INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
VOL. 13 NO. 1 (2022) 243-256

IJSCET

http://publisher.uthm.edu.my/ojs/index.php/ijscet

ISSN : 2180-3242 e-ISSN : 2600-7959

International Journal of Sustainable Construction Engineering and Technology

Use of Quarry Dust in the Binding Mortar and Its Effect on Mechanical Characteristics of Brick Masonry

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DOI: https://doi.org/10.30880/ijscet.2022.13.01.021
Received 09 March 2022; Accepted 13 March 2022; Available online 16 May 2022

Abstract: The strength characteristics of masonry is greatly affected by the brick strength, mortar strength and bond between brick-mortar interface. Especially, binding mortar significantly affects the shear and flexural strength of the masonry. In conventional masonry construction, river sand or natural sand is mixed with cement and used as binding mortar. However, due scarcity of good quality river sand, the extensive focus is on finding alternative materials for river sand for construction purposes. Quarry dust is one of the best alternatives for river sand, which can be used as fine aggregates in binding mortar. This study investigates the strength characteristic of the masonry made of quarry dust incorporated binding mortar instead of conventional cement-sand mortar. The binding mortar with four different river sand replacement levels of 0%, 33.3%, 66.7% and 100% quarry dust, was used for construction masonry. Compression test, direct shear test and cross-couplet test were conducted to evaluate the strength characteristic. The test results revealed that compressive, shear and bond strength of masonry was improved with increased quarry dust content in the binding mortar.

Keywords: Masonry, binding mortar, river sand, quarry dust, characteristic strength

1. Introduction

Binding mortar (joint layer mortar) has a pivotal role in the mechanical characteristics of masonry. A good bond between masonry unit and binding mortar contribute to improvement in compression, shear and bond strengths. The bond between masonry unit and mortar is influenced by several factors such as surface roughness of brick, water absorption rate of the brick, initial moisture content of the brick, sand grading used for binding mortar, mortar composition, mortar consistency and water retention capacity of the mortar [1-3]. In conventional masonry construction, river sand or natural sand is mixed with cement and used as binding mortar. The major constituent of the binding mortar is river sand and it is contributed 80% to 90% by volume.

In recent years, due to the rapid growth of construction activities, the demand for river sand is increased but the supply of river sand has not satisfied this demand. This is due to the strict restriction of sand mining from river bed as over-exploration of sand from river bed create a lot of adverse environmental impacts [4-5]. Due to that, in addition to the scarcity of river sand, the supplied river sand is also not in recommended quality. Therefore, in recent years, the extensive focus is on finding alternative materials for river sand for construction purposes.

There is widespread published literature on using agricultural waste [6-9], industrial waste [10,11], construction and demolition waste [11-13] and lateritic soil [14] as river sand replacement for construction materials. Published literature shows that incorporating these alternative materials, in construction materials such as concrete, cement blocks, and stabilized soil blocks is not only satisfied the strength and durability requirement but also the production is more cost-

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effective and sustainable. But using these alternatives in binding materials is more challenging as fine aggregates used for binding mortar should satisfy the recommended particle size grading limits and water retention capacity. Because these two characteristics of the mortar highly influence the strength of masonry.

Venkatarama Reddy and Gupta [15] reported the impact of sand grading on the cement-soil block masonry with cement mortar and cement-lime mortar. Results revealed that with the increase in fineness of sand, the water retention capacity of the cement mortar increased but cement-lime is not shown and significant variation in water retention capacity. Compressive strength mortar decreased with an increase in fineness of sand and cement-lime showed higher strength reduction compared to cement mortar with an increase in fineness. Also, the bond strength between block and mortar decreased with an increase in fineness of sand but limited variation showed in the compressive strength of cement-sand block masonry. Dehghan et al. [3] also reported similar findings from their study, where three mortar mixes with fine and coarse sand grading were used for solid clay brick masonry.

On the other hand, as the mortar placed over the absorptive materials such as fired clay bricks or concrete blocks, water retention capacity of the fresh mortar mix is more significant [16]. If the mortar retaining enough water for long enough, it can be preserved sufficient plasticity and provide good bond between brick and mortar. The water retention capacity of the mortar is significantly depended on structure and texture of the fine aggregate used [17].

Considering sand grading and water retention capacity, quarry dust is one of the best alternatives for river sand, which can be used as fine aggregates in binding mortar. Generally, well-graded particle distribution and the presence of cubically shaped particles in quarry dust provide a better contribution to cement-based materials compared with river sand [18]. Also quarry dust can absorb more water and the water might be released back when there is limited water available in the mortar for the hydration process of the cement [17]. This will positively affect the strength of mortar itself and bond between brick and mortar.

