [Fig. 1]. A plurality of these building blocks with corresponding projections and depressions were attached to each other to form wall.

Experimental Program

5.1 Compressive Strength

The depressions and openings [Fig. 2] in the block were filled with cement mortar with cement and sand ratio of 1:1 [Fig. 6] and cured for 7 days. The unevenness on the block faces can be eliminated by grinding, leading to two flat and identical faces, and then immerse in water at room temperature for 24 hours. Place the specimen in the CTM machine facing the mortar filled face upwards and check whether the force was applied evenly or not. If not, use a wood sheet to ensure consistent load distribution on the whole block. Apply load axially at a uniform rate of 14 N/mm^2 per minute (IS3495:1992 Part 1 1992). The load was applied till the failure of specimen and the ultimate load should be noted. Brick compressive strength was calculated by dividing the load at failure by the average region of the bed faces.

5.2 Water Absorption

Dry the specimen (IS3495:1992 Part 2 1992) at 105 to 115°C in a ventilated oven until it reaches a relatively steady density. Before weighing the specimen, allow it to cool to room temperature. The use of warm-to-the-touch specimens is prohibited. Immerse the completely dried specimen in clean water at room temperature for 24 hours. Remove the specimen and use a wet rag to clean away any signs of water before weighing it. Three minutes later, measure the weight of specimen after it has been removed from the water. The percentage increase in mass after immersion is identified as water absorption.

5.3 In - Plane Vertical Load

To evaluate the joint strength of conventional technique and interlocking mechanism, an in plane vertical load test was adopted. In this experiment, a vertical load was applied perpendicular to the blocks' joint. On compression testing machine, two timber supports have been mounted [Fig. 3] on lower disk to apply load at the joint. Steel circular rod was attached to the upper disk to concentrate the load at the joint. The blocks joint was facing towards the loading point i.e., means the blocks are rotated 90^o about its bed face. The load has been applied till the failure and the ultimate load is recorded.

5.4 Numerical Modelling of Tradition and Interlocking Block Wall:

The model was created in ANSYS using the APDL module [Fig. 5] in window graphic interface (GUI). Solid185 was used to generate 3D model of both TBW and IBW. This element has 8 nodes, and it has 3 degrees of freedom at each node. This element [Fig. 4] has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. In this study, a homogeneous structural solid was used. The young's modulus and poisons ratio were specified in material properties. The volume was created with block function and the interlocking pattern (projections) was inserted by Booleans. The solid 65 element was used for mortar between traditional blocks. The element size is considered as 5 mm for meshing the volumes. The wall's boundary conditions have been applied, and the load has been assigned in the z direction. The displacement was compared between TBW and IBW.

Results And Discussion

6.1 Compressive Strength of Eco - friendly Interlocking Block

Bricks were mostly used to construct walls, floors, cornices, and arches. Compressive load governs in all above-mentioned cases. Due to this, compressive strength of brick was considered as an essential property. The sample was prepared as [Fig. 6] before applying uniaxial compression on the block. The compressive strength test is performed at two different curing ages as mentioned in [Fig. 7]. The compressive strength of eco-friendly IB is affected by the fly ash binder ratio. The adhesion between particles plays vital role in compressive strength of specimen. For all mix proportions in this study, a constant quantity of solutions was used in order to evaluate the effect of fly ash to quarry dust ratio. The compressive strength was reduced with decrease in fly ash content. Blocks exposed to 28 days ambient curing has attained the minimum strength requirement in all cases. The compressive strength of blocks produced with FQD05 was reduced by 35 % compared to FQD01. The traditional burnt clay brick (first class brick) has 10 MPa strength. Blocks with FDQ01 matrix has achieved 34% more compressive strength compared to traditional burnt clay brick. While testing interlocking blocks, the micro cracks were identified at the depressions filled with mortar and the propagation of crack was rapid and lead to failure of block at square projections. The compressive strength of geopolymer IB was directly proportional to fly ash quarry dust ratio. The adhesion between the geopolymer gel and quarry dust portrays crucial part in compressive strength of block. Since, Fly ash was a fine powdered material, this results in good packing density eventually higher fly ash content increases the compressive strength of block.

