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Effect of Wet Condition and Aggregates Type Used in Cement-Based Blocks on Mechanical Behavior of Masonry

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Abstract: Water penetration into masonry walls can occur in the masonry structures during the rainy climate. Water penetration not only causes discoloration or efflorescence but also can be damaging to material property. Even though several studies from past literature focus on wet conditions effect on brick masonry, but there is limited study on cement block masonry. The present research aimed to evaluate the effect of wet conditions on the mechanical characteristic of cement block, binder mortar and masonry. Where three types of fine aggregates, namely river sand, lateritic soil and manufactured sand were used for masonry block production. For binding mortar, two mortar classes M2 and M6 according to British Standard European Norm were used. Compression, flexural bending, and splitting tensile tests for blocks and binding mortar were performed in dry and wet conditions. Also, compression, direct shear and bond test were performed on masonry prisms in dry and wet conditions. The results demonstrate that a considerable amount of strength reduction was observed in wet conditions. In wet conditions, cement-soil block masonry showed a higher reduction in compression strength and bond strength, but showed lesser shear strength reduction when compared with the other two masonry types. Overall, cement-river sand block masonry has shown better performance in wet conditions.

Keywords: Masonry, moisture, river sand, lateritic soil, manufactured sand

1. Introduction

Masonry is normally a highly durable material form of construction. However, the materials used for the masonry, the quality of the mortar and workability, and the pattern in which the masonry units are assembled can substantially affect the strength and durability of the overall masonry structure. On the other hand, the severity of the environmental exposure such as water immersion, wet and dry cycling, freeze and thaw cycling and chemical attacks also severely affect the strength and durability of the masonry structures [1]. Water penetration into masonry walls can occur in the masonry structures during the rainy climate. Water penetration not only causes discoloration or effloresce but also can be damaging to material properties.

There are intensive studies on moisture effect on construction materials such as concrete [2-5], fired clay brick [6-9] and soil block [10,11]. These studies showed that the compressive strength of construction material in wet condition have lower compressive strength than in dry condition. Also revealed that the compressive strength of the materials decreases gradually with the increased moisture content. For moisture effect on masonry structures, the majority of the studies were conducted on fired brick masonry.

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Franzoni et al. [7] investigated the compressive strength and young's modulus of fired clay brick masonry with cement-based mortar and lime-based mortar in dry, moisture and wet conditions. Results showed that the compressive strength of cement-based mortar is significantly reduced in wet conditions compared with lime-based mortar. For masonry prism, the effect of wet conditions on compressive strength and young's modulus is quite limited.

Sathiparan and Rumeshkumar [6] studied the compressive strength of fired clay bricks and three different cement mortars (Mortar class M2, M4 and M6 according to BS-EN-998-2 [12]) under different moisture conditions: air-dry, oven-dry and wet condition. Also, compressive, bond and direct shear strength of masonry prisms were evaluated under three different moisture conditions. The results reveal that wet condition significantly reduces the compressive strength of brick and cement mortar. In the case of masonry, there was an 8% reduction in compressive strength for prism with mortar class M2. However, masonry prism with stronger mortar M4 and M6, higher compressive strength reduction of 17% and 23% was observed. This shows that masonry prism with stronger mortar (high cement content in the mix) significantly affect the compressive strength in wet condition. For shear and bond strength, a reduction of around 10% to 20% was observed for all three binding mortar classes.

Bompa and Elghazouli [13] investigated the mechanical properties of fired clay brick, hydraulic lime mortar and masonry components under dry and wet conditions. Results show that the compressive strength reduction was around 13–18% for masonry components in wet conditions compared with the control environmental condition.

Most of the previous studies on masonry under wet conditions were focused on brick masonry. However, compared with concrete blocks, bricks are weak (especially weak in tensile loading) and less durable and limited in sizes and colors. Also, brick production required clay soil from agricultural land and bricks have to be burned, and both generate a lot of environmental issues. On the other hand, concrete block production is also not environmentally friendly. Especially it is required river sand and excessive sand mining from river bed also harmful to the environment [14,15]. Therefore, in recent times, in addition to river sand as fine aggregate for concrete blocks or cement sand blocks, there is an increased interest in using alternative materials such as lateritic soil and manufactured sand in cement blocks production. Published literature shows that cement blocks with lateritic soil or manufactured sand satisfied the minimum strength requirement recommended by local standards [10,16]. However, studies on the durability of these blocks especially threatened by extreme weather such as heavy rainfall or flood are rare to find in published literature.

Therefore, the present study focused on determining the influence of wet condition cement block masonry. In here, river sand, lateritic soil, or manufactured sand were used as fine aggregates. Two types of binding mortar (mortar class M2 and M6) specified in BS-EN-998-2 [12] were used for the casting of masonry prisms. The study examined how the wet condition affects the compressive, bond and shear strength of the masonry.