Studies on using quarry dust as river sand replacement in construction materials conducted for several decades [19-32]. Dilek [25], Zhao et al. [26] claimed that quarry dust increased the water demand for the concrete mortar mix for desirable workability compared with river sand. Gonçalves and Tavares [23] and Shen and Yang [24] stated that the water absorption rate of the concrete increased with an increase in quarry dust content. Donza et al. [27] and Gonçalves et al. [23] stated that quarry dust contributed to better mechanical properties and durability characteristics of conventional concrete. Nanthagopalan and Santhanam [28] claimed that particle size grading, particle shape and fine content of the quarry dust affect the physical and mechanical properties of the self-compacting concrete. Benabed and Kadri [29] and Bosiljkov [30] stated that the workability of the self-compacting concrete at the fresh stage is reduced with an increase in quarry content. Muhit Imrose et al. [31] and Mahakavi et al. [32] stated that the compressive strength of self-compacting concrete increased, when 50 to 60% river sand was replaced with quarry dust. Sundaralingam et al. [18] reported on incorporating quarry dust in cement-sand mortar. Results show that with river sand replaced by quarry dust the compressive strength and flexural strength was improved. However, water absorption rate, sorptivity and evaportation rate also increased with quarry dust content in the mortar.

Although there are several published literatures on the use of quarry dust as river sand in conventional concrete, self-compacting concrete and cement mortar, the study on how quarry dust incorporated cement-sand mortar is affect the mechanical characteristic of masonry is still limited. Therefore, the present study conducted a comprehensive analysis on compressive, shear and bond strength of masonry with binding mortar have different combination river sand and quarry dust as fine aggregates. In addition, fresh mortar properties and strength of hardened binding mortar were also studied.

2. Methods

2.1 Material Used

For the experimental program, the following raw materials were used.

- Cement: Ordinary Portland cement (OPC) was used as the binder material, described in Sri Lanka standard SS855.
- River sand: It was obtained from the river bed at Muthayankattu in Sri Lanka. It was sieved in the size range of less than 10 mm.
- Quarry dust: It was obtained production plant situated in Divulapitiya in Sri Lanka.
- Brick: Brick available in the local market with a size of 200×85×55 mm³ were used for casting masonry prisms. The characteristic compressive strength and water absorption rate are 5.88 MPa and 8.3%, respectively.

The characteristics of raw materials are summarized in Table 1. Figure 1 presents the particle size distribution of the river sand and quarry dust.

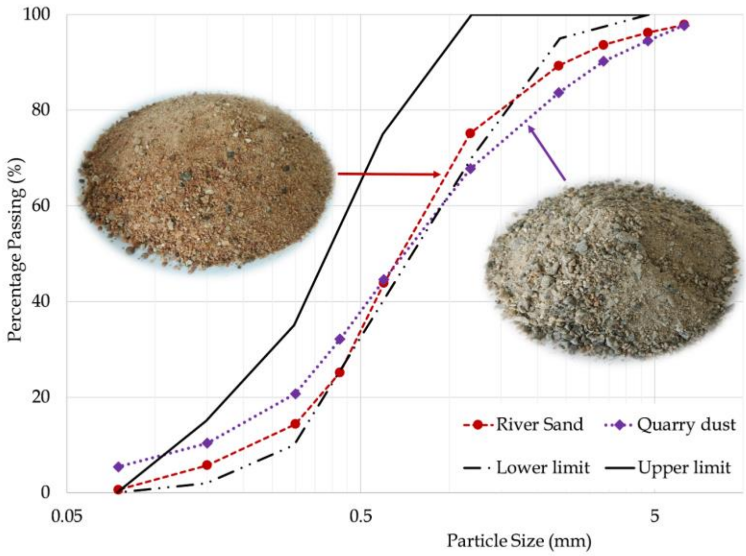

Fig. 1 - Particle size distribution of the river sand and quarry dust

Table 1 - The physical properties, chemical composition, and soil classification of the raw materials

	Cement	River sand	Quarry dust
Physical properties			
Density (kg/m³)	1182	1680	1641
Specific gravity	3.15	2.41	2.34
Water absorption (g/kg)		174	198
Fineness	1.10	2.89	2.97
Chemical composition			
CaO	66.55	0.6	3.81
SiO2	20.6	80.4	66.76
Al2O3	4.51	2.46	19.2
Fe2O3	3.62	1.14	3.62
MgO	1.17	0.19	1.64
Na2O	0.4	1.3	1.27
K2O	0.39	0.78	2.16
Soil classification			
Silt + Clay (%)		0.6	5.4
Sand (%)		95.6	89.1
Gravel (%)		3.8	5.5
Coefficient of gradation (Cc)		1.10	1.12
Uniformity coefficient (Cu)		4.01	6.72

2.2 Mix Design

Table 2 summarizes the quantity of material used for each mortar mix. The quantity of water added to each mortar mix was decided by to achieve the predetermined slump value, which was set as 25-35 mm. When the amount of quarry dust was increased in the mortar mix, the water requirement of the mix increased considerably.