6.2 Water Absorption of Eco - friendly Interlocking Block

The water absorption ability of a hardened matrix can be influenced by the water absorption nature of an individual material. The water absorption results of geopolymer IB [Fig. 8] vary from 6.74 % to 7.63 %. FQD01 has 7.63 % and FQD 05 has 6.74%. Water absorption of traditional burnt clay brick should not be more than 20%. The eco-friendly interlocking blocks were absorbing less compared to clay bricks. Decrease in water absorption was identified, the blocks having high fly ash content has more water absorption compared to low fly ash content blocks. Since, fly ash is a water absorbent material, blocks with a higher fly ash content absorb more water. Generally, the water absorption of matrix is inversely proportional to compressive strength but in this study, the blocks having high fly ash content possess high strength but comprises of high-water absorption.

6.3 In-Plane Vertical Load Test

The Load has been applied on joint of two blocks by rotating the top face of block [Fig. 9]. Load was concentrated monotonically to estimate the joint strength. Tang (Tang, Ali, and Chouw 2014) has studied about the in-plane shear and out-plane shear test on interlocking blocks and the experiment procedure was adopted from that study. The dry staked interlocking blocks were used for this study and subjected to loading at interlocking pattern. The TB are united with 12 mm thick mortar as an adhesive between blocks and the load is applied on the mortar joint in TB case. While in IB case the load was applied without providing adhesion. The joint load resistance [Table 2] of IB was 76% more compared to TB. The failure pattern of TB joint was brittle and sudden whereas IB joint has gone through some displacement as shown in [Fig. 9] and then the cracks has been originated from projections and the cracks propagated till the other end of square projection causing de-attachment of square projection from the block. The IB has potential to withstand additional horizontal load compared to TBW apart from vertical load.

Table 2
Load Values for in-plane vertical load test

Type of Block	Load (KN)
Interlocking Block	0.8
Traditional Brick	3.4

6.4 Comparison of Horizontal Load Resistance between TBW and IBW:

The load has been provided in z direction (horizontal direction) [Fig. 10] on two separate walls to calculate the displacement. Solid 185 element having 8 nodes has been opted for this study and each TB and IB was modelled separately and attached to one other because to create construction environment. The load was employed like pressure on the line at the tip of the wall throughout length of the wall (x-direction). The displacement values [Table 3] has been noted and compared between these walls. The load resistance of IBW was 57% more compared to TBW. Generally, the area between brick substrate and mortar was weakest point in the TB masonry, this leads to failure of masonry wall. The dry stacked IBW has no such drawbacks as it depends on individual block strength. The TB was consuming mortar as an adhesion between bricks and possess less horizontal strength. Even though the IB was not using any adhesion between them, but it has great resistance to horizontal load because of interlocking mechanism.

Table 3
Displacement Values of Walls

Type of Block	Displacement (mm)
Interlocking Block Wall	12.251
Traditional Brick Wall	28.806

Conclusion

This research focuses on potential use of interlocking mechanism and geopolymer composition for efficient construction of masonry structures. This paper presents experimental study on geopolymer interlocking blocks and numerical modelling of IBW and TBW for lateral load resistance comparison. The accomplished results in this study led to following comments and conclusions.

1. The amount of fly ash and duration of curing has substantial effect on compressive strength of geopolymer interlocking blocks, higher amount and more duration has exhibited great results.
2. The water absorption of geopolymer quarry dust matrix was considerably low and the increase in water absorption is identified in blocks having high fly ash content.
3. The effective way of using natural resources was essential to get rid of environmental disasters. The concept of using industrial waste as matrix for blocks can reduce environment issues and consumption of natural resources.
4. The interlocking mechanism presented in this study has potential to with stand additional horizontal and lateral loads compared to TBW without consuming any type of adhesion between individual blocks.

Declarations

Authors Contribution: Venkata Veera Himakar Chunduri - Conceptualization, Methodology, Resources, Analysis, Writing - Original Draft preparation.