2. Methods

2.1 Material Used

To cast the masonry blocks, three types of aggregates; river sand, manufactured sand (M-sand) and lateritic soil were used. In this study, the river sand extracted from Muthayankattu river bed, Northern province, M-sand obtained from manufacturing plant situated in Divulapitiya, Western province and lateritic soil from university promises, Kilinochchi in Northern province in Sri Lanka were used. Ordinary Portland cement was used as a binder and has a density and specific gravity of 1182 kg/m^3 and 3.15, respectively. Figure 1 presents the particle size distributions of fine aggregates.

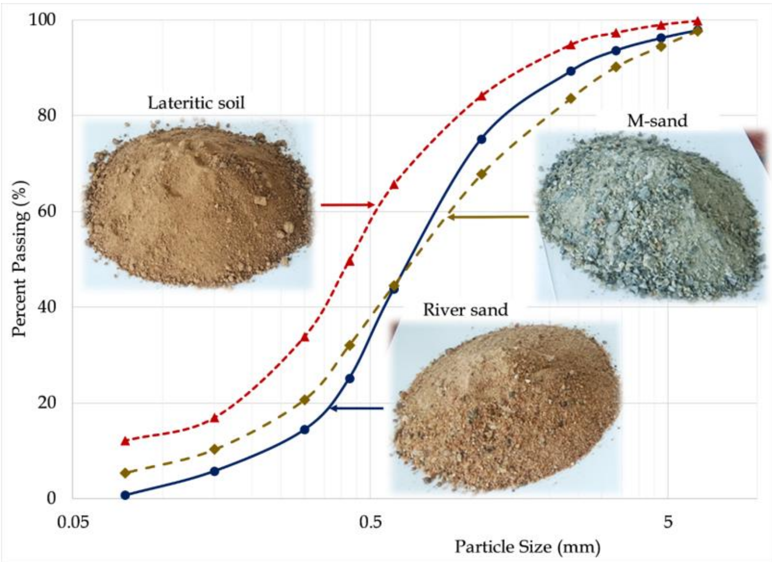

Fig. 1 - Particle size distribution of cement and fine aggregates

The characteristics of river sand, M-sand and lateritic soil used in this study were summarized in Table 1. Lateritic soil was a relatively lighter aggregate with higher silt and clay content. River sand and M-sand were almost the same density, but river sand had more gravel and sand compared to M-sand. The effective sizes of river sand, lateritic soil and M-sand corresponding to 90% finer were 2.52, 1.83 and 3.31 mm, respectively, and that of 10% finer were 0.22, 0.06 and 0.15 mm, respectively.

Table 1 - Characteristic of aggregates

	River sand	Lateritic soil	M-Sand
Density (kg/m³)	1680.5	1316.5	1641.0
Specific density	2.41	2.26	2.34
Water absorption (g/kg)	174	194	198
Fineness	2.89	2.28	2.97
Gravel (%)	3.8	1.0	5.5
Sand (%)	95.6	86.9	89.1
Silt + Clay (%)	0.6	12.1	5.4
Uniformity coefficient (Cu)	4.01	12.61	6.72
Coefficient of gradation (Cc)	1.10	3.09	1.12
Liquid limit (LI)	-	31.2	-
Plastic index (PI)	-	8.9	-
USCS classification	Poorly graded sand (SP)	Clayey sand (SC)	Well graded sand (SW)

2.2 Mix Design and Specimen Preparation

For the preparation of the blocks, 1:6 volume ratio of cement to fine aggregates was used. The water to cement ratio was determined by workability, where the slump was fixed as 30 mm. Before preparation of the wet mix, the river sand, lateritic soil and M-sand were sieved through a 6.3 mm BS sieve. For binding mortars, two types of mortar mix were designated: mortar class M2 and M6 classified in BS-EN-998-2 [12]. For these two mixes, Ordinary Portland cement is used as a binder and river sand is used as fine aggregate. River sand was sieved through a 3.6 mm BS sieve. A mix ratio of 1:4 and 1:7 by volume of cement to river sand was used for mortar class M6 and M2, respectively. The amounts of cement, river sand, lateritic soil and M-sand required for each block type and binding mortar were shown in Table 2.

Table 2 - Mix proportion used for specimens

Mix ID	Cement	River sand	Lateritic soil	M-Sand	W/C ratio
B-RS (Block - River sand)	1.0	8.53	-	-	1.35
B-LS (Block - Lateritic soil)	1.0	-	6.46	-	1.50
B-MS (Block - M-sand)	1.0	-	-	8.33	1.50
M2 (Mortar class M2)	1.0	9.96			1.60
M6 (Mortar class M6)	1.0	5.69			1.30

Cube size of 100×100×100 mm^3 for compression test and block size of 200×100×60 mm^3 for flexural bending test was used for both blocks and binding mortar. Block dimensions of 100×100×60 mm^3 were used for the preparation of masonry prism for compression and direct shear test. Block size of 200×100×60 mm^3 for used for the preparation of masonry wallet for the bond test. Once cubes and blocks were removed from the mold after one day, they were placed in ambient conditions for another 28 days. To check the strength in wet conditions, the specimens were kept in water for 24 hours before testing.

2.3 Testing

Following tests were conducted on each block type and binding mortar to obtain the physical and mechanical characteristics according to the given standards. For each block and binding mortar type, six identical specimens were tested and the average value was used for comparison.

