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Mud-concrete block (MCB): mix design & durability characteristics

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ABSTRACT

Mud-Concrete is a novel concept which employs a form of 'Concrete' produced using soil, cement and water. The initial concept of developing Mud-Concrete was to incorporate both the strength and durability of concrete into mud-based constructions to introduce a low-cost, load-bearing wall system with easy construction techniques which ensured indoor comfort while minimizing the impact on the environment. Here the fraction of soil is fulfilling the role of aggregate in the material and low quantities of cement will act as a stabilizer. Precisely the usable gravel range and the gravel percentage governs the compressive strength of the material. The considerable high-water amount is used for the hydration of cement and keep the flow of this material. This excessive water amount is enhancing its self-compacting quality, which is capable of self-consolidation, having the ability of passing, filling and being stable without the need of any external forces. Experimental test findings determined the mix proportions of Mud-Concrete block as 4% cement (minimum), fine ≤ 10% (≤ sieve size 0.425 mm), sand 55–60% (sieve size 0.425 mm ≤ sand ≤ 4.75 mm), gravel 30–35% (sieve size 4.75 mm ≤ gravel ≤ 20 mm) and water 18% to 20% from the dry mix. Findings further confirmed that the durability of the Mud-Concrete block satisfied the required durability standards recorded in SLS 1382.

1. Introduction

Materials are considered as the most imperative component of a building construction. Presently, an increasing demand for materials in the construction industry has resulted in the significant consumption of natural resources. This has gradually led to an increase in prices of construction materials as well as to a scarcity of resources [1]. Furthermore, 40% of today's global energy is consumed by the building construction industry which also contributes 1/3 of the total greenhouse gas emissions, both in developed and developing countries [2]. This situation has created a need for sustainable materials with low energy consumption and environmental impact during both the manufacturing process and at the operational level. Therefore, identifying alternative building materials with simple construction technologies are required to promote sustainable & affordable construction that satisfies the comfort standards required today. 'Soil' can be considered as one such sustainable raw material which has been used extensively for building construction since ancient times [3]. Adobe construction dates back to the walls of Jericho which were built around 8300 B.C and earth is the most conspicuous building material in the civilisations of Mesopotamia dated 6000 years ago [4,5]. Earth has been used in the construction of shelters for thousands of years and approximately 30% of the world's present population still lives in earthen structures and is extensively used for wall construction around the world, particularly in developing countries [6,7]. Soil construction offers a number of environmental benefits, including lower embodied energy levels, high thermal mass and increased use of locally sourced materials [8]. However, with the development of newer building materials, earthen building systems have been largely abandoned in parts of the world where they were once commonly used [4]. Considerable research has been undertaken in

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modern times to adapt earth as a sustainable construction material. This has led to the development of technology using earth in the form of rammed earth and unfired bricks popularly known as Compressed Stabilized Earth Blocks (CSEBs) [9]. The main advantage of manufacturing unfired bricks is that it requires lesser energy than fired bricks, and resultantly releases 80% less carbon dioxide into the atmosphere [10,11]. It has been attempted extensively for more than 6 decades to improve unfired stabilized bricks into a reliable substitute for the more expensive fired bricks and concrete blocks [12,5].

Constituents of earthen building systems include a binder soil, typically clay, clay-silt mixture or loam and inorganic or organic tempering materials or both. Sand and gravel are the most commonly used inorganic tempers while straw, hair, and chaff are the commonly used organic tempers. Soil may be stabilised, using materials such as cement, asphalt emulsion, calcined gypsum or cactus juice, or maybe unstabilized. Adobe bricks may be held together by a variety of mortars. Systems may be finished with plaster or pigments, or both, or left unfinished [12].These mixtures may be naturally occurring local soils or engineered by mixing different soils [4]. According to the literature, laterite soils and clayey soils are favourable for cement stabilised soil blocks [13]. Literary sources also state that maintaining a fine content below 20% in rammed earth wall construction by using laterite soils with sandy, hard laterite or clayey compositions would result in higher wall strength [4,14]. Furthermore, proper grading of the soil mix, proper compaction and proper stabilisation using admixtures would ensure increased density, reduced water absorption, and increased frost resistance thereby increasing the wet compressive strength of masonry blocks [9].

Earthen building systems have not been engineered historically. The first written standards for adobe were developed in the United States in the 1930s and were based on common construction practices. It was is only during the last 20 years that architects and engineers have attempted to engineer adobe and rammed earth for conventional use in compliance with contemporary building codes [4]. Even though mud-based construction was very popular in ancient times, it is not as publicly accepted in the industry at present due to several reasons. The primary reason stems from concerns relating to strength and durability. Social constructs of perceiving soil based building techniques as a low-cost solution for the housing needs of the poor has also resulted in creating a prejudice against earthen construction.

Therefore, the aim of this study is to develop the concept of Mud-Concrete technology with the required strength and durability standards and to combine traditional techniques with modern technologies to provide a highly sustainable material for the future of construction. Thus, the primary objectives are adopted to find the mix design and the durability of the Mud-Concrete blocks.