Table 2 - Mix design adopted for mortars

Mix ID	Mix proportion (C:QD:RS) *	Cement	Quarry dust	River sand	w/c ratio
Q0	1:0:6	1.00	0.00	8.53	1.35
Q2	1:2:4	1.00	2.78	5.69	1.40
Q4	1:4:2	1.00	5.56	2.84	1.45
Q6	1:6:0	1.00	8.33	0.00	1.50

* C: cement, QD: quarry dust, RS: river sand

To check the mechanical properties of the mortar, cubes with dimensions 100×100×100 mm³ were cast to measure compressive strength. Similarly, blocks with dimensions 200×100×60 mm³ were cast to determine the flexural strength. To evaluate the mechanical properties of masonry, each mortar case, six masonry prisms, eight masonry triplets and 8 couplets are cast as shown Fig. 2. The thickness of the binding mortar was 10 mm. All the specimens were kept in moisture-curing for 28 days.

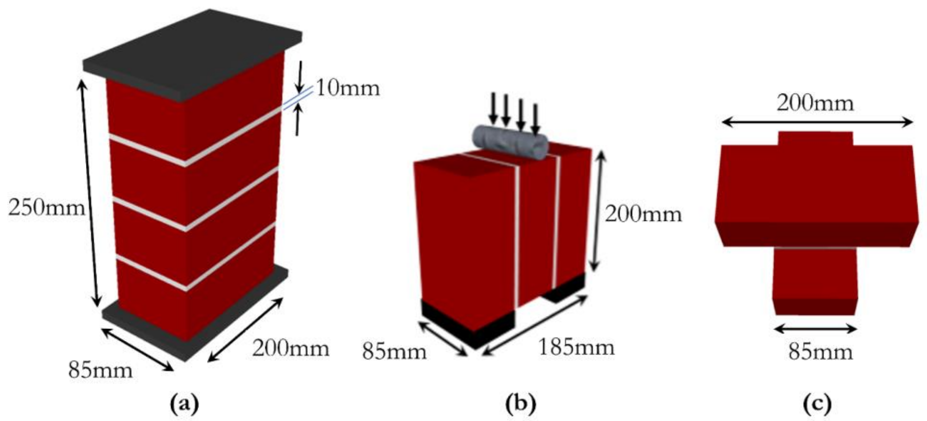

Fig. 2 - Outline of the test specimens; (a) compression test; (b) shear test and; (c) bond test

2.3 Testing

2.3.1 Test on Fresh Mortar

At the fresh stage, slump, slump flow, initial setting time, final setting time and moisture retention capacity were measured. Slump and setting time were measured following ASTM C143 [33] and ASTM C403 [34], respectively.

To check the water retention capacity of the fresh mortar, a drying test was done according to CSN EN 16322 [35]. The fresh mortar was filled in the aluminium cylinder (diameter of 100 mm and height of 25 mm) and then the specimen was kept in the laboratory environment (temperature of 30 °C and humidity of 80%) to dried out. The weight of the specimen was measured at certain time intervals. The moisture content per unit area at a particular time was given by the function of the mass of the mortar with container after a certain time (mt) and mass of dry mortar with container (md) and area of the aluminium cylinder (A) as Eq. (1).

$$\text{Moisture content} = (mt - md)/A \qquad (1)$$

The gradient of the initial linear segment of the moisture content vs. time is defined as the initial drying rate, D1 (expressed in kg/m2h). The gradient of the linear segment of the moisture content vs. square root of time is defined as the second phase drying rate, D2 (expressed as kg/m2h½).

2.3.2 Test on Brick and Binding Mortar

Bricks with the dimension of 200×85×55 mm³ and mortar cubes with a dimension of 100×100×100 mm³ were used for the compression test. Blocks with a dimension of 200×100×60 mm³ were used to determine the flexural strength of mortar. The tests for compressive strength and flexural strength were done according to ASTM-C109 [36] and ASTM-C348 [37], respectively. The load was applied at a force control rate of 0.01 KN/s. A water absorption test was done on both brick and mortars according to ASTM-C140/C140M [38].

2.3.3 Test on Masonry

The compression tests were executed according to BS EN 1052-1 [39]. The masonry prisms consisted of four bricks and three joints of mortar as shown in Fig. 2(a). The masonry prisms were cured under moist burlap for 28 days. Axial load was applied under displacement control at the rate of 1 mm/min. The compressive strength of the masonry prism (fcm) is calculated as ultimate load withstand by prism divided by area of bed face. For each mortar type, six specimens were tested.

To measure the shear strength of the masonry, the triplet test was adopted according to BS EN 1053-3 [40]. The triplet consisted of three bricks and two joints of mortar as shown in Fig 2(b). A distributed line load was applied at the top of the middle brick under displacement control at the rate of 0.3 mm/min. The shear strength of masonry was calculated using Eq. (2).

$$\text{Shear strength} = (P+W)/2A \qquad (2)$$

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

To measure the bond strength between brick and binding mortar, a masonry cross-couplet test was adopted according to ASTM C952 [41]. Figure 2(c) and Fig. 3 show the outline of the masonry couplet and test setup, respectively. The load was applied under displacement control at the rate of 0.3 mm/min. The bond strength of the masonry was calculated using Eq. (3).

$$\text{Bond strength} = (P+W_c+W)/A \qquad (3)$$

where, P is the maximum load before bond failure, Wc is the weight of the concrete cap, W is the weight of a brick and A is the area of the brick-mortar contact surface.