- Density: ASTM-C140/C140M [17]
- Compressive strength: ASTM-C109 [18]
- Flexural bending strength: ASTM-C348 [19]
- Saturated water content: ASTM-C140/C140M [17]

Following tests were conducted on masonry prisms according to the given standards. Figure 2b shows the test setup used to determine the mechanical properties of masonry.

- Compressive strength: BS-EN-1052-1 [20]
- Direct shear strength: BS-EN-1052-3 [21]
- Bond strength: ASTM-C952 [22]

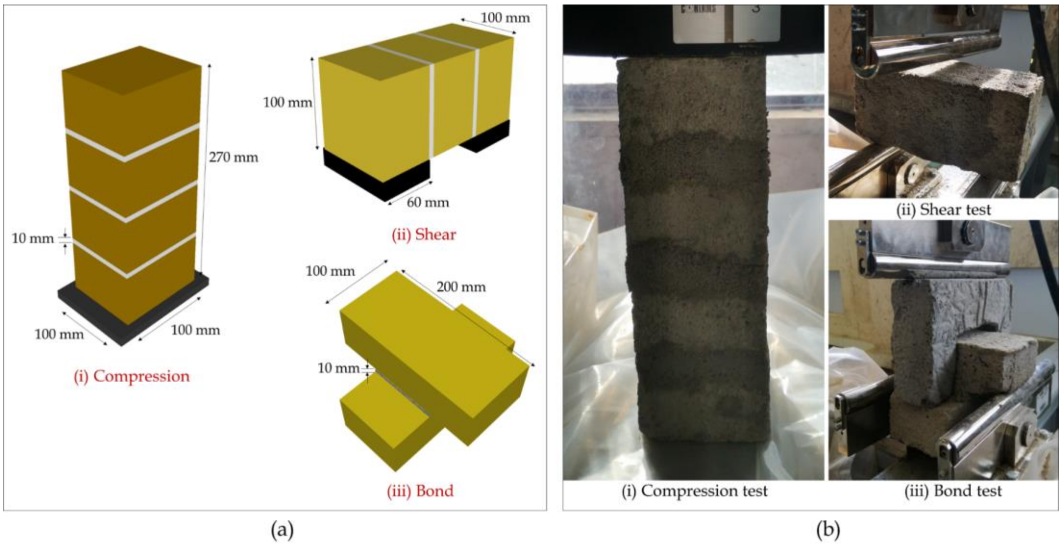

Fig. 2 - (a) Details of the specimen used for testing and; (b) test setup for masonry

For the compression test, four blocks of high masonry prisms were used as shown in Fig. 2a(i). The triplet consists of three blocks that were used for the shear test as shown in Fig. 2a(ii). To measure the bond strength, the cross-block couplets were made as shown in Fig. 2a(iii), according to the description given in ASTM-C952 [22]. In all the cases, 10 mm thickness of binding mortar was used and testing was done at the curing age of 28 days. The loading was applied in displacement control at the loading rate of 1 mm/min, 0.5 mm/min and 0.3 mm/min for compression, direct shear and bond test, respectively. The compressive, direct shear and bond strength were calculated using Eqs (1), (2) and (3), respectively. Six prisms, 8 triplets and 8 couplets were tested used for compressive, direct shear and bond tests, respectively and the average value was used for comparison.

$$\text{Compressive strength} = P/A \tag{1}$$

where, P is the maximum axial load, and A is the area of the bed face.

$$\text{Shear Strength} = (P+W)/2A \tag{2}$$

where, P is the maximum load, W is the weight of the triplet, and A is the area of the failure surface.

$$\text{Tensile bond strength} = (P+W+W_c)/2A \tag{3}$$

where, P is the maximum, W is the weight of the one block, Wc is the weight of the loading cap, and A is the area of the failure surface.

3. Results and Discussion

3.1 Physical Properties of Blocks and Mortar

Table 3 summarizes the physical properties of the cement blocks and binding mortar. Both dry and wet densities of the B-LS were less than that of B-RS and B-MS.

Table 3 - Physical properties of the blocks with different aggregates and binding mortar

	Blocks				
	B-RS	**B-MS**	**B-LS**	**M2**	**M6**
Density (kg/m³)					
Dry	2047.6	2093.6	1883.5	2078	1973
Wet	2188.9	2265.7	2051.9	2242	2165
Saturated water content (%)	9.7	11.6	17.6	8.6	10.6

Porosity (%)	19.3	23.7	30.7	17.7	16.5

The low density of the soil aggregates is attributed to the less dry density of B-LS. Wet density mainly depends on the pore microstructure of the blocks and the water absorption characteristics of the aggregates used. Lateritic soil blocks absorbed relatively more water than the other two types, and hence the wet density got higher.

3.2 Mechanical Properties of Blocks and Mortars

Figure 3 illustrates the compressive, splitting tensile and flexural strength of the blocks in dry and wet conditions. The B-MS has shown better strength than the other two block types in both dry and wet conditions. The strength of cement blocks depends on cement and aggregate properties, aggregate to cement ratio, water to cement and environmental condition. When it comes to properties of aggregates, quality of fine aggregate, size of aggregates, the shape of aggregates and grading of aggregates are the major factor that affects the strength of cement blocks. Angular aggregates have rough-textured and therefore it exhibits better interlocking to create a good bond between cement and aggregates. Angular and well-graded particles of the M-sand contribute to the better strength of B-MS.