2. Materials and methods

2.1. Concept of developing mud-Concrete technology

Concrete is a composite construction material made out of cement, sand, coarse aggregate and water [15]. The coarse aggregate in the composition governs the strength, cement acts as the binder while sand (fine aggregate) reduces the porosity and water acts as the reactor for cement. In Mud-Concrete technology, the sand and coarse aggregate constituents of concrete are replaced by fine and coarse aggregates of soil (Fig. 1). The intended functions of sand and coarse aggregate are obtained by varying the particle sizes of soil. In this experiment, soil has been classified as follows [16]; (Table 1).

The main objective of the Mud-Concrete mixture was to develop a self-compacting mix which would be able to consolidate under its own weight. This self-compacting mix would not require any mechanical vibration or compaction after pouring and would follow the shape and surface texture of the mould/formwork once set [17,18]. To conceive the mud-concrete mixture as a self-compacting mix, it was essential to manage its fluidity while retaining its strength and durability properties. Thus, water became a key constituent of the mix. The initial task was to determine the proportion of water required to achieve the self-compacting phenomenon in Mud-Concrete. To prepare the self-compacting specimens, the designed amount of water was firstly mixed with the sample, consisting of dry soil, gravel, sand and cement to obtain fluid mixtures. After 10 min of mixing in a concrete mixer machine, the composition started to show self-compacting properties such as continuous flow, viscosity and filling ability. In this research process, the next important question is raised: how to test the workability of this soil mix? There is no standard method written to follow the self-compacted mix developed through soil based material in the literature. Due to the cohesiveness between the clay and the gravel particle in the mix, it is difficult to measure the direct flow of Mud-Concrete like the methods such as slump flow testing to measure the workability of fresh concrete. Therefore, we followed alternative simple technique to identify and standardise the self-compacting consistency of the Mud-Concrete mix.

As the first attempt, the research was designed to check the slump height and the slump diameter of the Mud-Concrete mix with

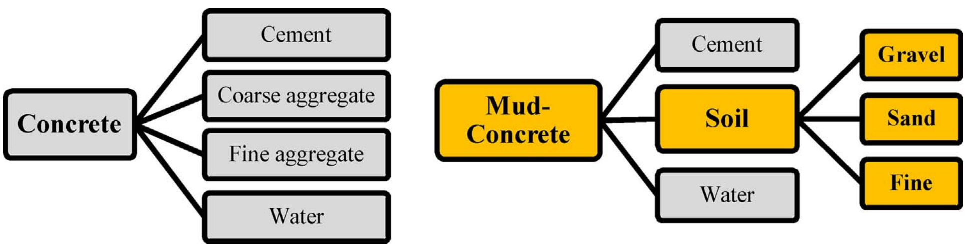

Fig. 1. Similarities of Concrete & Mud-Concrete.

Table 1
Soil classification in MCB technology.

Particle type	Sieve sizes
Gravel	Particle passes from 19mm (3/4") and retained in 4.75mm (No.4) sieve
Sand	Particle passes from 4.75 mm (No.4) and retained in 0.425 mm (No.40)
Fine (Sandy fine, silt and clay)	Particle passes from 0.425 mm (No.40)

Table 2
Added water% to achieve the workability of Mud-Concrete.

Number of blows	25		
Added water amount (ml)	Water from the dry mix (%)	Slump diameter (mm)	Slump height (mm)
2000	15%	388	60
2500	16%	423	90
3000	18%	462	130
3500	**20%**	**510**	**173**
4000	23%	569	241
4500	26%	610	292

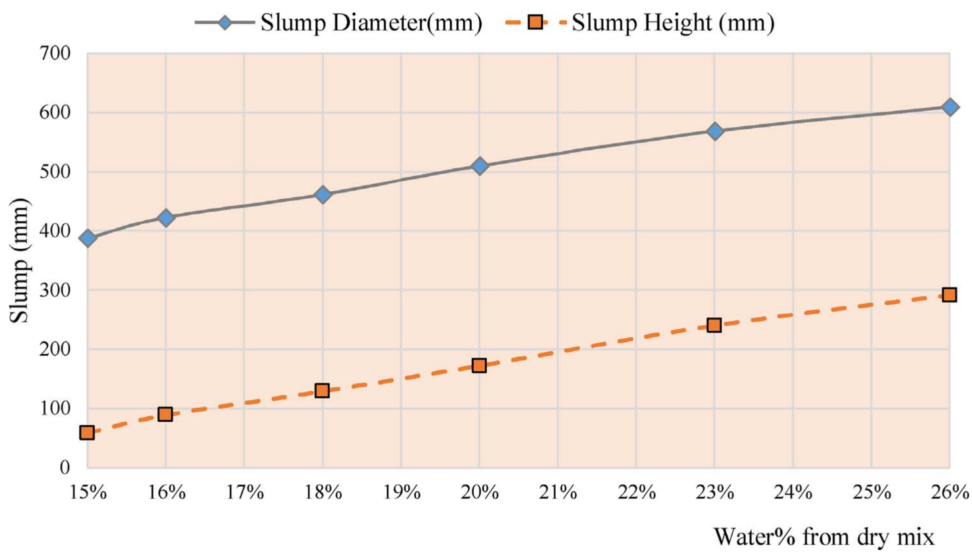

Fig. 2. Slump test results with different moisture contents of Mud-Concrete mix.

different moisture contents while giving a constant number of blows (25 blows). According to the results, it shows approx. 20% water from the dry mix gives the workable mix of Mud-Concrete (Table 2 & Fig. 2).