Veerendrakumar C. Khed - Supervision, Writing - Review & Editing.

Availability of Data & Materials: All data generated or analysed during this study are included in this published article.

Conflict of Interest: We have no conflict of interest to disclose.

Ethical Approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: The manuscript has been read and approved for submission by authors.

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Figures

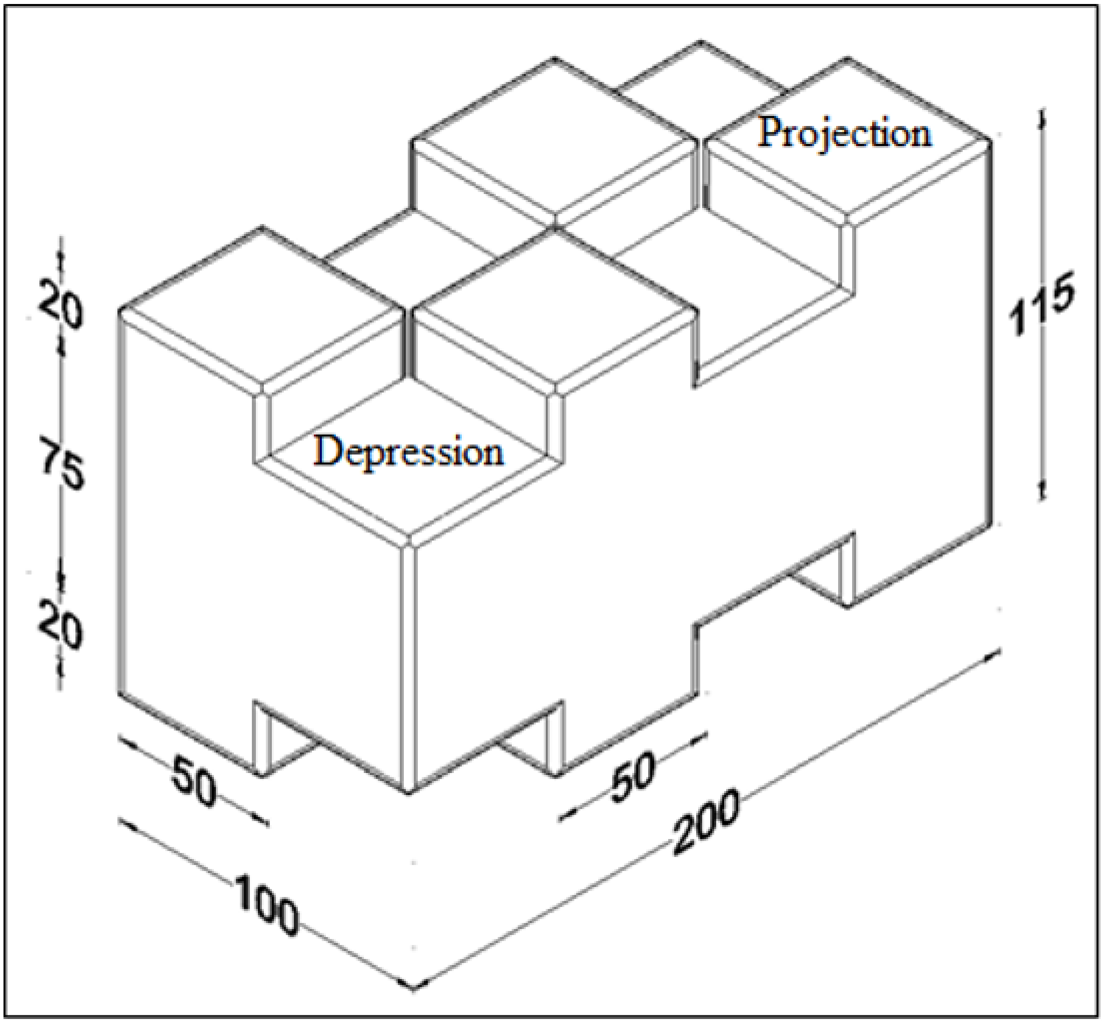

Figure 1

Dimensions of Interlocking Block

Figure 2

Fabrication of Interlocking Block