All the strength cases, characteristics strength of masonry was calculated using Eq. (4).

$$\text{Characteristics strength} = \text{Mean strength} - 1.64 * \text{Standard deviation} \qquad (4)$$

Fig. 3 - The test setup used for the measure of bond strength of masonry cross-couplet

3. Results and Discussion

3.1 Fresh Mortar Properties

For the good bond between brick and binding mortar intersections, some specific properties of fresh mortar are important. The significant properties of fresh mortar are slump, slump flow, setting time and water retention capacity.

3.1.1 Slump and Slump Flow

Slump and slump flow values for each mortar were measured for various water to cement (w/c) ratios by increasing the ratio by 0.5 and the results are presented in Fig. 4. For particular w/c ratio, the slump and slump flow reduced with increased quarry dust content. As quarry dust has some amount dust, which can absorb additional water was the reason for this behaviour. To make constant workability for all the mortar, the slump value was fixed as 30±5 mm. To achieve this slump value, the w/c ratio requirement was 1.35, 1.40, 1.45 and 1.50 for mortar mix Q0, Q2, Q4 and Q6, respectively.

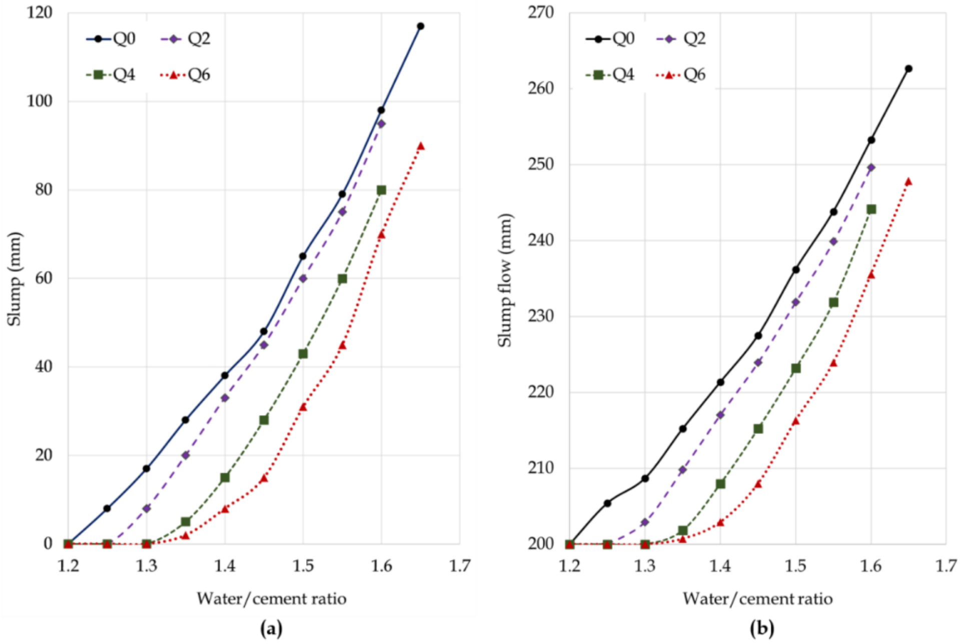

Fig. 4 - Slump and slump flow for various mortar mix

3.1.2 Setting Time

Figure 5 shows the setting time of fresh mortar mix with different quarry dust content. The longer setting time indicates that the fresh mortar can be workable for a longer period. Both initial and final setting time increased with an increase in quarry dust content in the mix. Higher finer particle content and water retention nature of the quarry dust may attribute to extended setting time. Compared to the fresh mortar with 100% river sand, the setting time of mortar with 100% quarry dust was extended by 45.8 and 19.1% for initial and final, respectively.

