Sustainable Alternatives for Green Mortar: Quarry Waste and Ultra high fly ash utilization

I Zafar
Department of Civil Engineering, College of Engineering, Imam Mohammad Ibn Saud Islamic University, P. O. Box 5701, Riyadh 11432, Saudi Arabia
izhussain@imamu.edu.sa

Abstract. The use of waste materials from different industries as a replacement of cement has gained much attention all over the world. In addition, many attempts have been done to replace partially or totally one of the ingredients from the mix design to lower the negative impacts of construction industry. In this study, quarry waste and fly ash were used as two different sustainable approaches to replace the maximum volume of natural alluvial sand and cement, respectively, in the traditional mortar matrix. The quarry waste is a by-product of quarries characterized with a large volume of fines, whereas, fly ash is the by-product of coal-fired electric generation plants. The performance of the green mortars containing the maximized volume of quarry waste and fly ash were evaluated with regard to the mechanical properties. The results have clearly indicated the beneficial use of the quarry waste and fly ash as a substitute for siliceous sand and cement respectively in preparation of green mortars. In addition, the cost and parametric analysis was also performed for a multi-story reinforced concrete building using the designed quarry sand and fly ash as concrete ingredients.

1. Introduction
Construction industry has been under the spotlight for last few decades due to its consumption of natural materials and emission of greenhouse gasses during the production process of several construction materials. Sustainable and green construction materials and methods are the need of the hour for construction industry to cope up with the environmental challenges. In this regard, the concrete experts and scientists have incorporated different waste or by-products of various industries as a replacement to one of the major constituent of concrete i.e. cement, sand and coarse aggregates. The focal point of the researchers in selecting the waste or by product was to maximize the positive impact on environment concerns minus the negative effects on mechanical and durability properties of resulting concrete. Ground granulated blast furnace slag, silica fume and fly ash has been used in the past as a potential replacement for binders in concrete [1, 2, 3]. Recently, the potential candidates for sand replacement in concrete i.e. marble leftover, scoria and bottom ash were also evaluated [4, 5]. In addition, a binding material, geopolymer, has become the pivotal point of concrete researchers for the last one decade as a promising replacement for cement which account for almost 88% of the total emissions of concrete mix [6, 7].

Mortar is one of the most common construction materials being used in masonry and repair works for existing structures. Traditional mortar is a mix of water, cement and sand in different proportions depending upon the utilization. The mortars used for maintenances and repairs help in extending the service life of the existing structures, as a result lower the additional production of cement and concrete. Thus, the sustainable and durable mortars can play a significant role in preservation of
structural integrity of standing structures along with taking down the undesirable environmental sways of construction industry. In 2019, the assessed worldwide usage of the repair mortars was around USD 2.5 billion [8]. This amount is anticipated to increase by a predictable compound annual growth rate of 4.7 % over the next few years because of the global increase in the infrastructure growth of megacities striving for better accommodation & transportation facilities in addition to the maintenances and repairs of standing structures.

Therefore, in the light of above discussion, the current study focused on evaluating the use of the wastes/by-products of coal fired energy sources and quarry sites i.e. fly ash and quarry wastes as a replacement to cement and sand respectively for the formulation of sustainable mortars. It was proposed to replace both basic ingredients i.e. sand and cement, as the former represents higher volume while the latter is higher in cost. Although, the fly ash has been extensively used in the past as a cement replacement but in the majority of the studies its percentage was limited to 30%, nonetheless, in this study, the ultra-high replacement percentage will be targeted. Three main types of mortar series were prepared, i.e. mortars with 100% replacement of quarry waste, mortars with different percentages of fly ash as cement replacement (50% and 60%) and fly ash with 100% replacement of cement. Compressive strength was selected as the prime criteria to determine the potential feasibility of these mortars to be used for practical purposes. In addition, the detailed cost analysis based on two damaged scenarios for a reinforced concrete multi-storey building was also done to evaluate the economic aspects of the formulated mortars in comparison to standard/traditional repair mortars.