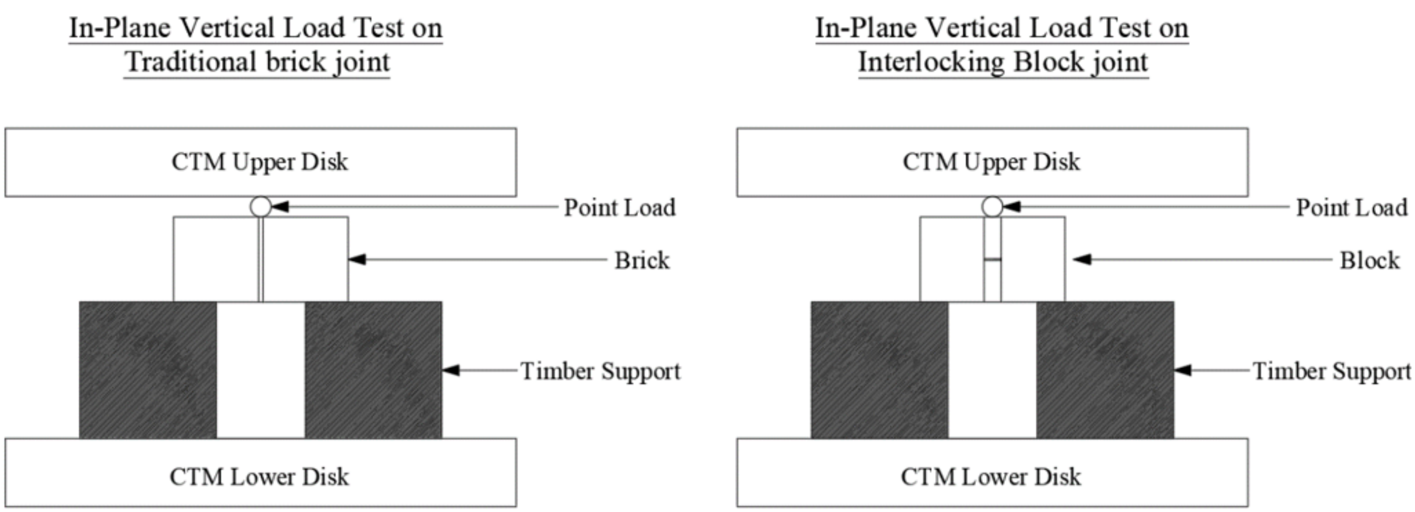

Figure 3

Schematic diagram of In-plane vertical load test

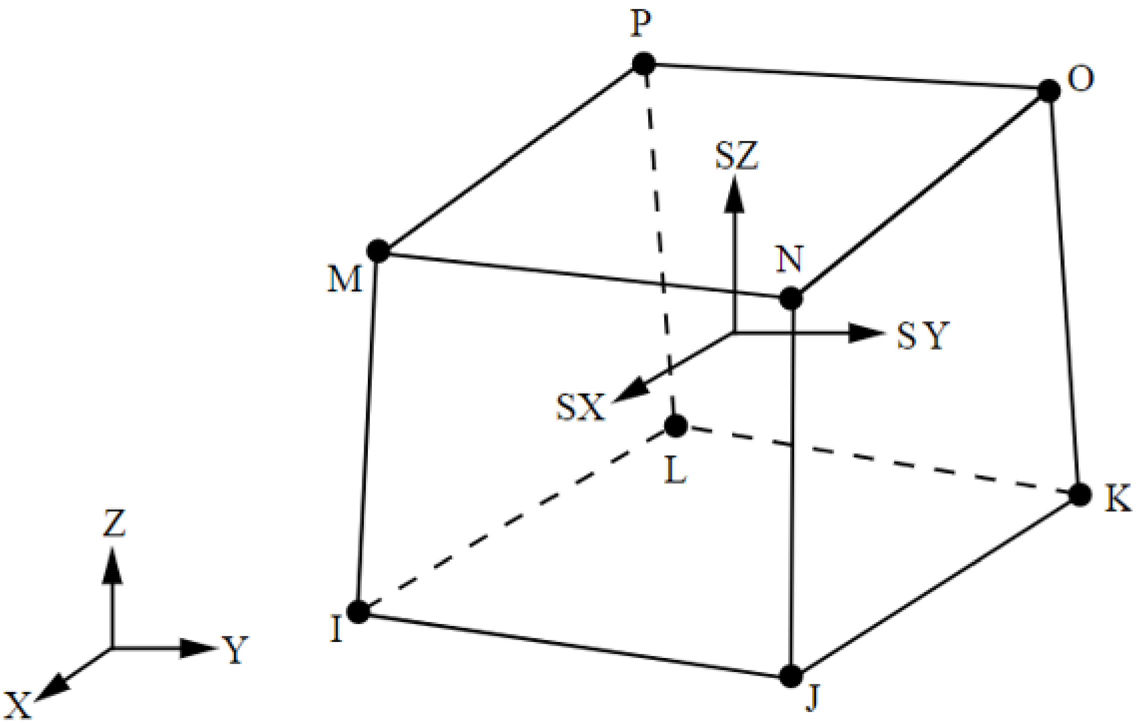

Figure 4

Stress directions of Solid 185 shown for global directions.

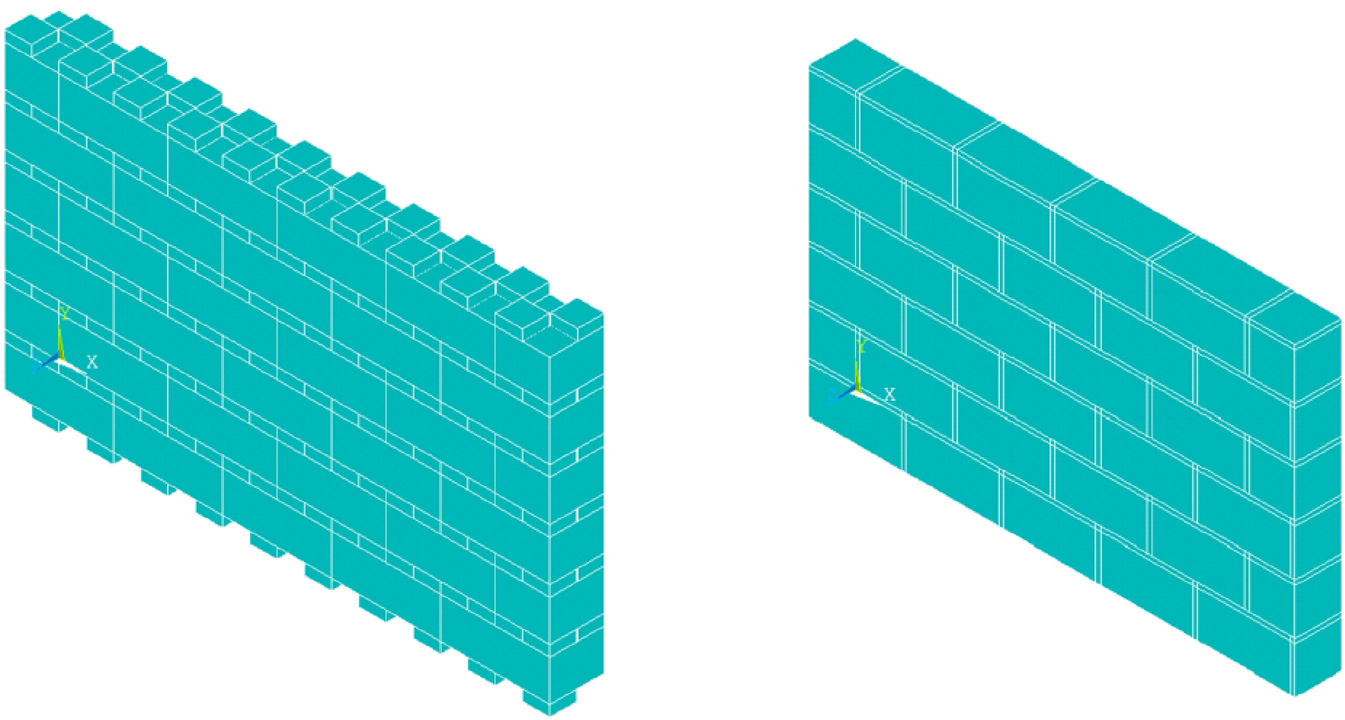

Figure 5

Numerical Modelling of TBW and IBW.