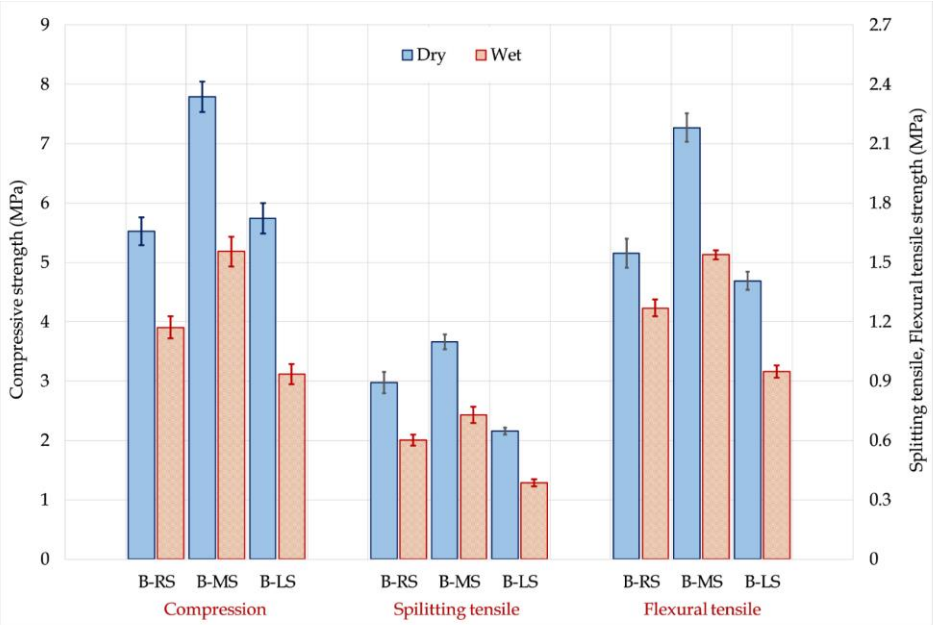

Fig. 3 - Mechanical properties of the blocks

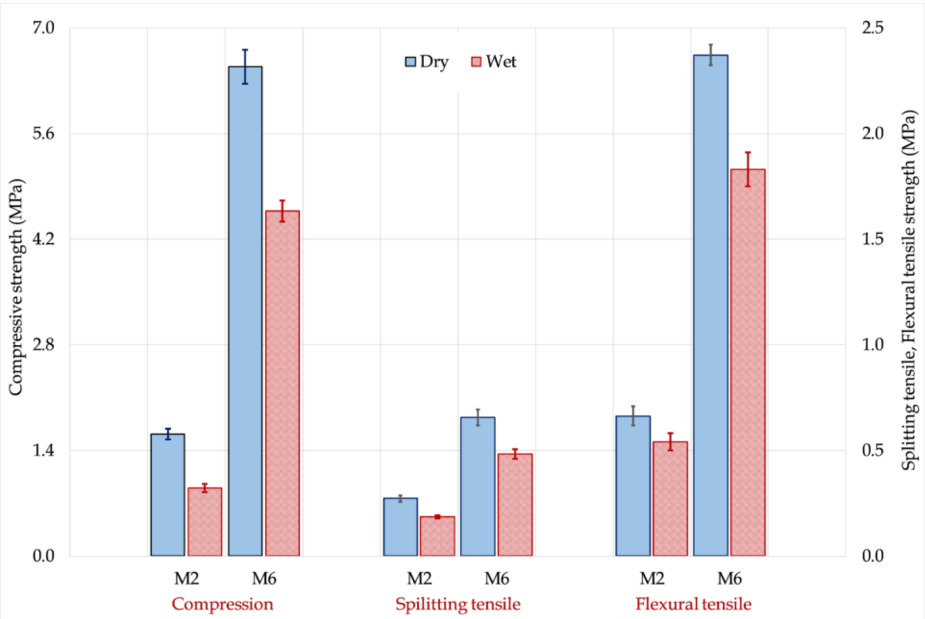

Fig. 4 - Mechanical properties of the mortar

The test results demonstrate that the wet condition of the blocks affects the compressive, splitting tensile and flexural strength of the blocks to a great extent (Figure 3). In wet conditions, pores filled with the full of water, it raises the hydraulic pressure and drives to push the particles apart. This phenomenon encourages crack initiation within the material, even with a lesser compressive load. As a result, the compressive strength of the blocks is reduced. The compressive strength reduction in wet conditions for B-RS, B-MS and B-LS was 29%, 33% and 46%, respectively. This strength reduction is almost proportional to its water absorption, where the water absorption rate is 9.7%, 11.6% and 17.6% for B-RS, B-MS and B-LS, respectively. A similar trend was detected for flexural tensile and splitting tensile strength.