This method is used to check the workability and the self-compacting consistency of all the Mud-Concrete samples used in casting the test blocks. Here the slump flow is measured after giving 25 blows using the flow table. If the mix achieved the workability it flows up to an approx. 500 mm diameter circle on the flow table (Figs. 3 and 5).

Soon afterwards the mixture was prepared it was poured into cast iron moulds as shown above. No compaction energy or vibration was needed to maintain the consistency of the Mud-Concrete mix (Fig. 4).

The intention was to remove labour-intensive construction methods and control the cost, quality and save the time during construction. Consequently, few main approaches were considered through the process of developing the Mix-design of Mud-Concrete (Fig. 6).

The identified process (Fig. 6) was used to implement the testing methodology of MCB. The compressive strength of a block has become the basic and universally accepted unit of measurement for specifying the quality of masonry units as it is an indirect measure of the durability of the blocks. Therefore, the methodology to determine the best mix of a Mud-Concrete Block was based on achieving the standard compressive strength by changing the variables as stated in the research process above.

According to the literature, compressed stabilised earth brick (CSEB) is regarded as the most sustainable load-bearing masonry unit to be developed from soil when compared to adobe and normal fired brick [19–21]. Furthermore, the specifications for

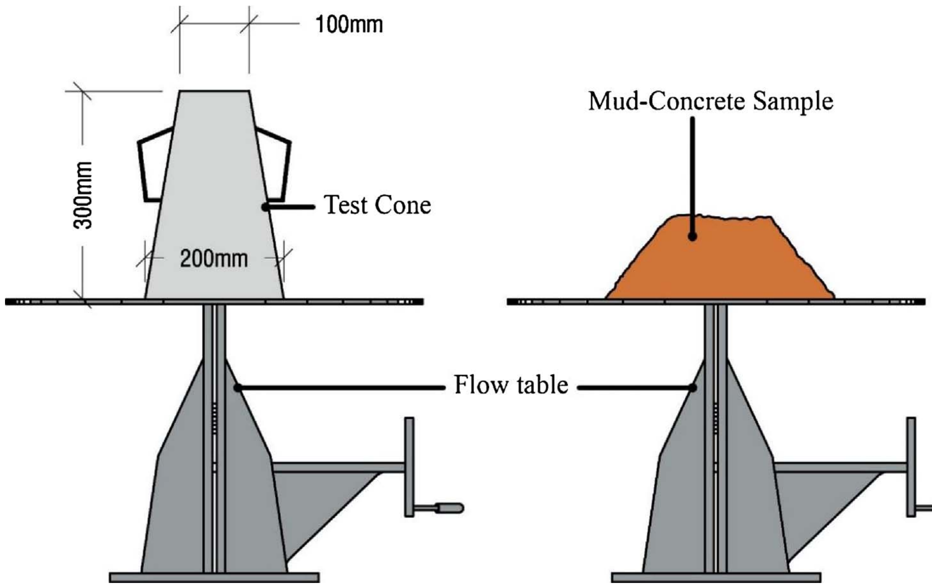

Fig. 3. Fill the test cone in one operation without mechanical compaction. Then strike off the excess mix from the top of the test cone. Allow the cone to stand for 60s. After that lift the cone in a single movement. Then it will be visible that the mix has not spread at once due to the cohesiveness of the material. Therefore, flow diameter was measured after giving 25 blows using the flow table. As a thumb rule after 25 blows, if the mix spread to about 500 mm diameter of a circle then the workability of the mix was achieved.

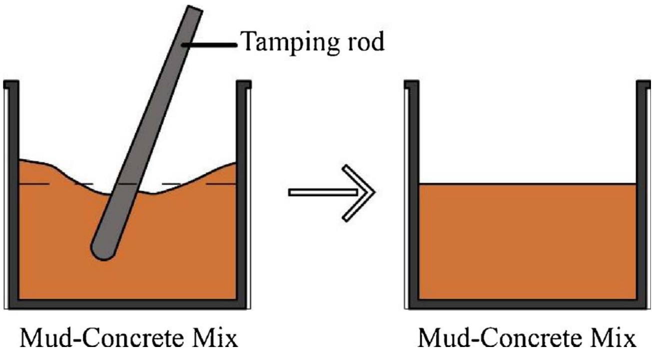

Fig. 4. The mixture was poured into 150 × 150 × 150 mm cast iron moulds in two layers and a tamping rod used to remove the air existing in the mixture.

compressed stabilised earth blocks (CSEB) manufactured with cement stabilisers were developed according to Sri Lankan standards (SLS standards) in 2009 [22]. Therefore, the minimum requirement achieved in CSEB can be regarded as a justifiable benchmark to be followed for the research. According to the specifications compiled for compressed stabilised earth blocks, the minimum requirement of 28 days wet compressive strength for a block should be 1.2 Nmm^{-2} and the dry compressive strength of a block should be 2.8 Nmm^{-2} with a minimum of 4% cement [22].These standard values have been taken into consideration in the following data analysis of the tests carried out for the Mud-Concrete Block.