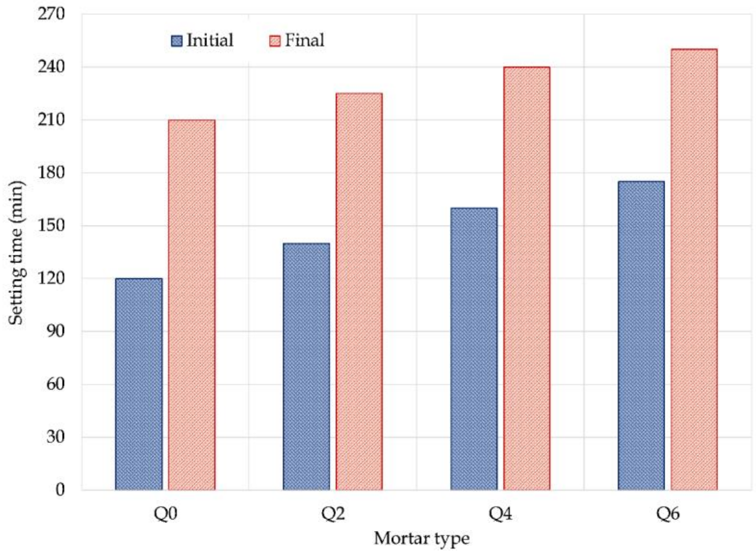

Fig. 5 - Initial and final setting time of the various mortar mix

3.1.3 Water Retention Capacity

The water retention capacity of the mortar is a vital property related to workability as well cause a good bond between brick and mortar. Higher water retention capacity is indicated by the mortar's ability to retain enough water and workable for a longer period, when carried into contact with absorptive brick [42]. Fine particle content and well-graded sand can improve the water retention capacity.

Fig. 6(a) and (b) show the moisture content variation of the fresh mortar mix with time and the square root of time, respectively. The initial moisture content of fresh mortar increases with quarry dust content. As quarry dust has finer content (5.4% and it is mostly dust) compared to river sand (0.6%), quarry dust absorbed more water during mixing. The initial moisture content of the fresh mortar was 3.04, 3.23, 3.26 and 3.55 kg/m2 for mortar mix Q0, Q2, Q4 and Q6, respectively. The results revealed that the initial evaporation rate decreased with quarry content in the mortar mix. The initial evaporation rate was 0.175, 0.099, 0.064 and 0.057 kg/m².h for mortar mix Q0, Q2, Q4 and Q6, respectively. However, at the second stage, there was no significant variation observed in the evaporation rate with quarry dust content. The secondary evaporation rate was 0.172, 0.175, 0.178 and 0.177 kg/m².h0.5 for mortar mix Q0, Q2, Q4 and Q6, respectively. These results revealed that incorporation of quarry dust in the fresh mortar improve the water retention capacity.

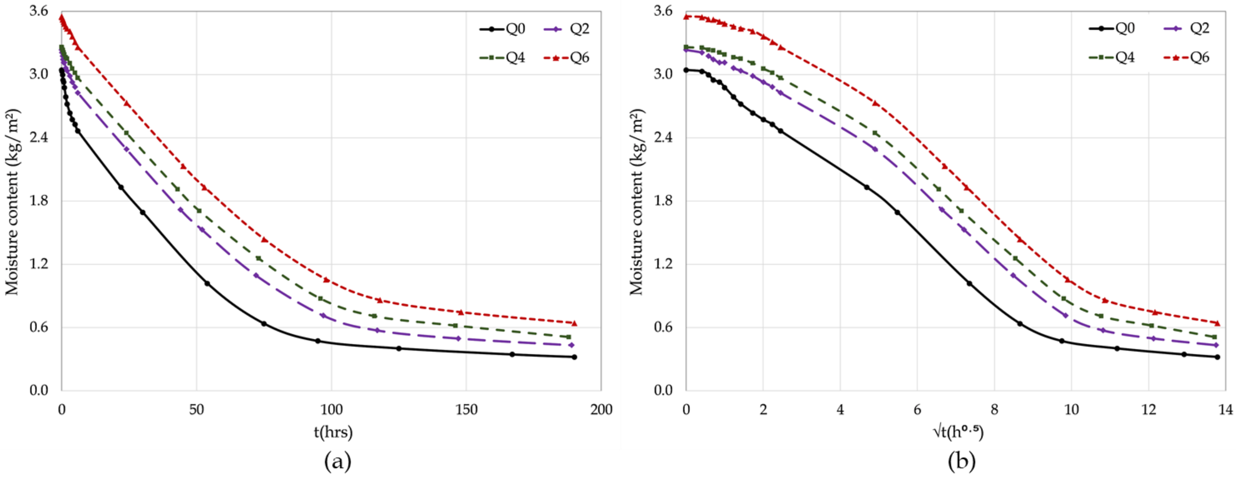

Fig. 6 - Moisture content variation of the fresh mortar with; (a) time and; (b) square root of time

3.2 Mechanical Properties of Brick and Binding Mortar

Figure 7 summarizes the Compressive strength, flexural strength and water absorption rate of brick and binding mortar. For all the binding mortar types, the mortar strength was lesser than brick strength. But flexural strength of mortars Q4 and Q6 showed higher flexural strength than brick. With the increase in quarry dust content, both compressive strength and flexural strength increased gradually. As quarry dust generate from crushing of rocks, quarry dust has angular shape and rough surface textures compared to smooth granular nature of river sand. Rough surface texture of the particle provides good interlocking and bond between cement gel and fine aggregates. Therefore, strength of the mortar was increased with quarry dust content in the mortar. The water absorption rate of the mortar was increased with quarry dust content. Due to angular shape of quarry dust, the surface area to volume ratio and void ratio are high. Therefore, mortar with quarry dust absorb more water.