Figure 6

Preparation of specimen before compression test.

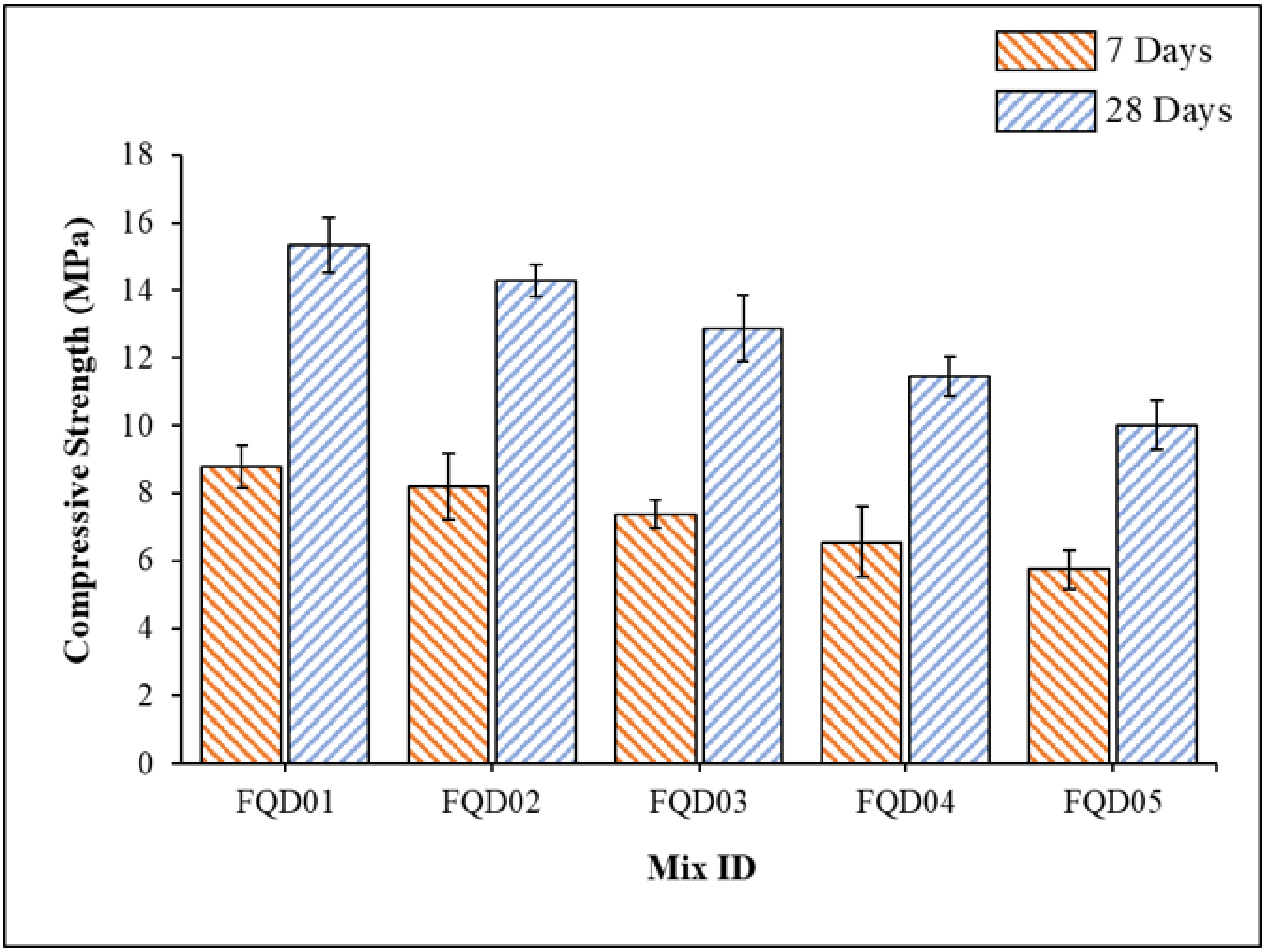

Figure 7

Results for compressive Strength of Interlocking Blocks