3. Results

3.1. Testing for mix design of MCB

Locally available laterite subsoil samples were used in the present study. Six soil samples were randomly extracted from selected areas around Colombo to determine the existing particle size distribution of the available soil. This was to understand the typical composition of the most commonly available soil around the area. According to the sieve analysis results, the available native soil contained a considerable amount of gravel. Thus, soil samples extracted from one pit were used in each & every test. 150 mm x 150 mm ×150 mm sized concrete cube moulds were used for the testing procedures. Prior to the start of testing the mix-design, the particle size distribution of the dry native soil was analysed through a sieve test to obtain a clear idea about the gradation of the native soil samples used. (Figs. 7 and 8)

All dry soil samples were sieved through a 19 mm (¾ inch) sieve prior to mixing water and cement. The first step was to find the optimum water percentage that is required to achieve the proper workable mix (Self-Compacting mix). In this investigation, a 10%

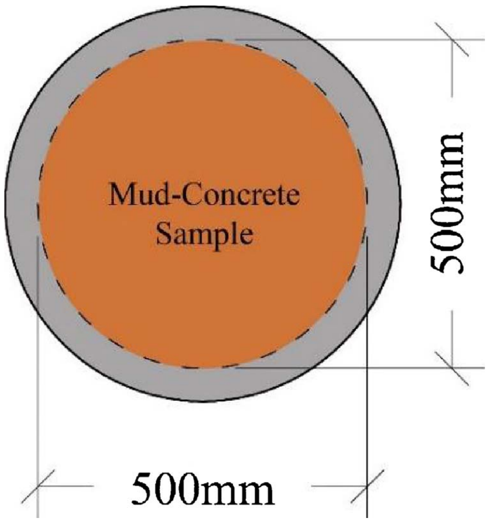

Fig. 5. Plan view of the flow Table Spread of the self-compacting Mud-Concrete mix after giving 25 blows using the flow table.

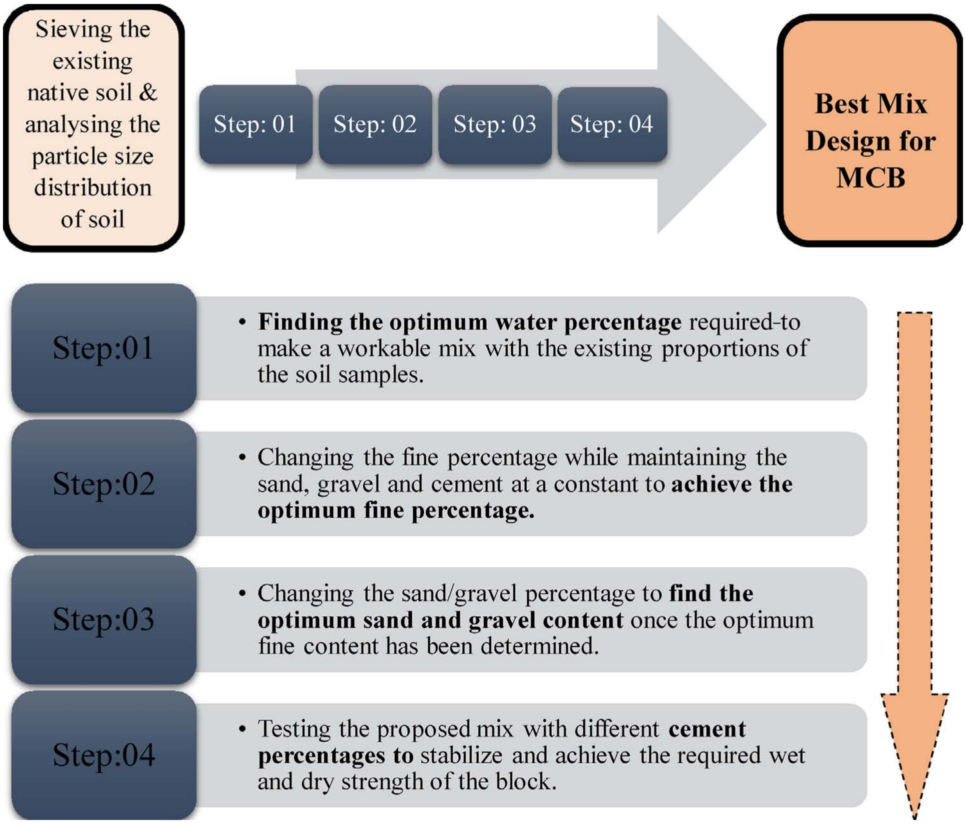

Fig. 6. Process of developing the Mix design of Mud-Concrete Block.

cement percentage was used with different moisture contents. At greater than 10% cement content stabilisation generally becomes uneconomical. According to Walker, cement stabilised soil blocks containing less than 5% cement are often too friable for easy handling [23]. A total of 72 blocks were cast with varying moisture content while keeping the other parameters constant (Table 3).