Figure 4 illustrates the compressive, splitting tensile and flexural strength of the mortar class M2 and M6 in dry and wet conditions. Mortar class M2 (weaker mortar) shows higher compressive strength reduction (45%) compared to mortar class M6 (30%) due to wet conditions. The effect of the wet condition is similar for splitting tensile and flexural strength for both mortar classes. There is a reduction of splitting tensile strength of 30% and 27%, and a reduction of flexural strength of 18% and 23% for mortar class M2 and M6, respectively.

3.3 Mechanical Properties of Masonry

3.3.1 Compression Behavior

Figure 5 illustrates the dry and wet strength of masonry prisms. For both mortar class M2 and M6, B-MS masonry shows higher strength and B-LS shows lower strength. The wet condition significantly affects the compressive strength of masonry. The average compressive strength reduction for masonry prisms with mortar class M2 and block types B-RS, B-MS and B-LS, exposed to wet conditions was 28%, 33%, and 36%, respectively. In the case of masonry prisms with mortar class M6 and block types B-RS, B-MS and B-LS, the average compressive strength reduction due to exposure in wet conditions was 33%, 32% and 39%, respectively. This reduction is much higher than recommended value by BS-EN-772-1 [23], where it is recommended that the compressive strength of masonry under wet conditions can be considered 20% less than the dry state. A study on brick masonry under wet conditions by Sathiparan and Rumeshkumar [6] observed that compressive strength reduction for brick masonry with binding mortar class M2 and M6 was 23.8% and 8.3%, respectively. In the present study, masonry with B-LS shows a higher strength reduction in wet conditions compared with the other two block types. As lateritic soil used as fine aggregate in B-LS have higher clay and silt content, which can observe more water and swell in wet condition. Therefore, uneven strain occurs in the interface between block and mortar, thus reducing the compressive strength.

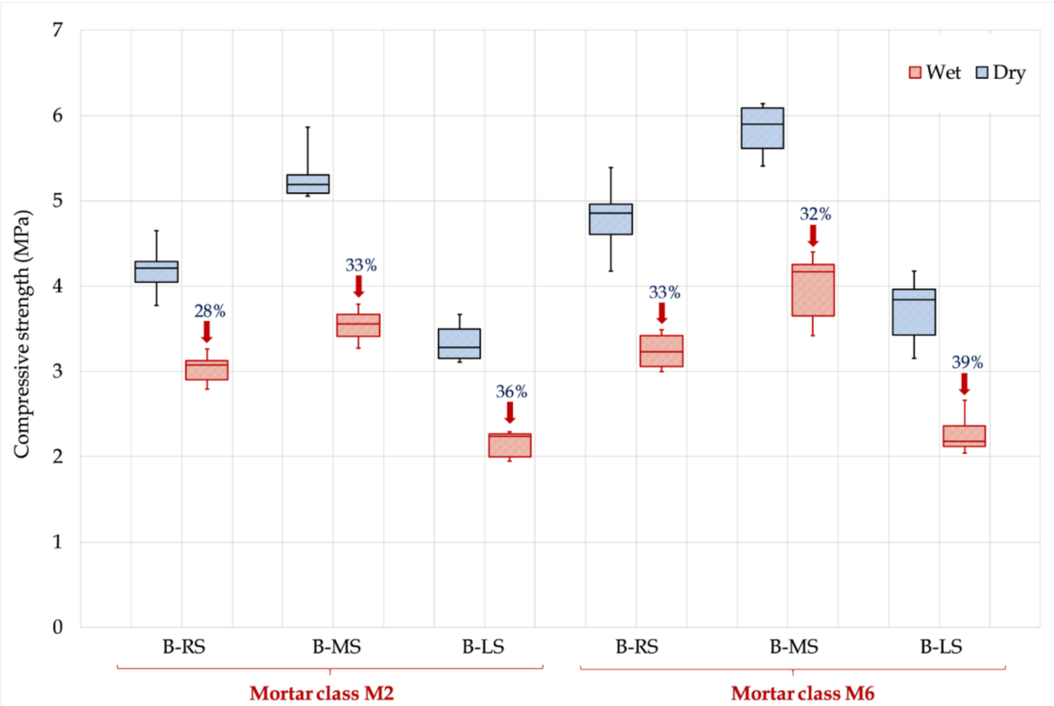

Fig. 5 - Compressive strength variation of the masonry

The compressive strength of blocks and mortar are the major factors that affect the compressive strength of masonry. Eurocode [24] provides a simple equation for the characteristic compressive strength of masonry (f_k) as a function of block or brick strength (f_b), mortar strength (f_m) and constants K, α and β as follows:

$$f_k = K \times f_b^{\alpha} \times f_m^{\beta} \tag{4}$$

The predicted compressive strength of the masonry prism in the wet condition can be determined according to the Eurocode 6 [24], transformed into a relationship as shown in Eq. (5).

$$\frac{f_k^{(w)}}{f_k^{(d)}} = \left(\frac{f_b^{(w)}}{f_b^{(d)}}\right)^{\alpha} \times \left(\frac{f_m^{(w)}}{f_m^{(d)}}\right)^{\beta} \tag{5}$$

where: $f_k^{(d)}$, $f_b^{(d)}$ and $f_m^{(d)}$ are compressive strength of masonry, blocks and mortar, respectively in dry conditions; $f_k^{(w)}$, $f_b^{(w)}$ and $f_m^{(w)}$ compressive strength for masonry, blocks and mortar, respectively in wet condition.