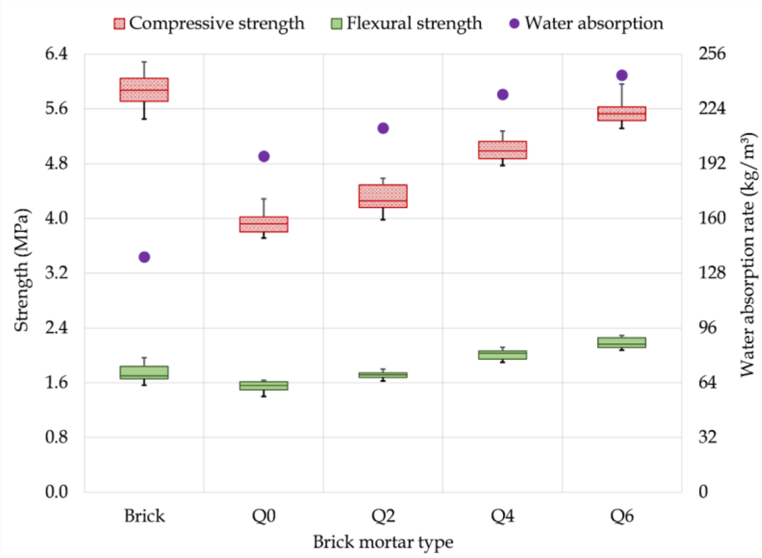

Fig. 7 - Compressive strength, flexural strength and water absorption rate of brick and binding mortar

3.3 Effect on Compressive Strength of Masonry

Figure 8 illustrates the typical compressive failure types of masonry prisms. There is a vertical tensile spitting failure that occurred along the axial loading direction. The crack initiated from mortar and it propagated through brick.

Fig. 8 - Typical compressive failure modes in masonry prisms

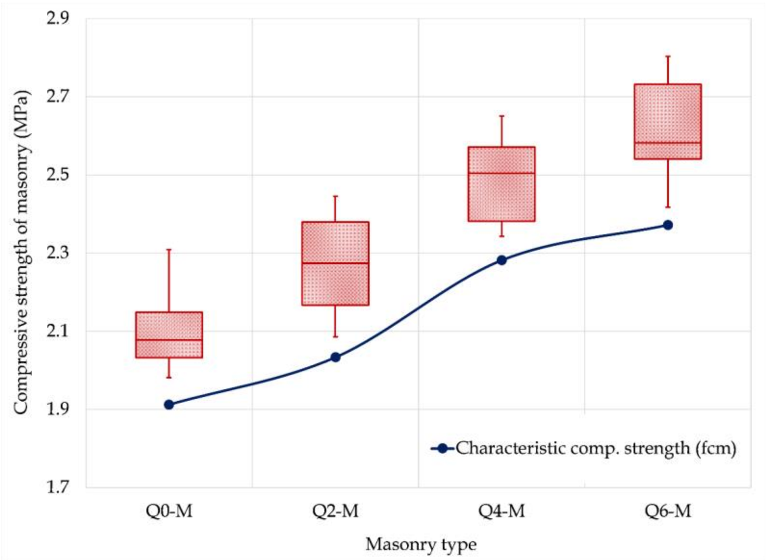

Fig. 9 - Compressive strength variation of masonry prisms with different binding mortar

Figure 9 illustrates the compressive strength variation of masonry prisms with a different type of binding mortar. Results indicated that an increase in the replacement of quarry dust contributed to the higher compressive strength of masonry. Compared with control mortar (Q0), the increase in compressive strength was 7.8, 18.2 and 24.2% for masonry prism with Q2, Q4 and Q6 mortar, respectively. The compressive strength of mortar itself and rough interface surface due to irregular shape and texture of the quarry dust may attribute to improvement in the overall compressive strength of the masonry.

3.4 Effect on Shear Strength of Masonry

Figure 10 presents the failure pattern of the masonry triplet observed in shear tests. All the specimens were failing along the interface between brick and mortar. This mainly occurred when bond strength between brick and mortar was lower than the tensile splitting strength of brick and mortar.

Figure 11 illustrates the shear strength variation of masonry prisms with a different type of binding mortar. When stronger brick and weaker mortar are used in masonry, the shear strength of the masonry depends on mortar strength itself, water absorption rate of the brick and water retention capacity of the mortar. In the present study, the same type of bricks was used, therefore shear strength improves with quarry dust content in the mortar as both compressive strength and flexural strength of mortar increased with quarry dust content. Considering the shear strength of masonry triplets with binding mortar of 100% river sand and 100% quarry dust, it is evident that with quarry dust, the shear strength increased by 111%.