The cubes were removed from the moulds following the second day of casting and later subjected to specified methods of curing. Cubes were covered with soaked gunny bag (carpet or gunny bag underlay) and were kept wet for 14 days to order to prevent cracking. The cubes were placed in an enclosed area to keep it at 25 °C room temperature.

The wet & dry compressive strengths of the blocks were tested after a period of 28 days. According to the results (Figs. 9 and 10), the dry & wet compressive strength of MCB is reduced with an increased moisture content. Therefore, it is necessary to keep the

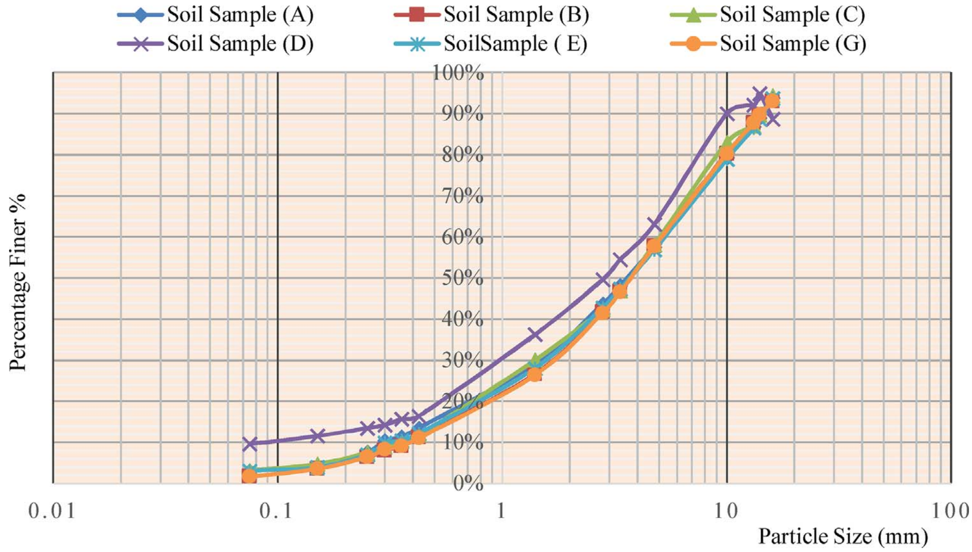

Fig. 7. Grading curve of the tested soil samples.

	Fine	Sand	Gravel
Soil Sample (A)	13.49%	44.05%	42.46%
Soil Sample (B)	11.30%	46.45%	42.24%
Soil Sample (C)	11.70%	46.4%	41.90%
Soil Sample (D)	10.27%	46.6%	43.09%
Soil Sample (E)	12.16%	44.73%	43.12%
Soil Sample (F)	11.06%	46.58%	42.36%

Particle Type	Fine	Sand	Gravel
Average fraction of Soil	11.5%	46%	42.5%

Fig. 8. Sieve Analysis – Particle Size Distribution of native soil sample used in testing.

Table 3
Detailed proportions of cast samples to check the optimum water% to achieve the workable mix of MCB.

Casting the Mud-Concrete block with 10% cement					
Sample no:	Sample blocks	Proportions			Moisture content %
		Fine%	Gravel %	Sand%	
A1	6	**30**	50	20	22.11
A2	6	**30**	50	20	23.75
A3	6	**30**	50	20	26.09
A4	6	**30**	50	20	28.46
A5	6	**30**	50	20	28.68
A6	6	**30**	50	20	29.63
B1	6	**10**	45	45	20.61
B2	6	**10**	45	45	20.59
B3	6	**10**	45	45	18.98
B4	6	**10**	45	45	23.91
B5	6	**10**	45	45	20.93
B6	6	**10**	45	45	22.38