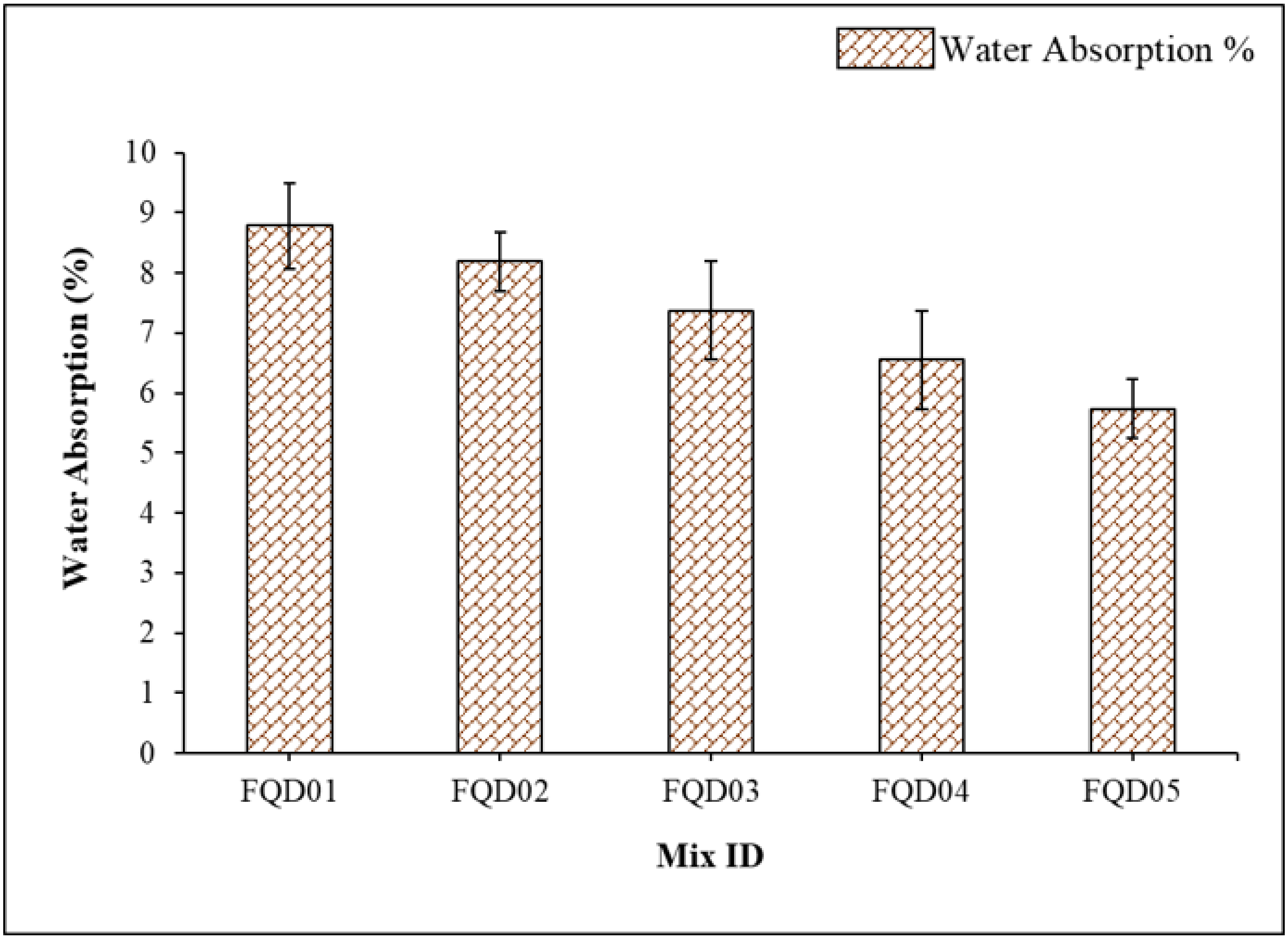

Figure 8

Results for water Absorption of Eco-friendly Interlocking Blocks

Figure 9