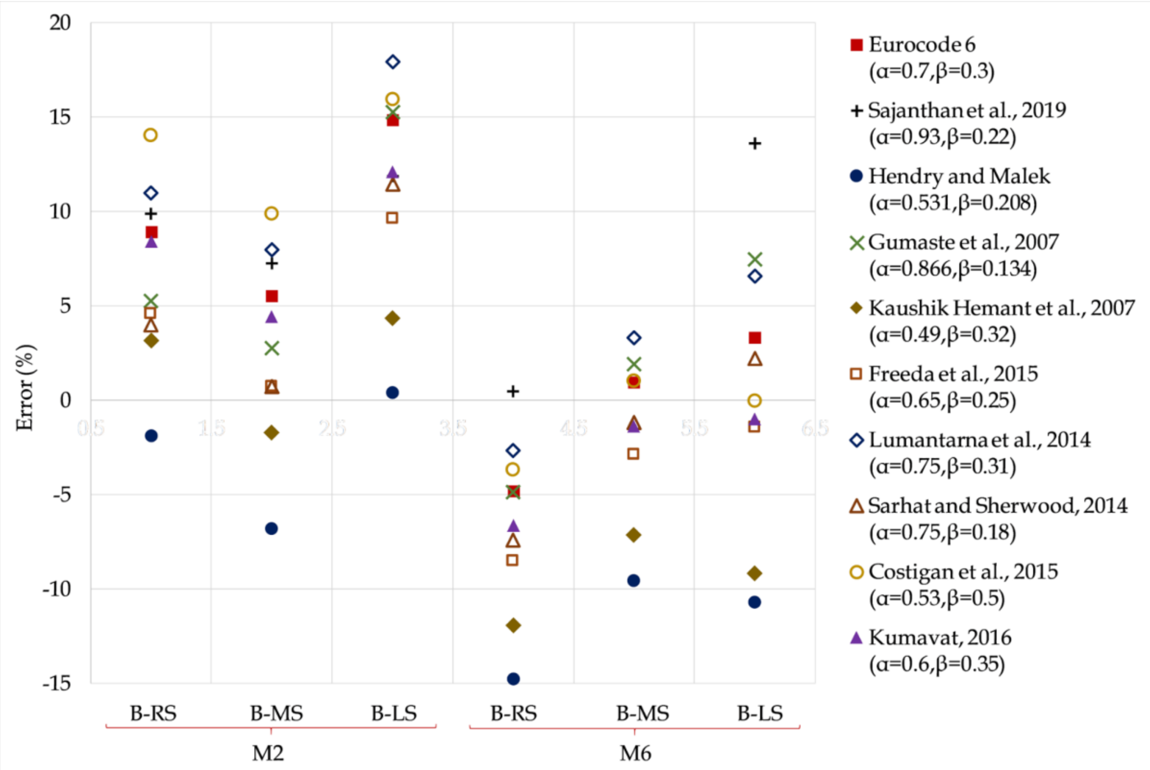

Fig. 6 - Error in predicted compressive strength in wet condition (error equal to the difference between the predicted value and experimental value as a percentage of experimental value)

Eurocode and several researchers recommended different values for K, α and β values based on experimental studies [24-33]. Figure 6 illustrate the error in the prediction value calculated for strength in wet condition using Eq. (2). It was observed that in most of the cases, predicted compressive strength was higher than the experimental value for masonry with weaker mortar (mortar class M2) and lower than the experimental value for masonry with stronger mortar (mortar class M6). When the Eurocode equation was used, the maximum error was 14.9% and the root-mean-square error (RMSE) was 7.82. From the equations proposed by published literature, the equation recommended by Freeda and Tensing [31] agree quite well with the experimental values, differences do not exceed 10% and RMSE was 5.73. So, it is revealed that with the use of an equation proposed by Eurocode or an empirical equation, the compressive strength of the masonry in wet conditions can be predictable.

3.3.2 Direct Shear Behavior

Figure 7 shows the failure pattern detected during the shear tests. For all the block types, binding mortar class and moisture condition; the shear failure of masonry prism occurred in the interface between blocks and binding mortar. This type of failure occurs when the bond strength between blocks and mortar is much less than a block or binding mortar itself.

Fig. 7 - Failure pattern detected during shear tests

Figure 8 illustrate the shear strength of masonry wallet in wet and dry condition. The results indicated that, in wet conditions, there is a considerable amount of reduction in the shear strength. Volumetric changes due to water presence in the blocks and mortar could be the main reason for this strength reduction. Another possible reason is the increase in hydraulic pressure due to the presence of water in pores generated [7]. When the wallet is subjected to the external load, water in the pore employs extra pressure on the material, quickening the initiation of microcracks. This leads the shear failure with a smaller load.