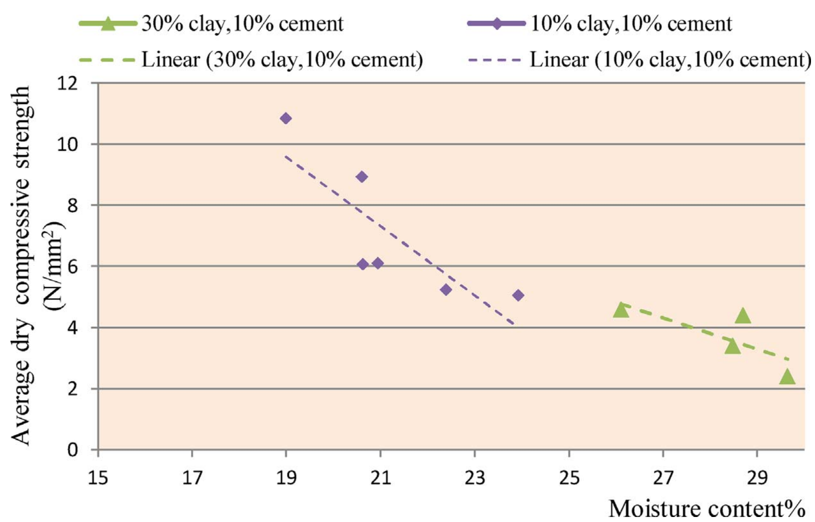

Fig. 9. The effect of moisture content on dry compressive strength of mud-concrete.

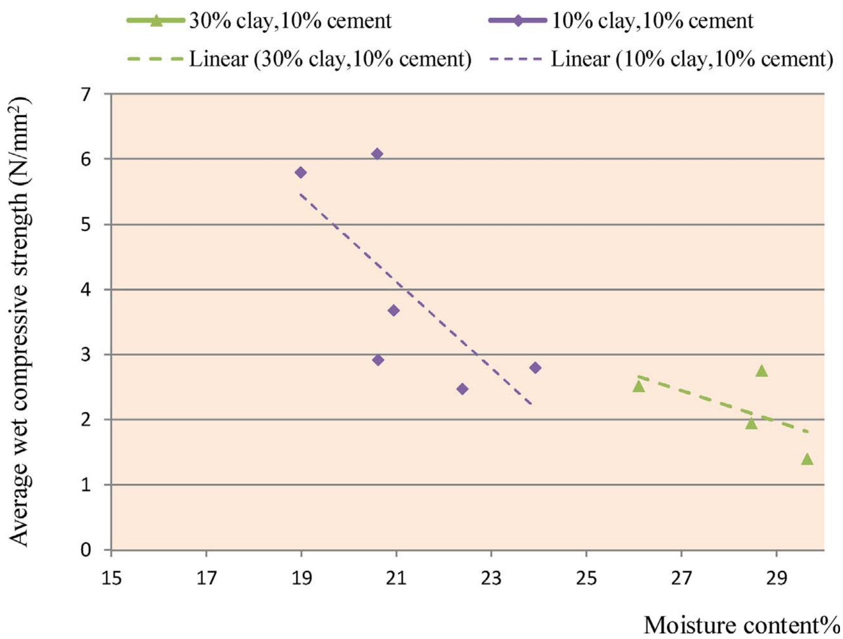

Fig. 10. The effect of moisture content on the wet compressive strength of mud-concrete.

Table 4
Detail proportions of casted samples to check the optimum fine% of MCB.

Casting the Mud-Concrete blocks with 10 % cement					
Sample no:	Sample Blocks	**Fine %**	Gravel %	Sand %	Sand: Fine
F1	3	**10**	30	60	6.00
F2	3	**15**	30	55	3.66
F3	3	**20**	30	50	2.50
F4	3	**25**	30	45	1.80
F5	3	**30**	30	40	1.33
F6	3	**35**	30	35	1.00

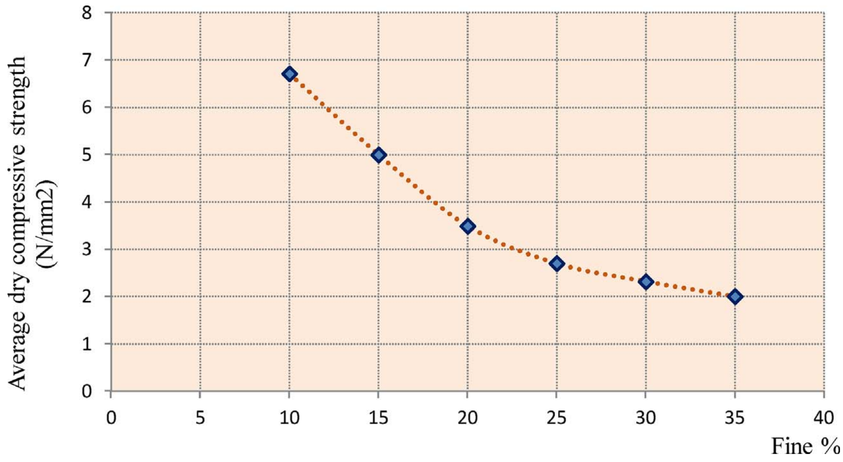

Fig. 11. The effect of fine% on the dry compressive strength of Mud-Concrete.

Table 5
Detail proportions of casted samples to check the optimum Gravel: Sand% of MCB.