Fig. 10 - Failure pattern of the masonry triplet under shear loading

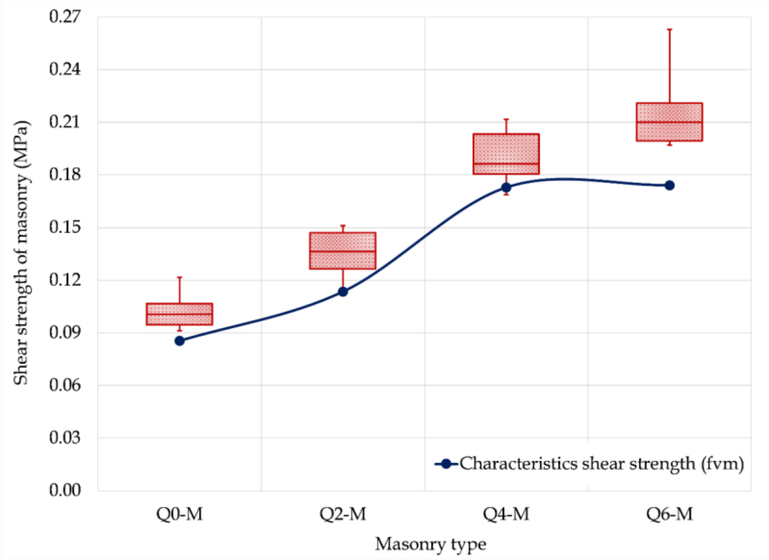

Fig. 11 - Shear strength variation of masonry prisms with different binding mortar

3.5 Effect on Bond Strength of Masonry

All the masonry couplets were failed in the brick-mortar interface during the bond test as shown in Fig. 12. This kind of failure occurs due to weak brick-mortar bond strength compared to the tensile strength of brick and mortar.

Figure 13 present the bond strength variation with masonry cross-couplets with different binding mortar. Similar to shear strength, bond strength also increased with quarry dust content in the mortar. Considering the bond strength of masonry couplets with binding mortar of 100% river sand and 100% quarry dust, it is evident that with quarry dust, the bond strength increased by 65%.

Fig. 12 - The failure pattern observed in the bond test

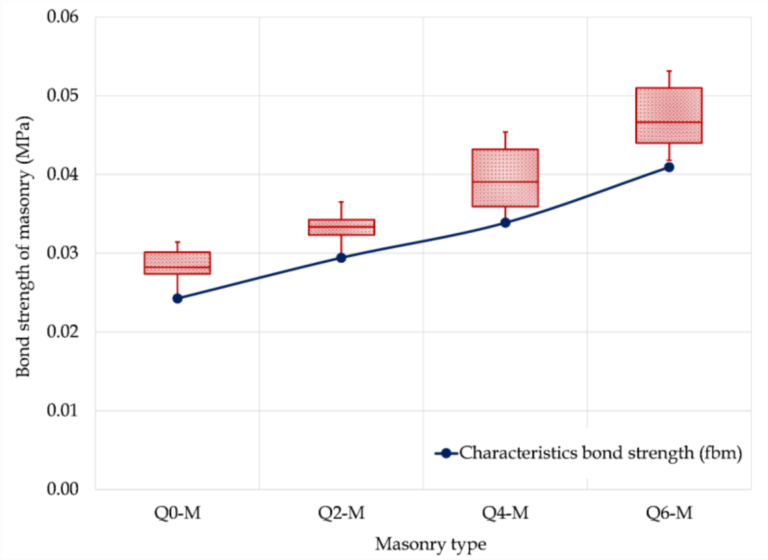

Fig. 13 - Bond strength variation with masonry cross-couplets with different binding mortar

3.6 Relationship Between Properties

Figure 14 illustrates the relationship between the characteristic compressive strength of masonry prism and binding mortar. Generally, the compressive strength of masonry depends on compressive strength brick, compressive strength binding mortar and type of brick and mortar used. Eurocode 6 [43] defines the equation for compressive strength masonry as Eq. (5).

$$f_{cm} = K\, f_b^{\alpha}\, f_j^{\beta} \qquad (5)$$

where f_{cm}, f_b and f_j are the characteristic compressive strength of masonry, brick and binding mortar, respectively. K, α and β are constant.

Eurocode recommended the K, α and β value for solid brick masonry with general-purpose mortar as 0.55, 0.7 and 0.3, respectively. However, several published literatures proposed a wide range of values for K, α and β depends on the type of masonry unit and binding mortar used [44-49]. When Eurocode Equation to predict the characteristic compressive strength of masonry, the results showed a very low coefficient of determination (R^2) value and standard error of 1.60 MPa, which is 74% of the mean measured value.