In-plane Vertical load Test

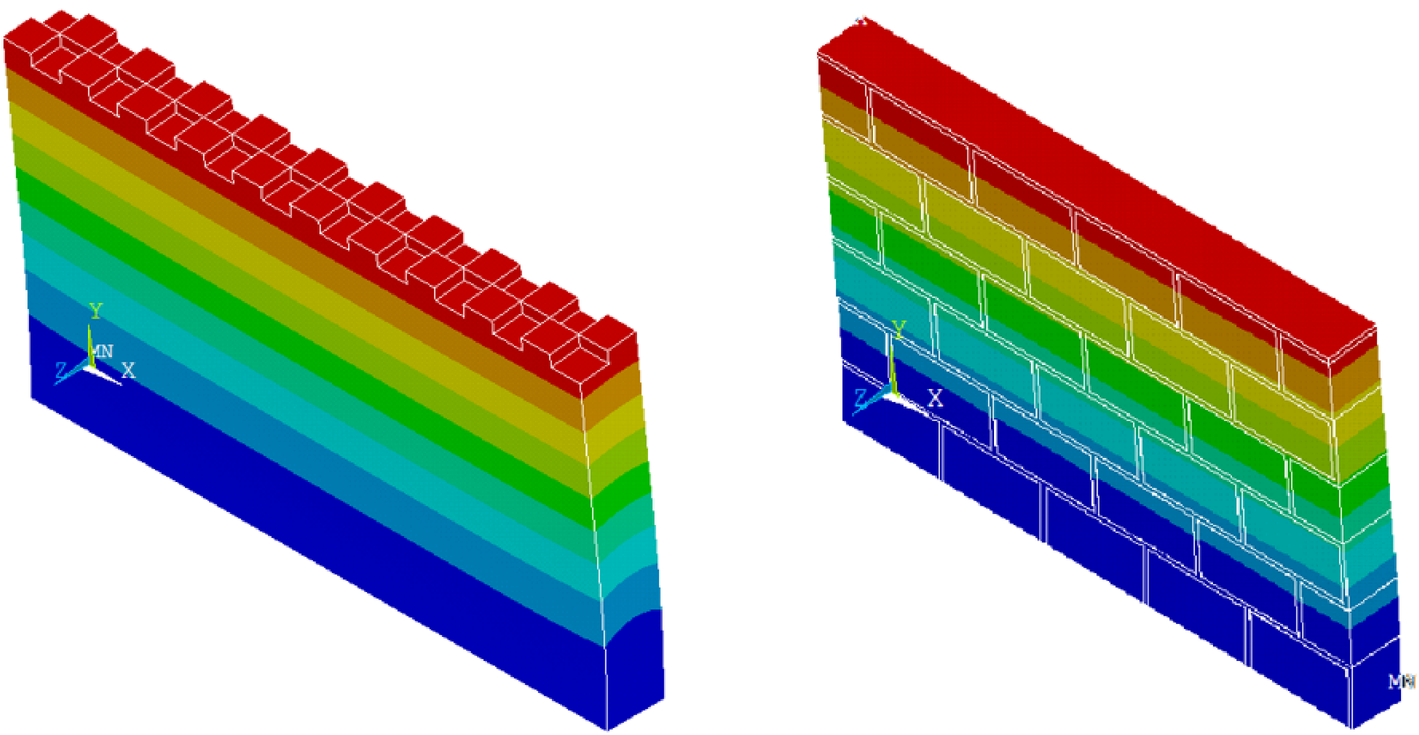

Figure 10

Horizontal load resistance of interlocking block and traditional brick wall