Casting the Mud-Concrete blocks with 10% cement											
Sample No:	Sample weight (kg)	Existing proportions (%)			Proposed proportions (%)			Proposed total weight (need to keep the 10% fine (kg)	Weight to be added or remove (kg)		
		Fine	Sand	Gravel	**Fine**	**Sand**	**Gravel**		Fine	Sand	Gravel
G1	36	11.5	46	42.5	**10**	**80**	**10**	41.4	4.14	16.56	-11.16
G2	36	11.5	46	42.5	**10**	**70**	**20**	41.4	4.14	12.42	-7.02
G3	36	11.5	46	42.5	**10**	**60**	**30**	41.4	4.14	8.28	-2.88
G4	36	11.5	46	42.5	**10**	**50**	**40**	41.4	4.14	4.14	1.26
G5	36	11.5	46	42.5	**10**	**30**	**50**	41.4	4.14	0.0	5.4
G6	36	11.5	46	42.5	**10**	**20**	**60**	41.4	4.14	- 4.14	9.54

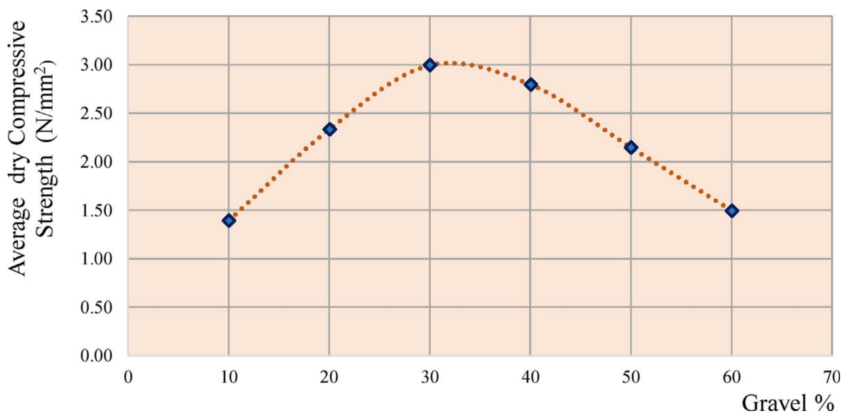

Fig. 12. The effect of gravel content on the dry compressive strength of Mud-Concrete.

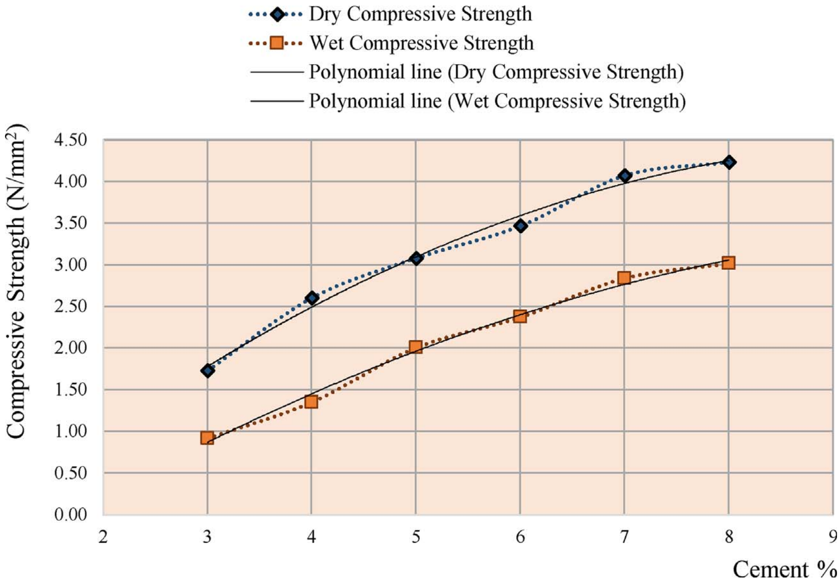

Fig. 13. The effect of cement content on the dry & wet compressive strength of Mud-Concrete.

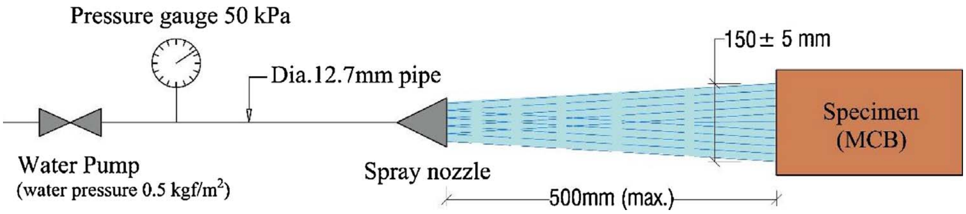

Fig. 14. Arrangement of apparatus for accelerated erosion test.

Fig. 15. Accelerated erosion test conducted in laboratory.

moisture content at a minimum while catering to the self-compacting nature of the mix. Experiments suggested that 18%-20% water percentage from the dry mix is required to satisfy this dual requirement of the mix.