To predict the compressive strength of masonry with quarry dust incorporated mortar, statical regression analysis was out and predicted equation is given in Eq. (6). The R^2 value and standard error are equal to 0.895 and 0.039 MPa, respectively.

$$f_{cm} = 0.33\, f_b^{0.53}\, f_j^{0.59} \qquad (6)$$

In present study, as same brick type used for preparation of masonry, fb become constant. So, the predicted equation simplifies as Eq. (7).

$$f_{cm} = 0.90\, f_j^{0.59} \qquad (7)$$

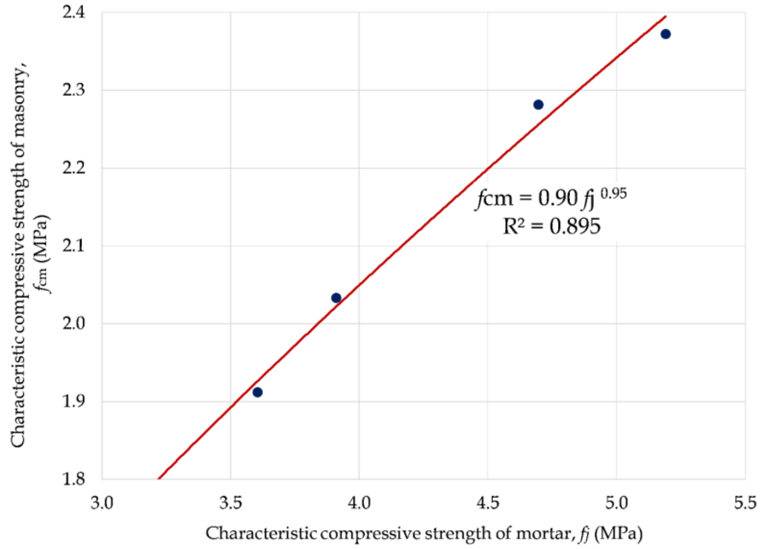

Fig. 14 - The relationship between characteristic compressive strength of masonry prism and binding mortar

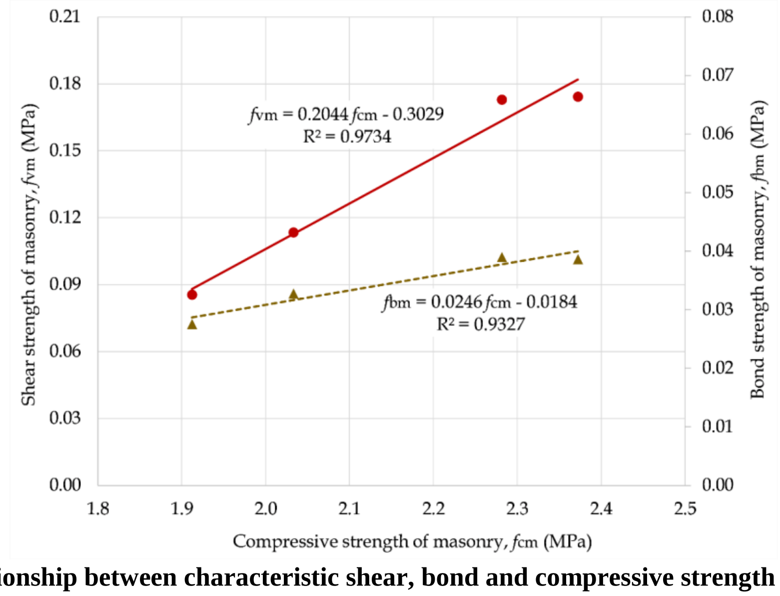

Fig. 15 - Relationship between characteristic shear, bond and compressive strength of the masonry

The characteristic shear strength variation of masonry triplet and characteristic bond strength variation with the compressive strength of masonry prism was mapped in Fig. 15. Which shows a linear relationship between characteristic shear strength and compressive of masonry, which can be obtained as Eq. (8).

$$f_{vm} = 0.2044 f_{cm} - 0.3029 \qquad (8)$$

Similarly, relationship between characteristic bond strength and compressive strength shows a linear relationship, which can be obtained as Eq. (9)

$$f_{bm} = 0.0246 f_{cm} - 0.0184 \quad (9)$$

4. Conclusion

The compressive, shear and bond strength of the brick masonry using quarry dust incorporated binding mortar was studied. To evaluate the effect of quarry dust as river sand replacement on binding mortar and overall strength improvement of masonry, binding mortar had been prepared using river sand and three levels of quarry dust replacement. The following inferences are concluded from the present study:

- The water demand to achieve the particular slump is higher for mortar mix with quarry dust. However, for particular slump, incorporation of quarry dust in binding mortar in the fresh state showed better setting time and improved water retention capacity.
- Hardened mortar with quarry dust shows higher compressive and flexural strength compared with mortar with river sand.
- Compressive, shear and bond strength of masonry improved with bind mortar, which incorporated higher quarry dust content. In general, the effect of quarry dust incorporated mortar on masonry strength was observed in the following order: bond, compressive and shear strength of masonry.

These results indicate that quarry can be used efficiently to produce more sustainable masonry binder mortar. The utilization of quarry dust for masonry binder mortar reduces the river sand usage and therefore, reduces environmental pollution caused by sand mining at the riverbed.

Acknowledgements

The authors express their sincere gratitude for the support given by Department of Civil Engineering, Faculty of Engineering, University of Jaffna.

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