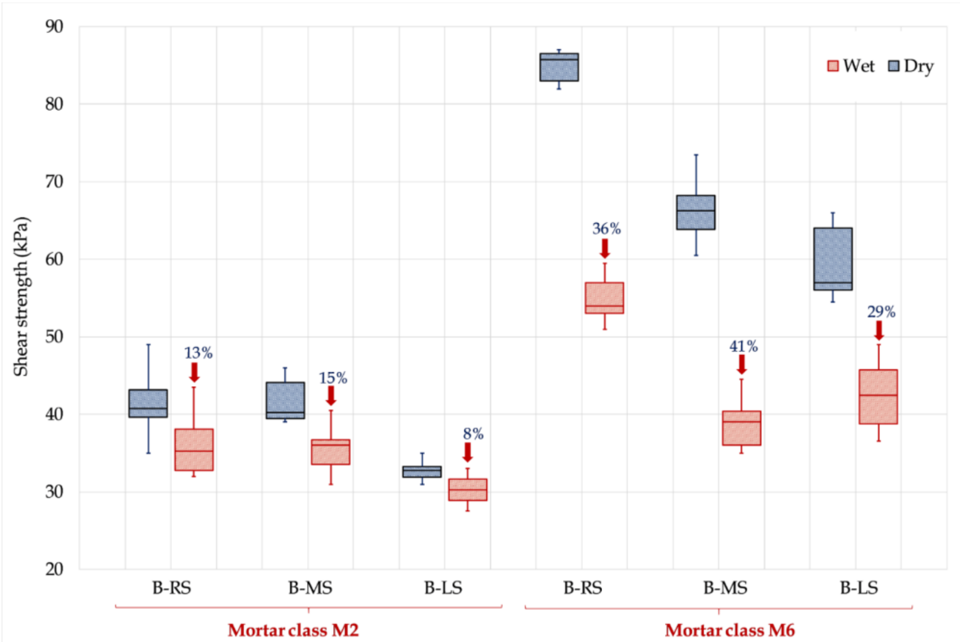

Fig. 8 - Shear strength variation of the masonry wallet

Effect on the wet condition has more influence in masonry with stronger mortar (mortar class M6) than weaker mortar (mortar class M2). As mortar class M6 has higher cement content, it led larger amount of cement gel presence in the mortar. Therefore, when it absorbed a larger amount of water and this will lead to the expansion of mortar [6]. It is attributed to a higher reduction in shear strength for masonry triplet with mortar class M6.

The reduction in shear strength for masonry wallet with mortar class M2 and block types B-RS, B-MS and B-LS, subjected to wet conditions was 13%, 15%, and 8%, respectively. In the case of masonry wallet with mortar class M6 and block types B-RS, B-MS and B-LS, subjected to wet conditions was 36%, 41% and 29%, respectively.

3.3.3 Bond Behavior

Figure 9 illustrates the failure pattern detected during bond tests. During testing, three types of failure occurred:

- Type A: bond failure between block and mortar interface.
- Type B: partially bond failure between block and mortar interface and tensile failure in the block.
- Type C: direct tensile or splitting tensile failure in the brick.

Fig. 9 - Failure patterns of the masonry wallet during bond failure (a) Type A; (b) Type B and; (c) Type C

The failure of the binding mortar itself was not observed for any of the specimens during loading. This could be due to the tensile strength of the weaker mortar (mortar class M2) being still more than the bond strength between block and mortar.

Table 4 summarizes the different bond failure types detected during tests. Masonry wallets constructed with mortar class M2 have shown only bond failure between block and mortar interface for all block types in both dry and wet conditions. A similar trend was observed for masonry wallets constructed with mortar class M6 in wet condition, except for one wallet with B-RS block. However, for masonry wallets constructed with mortar class M6 in dry condition, several wallets have shown type B and type C failure patterns.

Table 4 - Number of specimens fail in the particular pattern during bond failure

Condition	Brick type	Mortar class	Failure type		
			A	B	C
Dry	B-RS	M2	8	-	-
	B-MS	M2	8	-	-
	B-LS	M2	8	-	-
	B-RS	M6	7	1	-
	B-MS	M6	7	-	1
	B-LS	M6	4	2	2
Wet	B-RS	M2	8	-	-
	B-MS	M2	8	-	-
	B-LS	M2	8	-	-
	B-RS	M6	7	-	1
	B-MS	M6	8	-	-
	B-LS	M6	8	-	-

Figure 10 illustrates the bond strength of masonry wallets in dry and wet conditions. Compared with the dry condition, in wet conditions, there is a considerable reduction in bond strength. For masonry wallets with mortar class M2 and block types B-RS, B-MS and B-LS subjected wet conditions, the strength reduction was 59%, 67%, and 73%, respectively. In the case of masonry wallet with mortar class M6 and block types B-RS, B-MS and B-LS, subjected to wet conditions, the reduction in bond strength was 40%, 46% and 54%, respectively. Similar to shear behavior, extra hydraulic pressure due to the presence of water in the pore and expansion of the mortar is the reason for strength reduction in wet conditions. However, the reduction percentage for all masonry types was very high for bond strength in wet conditions compared with compressive and shear strength.