Once the optimum water percentage required to make the self-compacting workable mix was achieved, the second step of determining the optimum fine percentage while keeping gravel, cement and water at a constant was tested (Table 4). A total of 18 blocks were cast according to the following proportions and tested for dry compressive strength after 28 days.

The results of the tests indicated that the strength of Mud-Concrete gradually decreases when the fine/clay content is increased (Fig. 11). Therefore, a higher strength of the block can be achieved by reducing the fine content of the mix as much as possible.

Fig. 16. The surface of MCB before carrying out the accelerated erosion test.

Fig. 17. No significant cavities were visible in tested sample of MCB after carrying out the accelerated erosion test.

After finalizing the fine/clay percentage, the third step was to determine the optimum Gravel: Sand ratio while keeping the fine, water and the cement percentages at a constant. Soil samples were prepared according to the following proportions mentioned in Table 5 to test the above.

According to the results obtained in step three, mud-concrete has a higher strength when the gravel percentage falls within the range of **30% − 35%** (Fig. 12). This gravel percentage was achieved while keeping the fine content constant at a value of 10% of the weight of the soil sample. Consequently, this implies that the optimum sand content to be used in the mud-concrete block is 55% − 60%.

Once the optimum Sand: Gravel: water ratio was finalised, the Mud-Concrete mix was tested with different cement quantities to determine the minimum cement percentage which could satisfy the strength requirements of MCB. In this fourth step, the percentage of cement used in the mix was varied from 3% to 8% when casting the blocks and their compressive strength was tested after a period of 28 days (Fig. 13). The results indicate that a minimum 4% cement can satisfy the wet & dry compressive strength requirement of the Mud-Concrete Block.

3.2. Testing for durability of MCB

Once the optimum MCB mix design was finalized, an accelerated erosion test was conducted to determine the durability of MCB (resistance to weather) under extreme exposure conditions. Three samples were cast from the best mix of MCB and were tested after oven drying at 105 ± 5 °C for 24 h and then leaving the blocks for another 24 h under saturated surface dry condition (after 24-h immersion) [24].

The testing method involved placing the sample at a distance of 500 mm from a spray nozzle and spraying water horizontally at a pressure of 50 kPa. [24]. A surface area of 150 mm diameter was exposed to water. Each sample was exposed to the water spray for

1 h (60 min) and the pit depths were observed every 15 min (Figs. 14 and 15).

The results showed that (Figs. 16 & 17) there were no significant cavities visible in the tested Mud-Concrete Block samples after carrying out the accelerated erosion test. The surface appearance of three specimens remained almost unchanged to their appearance from before the erosion test was carried out. Thus, the finalised mix design of Mud-Concrete block satisfies the standard durability requirements according to SLS 1382.

4. Conclusion

The experimental data presented in this paper offers an important insight into the development of novel soil based techniques which are capable of catering to the demands of the building industry. Furthermore, it analyses how an ancient technology could be incorporated into fulfilling present demands and achieving the strength and durability of contemporary materials. The novel concept in MCB is that it employs a 'concrete' made using earth/soil. In Mud-Concrete, the sand and coarse aggregate constituents of concrete are replaced by the fine and coarse aggregates of soil. The precise gravel percentage governs the strength of Mud-Concrete. As a result, the mix proportions of the Mud-Concrete Block were finalized to have a minimum of 4% Cement, Fine ≤ 10% (≤ sieve size 0.425 mm), Sand 55–60% (sieve size 0.425 mm ≤ sand ≤ 4.75 mm), Gravel 30–35% (sieve size 4.75 mm ≤ gravel ≤ 20 mm) with a water content of 18% to 20% from the dry mix. The achieved mix design for the Mud-Concrete Block also satisfied the durability requirements up to the standard levels.

Special emphasis is placed on the Mud-Concrete Block due to the following innovative ideas;

- Soil will be modified slightly to form a concrete which is durable in service.
- The gravel acts as the strengthening agent while clay and cement act as the binder.
- The usage of a high water/cement ratio will reduce strength, but it can be recovered, by the proposed mix proportions.
- The proposed water content will allow the mix to flow freely which would create a mix that has the ability to compact itself.
- Excess water in the mix will create a porous structure that will later act in cooling the building through convection. This will increase the thermal comfort of the interior more than other earth-based construction techniques.
- The porous structure and the absence of compaction will ensure aeration which would cut down heat gain due to low thermal conductivity.
- The extra water within the block will ensure that the block achieves its strength with time without a curing process. This will allow the block to be used as soon as it achieves the required minimum strength.
- Since there is no burning involved the block can be cast to any dimension to match the available structural and architectural equipment.
- Due to the high-water content and presence of clay, the block will have a clear and smooth surface which would allow it to be used without plaster.
- The proposed manufacturing techniques, as well as the proposed proportions, results in creating a block that is low cost, has low embodied energy and requires lesser technical input/knowhow at the construction stage

The Mud-Concrete Block has also obtained a patent under Sri Lankan intellectual property act No.36 of 2003 and under the international patent classification. (IPC: E04C 1/100, B28B, B28C)

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