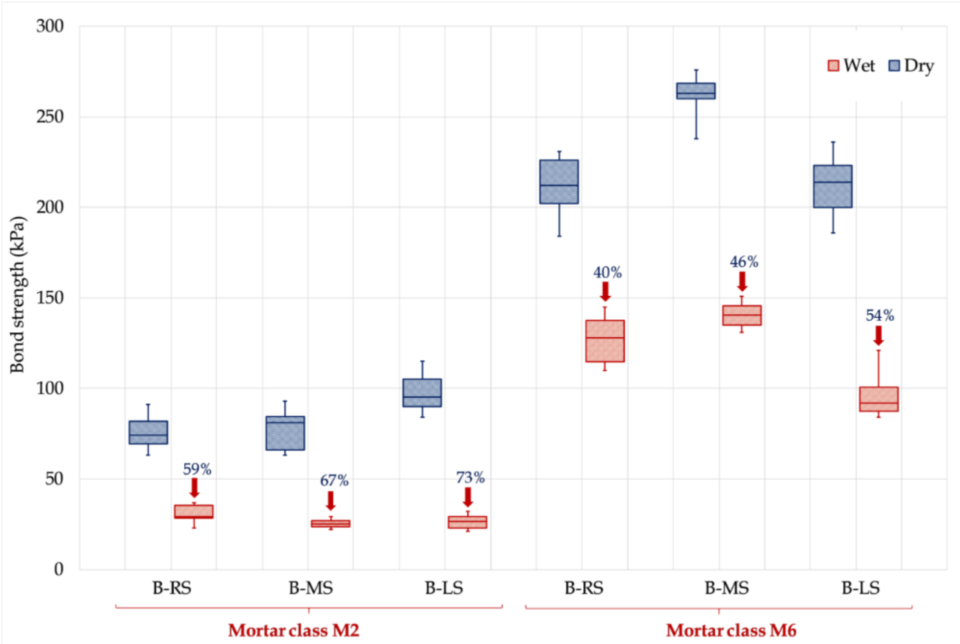

Fig. 10 - Bond strength variation of the masonry wallet

3.4 Static Analysis

A Three-way Analysis of Variance (ANOVA) was conducted to determine the effect of block type, mortar class and moisture condition on compressive, direct shear and bond strength. Results as shown in Table 5 show that all three factors significantly affect the strength of masonry. For compressive strength, moisture condition and block type are more influential factors than mortar class. On the other hand, the mortar class has more effect on the direct shear and bond strength.

Table 5 - Three-way ANOVA analysis for strength properties

	Source	Type III Sum of Squares	F	Sig.		Contribution (%)
Comp.	Condition	4711.28	621.00	9.9E-38	✓	50.6
	Mortar class	316.65	41.74	9.8E-09	✓	3.4
	Block type	4280.39	282.10	2.4E-35	✓	46.0
Shear	Condition	2.53	499.02	2.3E-36	✓	17.1
	Mortar class	7.99	1574.59	7.6E-55	✓	53.8
	Block type	4.32	425.92	1.0E-43	✓	29.1
Bond	Condition	15.02	1116.34	2.3E-48	✓	31.3
	Mortar class	32.38	2407.06	6.2E-61	✓	67.5
	Block type	0.57	21.32	3.9E-08	✓	1.2

4. Conclusion

In this research, the effect of wet conditions on the strengths of cement block masonry was studied. Three types of fine aggregates; river sand, lateritic soil and manufactured sand were used for casting cement blocks. The test results showed that,

- Cement blocks with lateritic soil showed higher strength reduction in wet conditions. The compressive strength reduction in wet conditions for blocks with river sand, M-sand and lateritic soil was 29%, 33% and 46%, respectively. A similar trend was observed for flexural tensile and splitting tensile strength.
- Weaker binding mortar (mortar class M2) in the wet condition showed higher compressive, flexural and splitting tensile strength reduction than stronger binding mortar (mortar class M6).

- In wet conditions, cement-soil block masonry showed a higher reduction in compression strength and bond strength, but lesser shear strength reduction, when compared with the other two masonry types. Overall, cement-river sand block masonry has shown better performance in wet conditions.

The results demonstrate that a considerable amount of strength reduction was observed in wet conditions. Except for shear strength for masonry with mortar class M2, in all other cases, a strength reduction of more than 20% was observed. These strength reduction values are higher than Eurocode recommended for masonry in wet conditions. Therefore, there is extra care needed for the design of cement base block masonry in a flood or rainy area.

In the present study, one cement-fine aggregate ratio, as well as one aggregate grading, was used for the experimental program. Both factors are affecting the water absorption of the blocks and they affect the overall behavior of the masonry. Therefore, the study has to extend to masonry blocks with various cement-sand used in the local market and different grading of sands. Also, in the present study, the blocks and masonry were tested under fully wet conditions. However, in general conditions, masonry structure becomes wet due to water absorption by capillary action. So, it is recommended to check the effect of moisture variation due to capillary action and their effect on strength of masonry for further study.

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