2. Materials and Experimental Procedures
The ordinary Portland cement was used in the current study with a density and Blaine fineness of 3.02 g/cm³ and 318 m²/kg respectively. The local quarry site supplied the quarry waste, which was utilized for the preparation of first type of mortars. The quarry fines are generally collected in the course of crushing the rocks of lime stone. The detailed chemical composition of quarry waste is shown in Table 1. The typical river sand was used to make the control mortar series for quarry waste mortar and also for the second type i.e. fly ash mortar series. The fineness modulus of quarry waste and river sand was found to be 3.53 and 1.63 respectively. The percentage of fines for quarry waste and river sand were found to be 14.1% and 3.1% respectively. The density of quarry waste and river sand was estimated to be 2.66 g/cm³ and 2.63 g/cm³ respectively. The aforementioned results showed the quarry waste to be finer in comparison to typical river sand. Class F fly ash was used in this study as a potential replacement for cement, and its chemical composition is shown in Table 2.

| Oxides | CaO | MgO | SiO₂ | SO₃ | Cl | Fe | Si | Al |
|--------|-----|-----|------|-----|----|----|----|----|
| Percentage | 37.5 | 13.35 | 0.89 | 0.7 | 0.05 | 0.17 | 1.91 | 0.12 |

Table 1. Chemical Composition of major constituents of quarry waste

| Oxides | SiO₂ | Al₂O₃ | CaO | Fe₂O₃ | MgO | K₂O | Na₂O | LOI |
|--------|------|-------|-----|-------|-----|-----|------|-----|
| Percentage | 56.34 | 23.08 | 9.02 | 6.43 | 1.70 | 0.56 | 0.28 | <3% |

Table 2. Chemical Composition of major constituents of fly ash used in this study

Two different mortar series were prepared, i.e. MQ (containing 100% quarry waste instead of river sand) and MF (containing different percentages of fly ash instead of cement). A water to cement ratio of 0.55 and sand to cement ratio of 3 was selected for MQ series, while water to binder ratio of 0.45 and sand to binder ratio of 2.75 was selected for MF. A little higher water to cement ratio was selected for the MQ series as the quarry fines have higher percentage of fines while fly ash particles are spherical in nature. The detailed mix proportions are shown in Table 3. All the ingredients including cement, sand and fly ash were mixed for three to five minutes along with the measured quantity of water to achieve the desired evenness in the mix. All the mixing and casting of the mortar specimens
was done in accordance with the ASTM C270-19 [9]. All the specimen series were water cured 28 days.

### Table 3. Mix proportions for mortar series used in this study

| Mortar Type | Nomenclature | Cement | FA  | Sand | Water/Binder |
|-------------|--------------|--------|-----|------|--------------|
| MQ          | MQ0          | 1      | -   | 3    | 0.55         |
|             | MQ100        | 1      | -   | 3    | 0.55         |
| MF          | MF0          | 1      | -   | 2.75 | 0.45         |
|             | MF50         | 0.50   | 0.50| 2.75 | 0.45         |
|             | MF60         | 0.40   | 0.60| 2.75 | 0.45         |

The compressive strength was determined for MQ series 7, 14 and 28 days, while for MF 28- and 56-days strength was determined as the fly ash shows delayed strength gain because of the expected pozzolanic reaction. The compressive strength for all the mortar series was conducted in compliance with ASTM C109/C109M [10]. The values of compressive strength represent the average of the three tested specimens.

### 3. Results and Discussions

#### 3.1. Mechanical Properties

The results of the compressive strength for MQ series are shown in Figure 1. The values of compressive strength have increased with age for both the control mix and mortar containing 100 percent quarry waste. It was observed that quarry waste replacement was shown an increase in the compressive strength values at all the ages. An increase in the compressive strength of 14.3%, 24.7% and 8% was observed at 7, 14 and 28 days respectively for the mortar series containing 100 % quarry waste as compared to the control mix. This increase might be because of the two factors, i.e. the filling effect due to higher percentage of fines at the early and minor degree of pozzolanic activity. The other researchers have also pointed out the reduction in the porosity of the mix incorporating the quarry waste [11].

The results of the compressive strength for MF series are shown in Figure 2. It was observed that as the percentage replacement of fly ash has increased the compressive strength values of the fly ash mortars had decreased. At 28 days, the mortar specimens containing 50% and 60% fly ash have shown a decrease of 53.1% and 51.3% respectively, in comparison to the control mix. While at 56 days, there was slight reduction in the decreasing trend of the compressive strength with the increase in the fly ash ratio i.e. M50 and M60 mortar series have shown a reduction of 43.4% and 42.3% respectively, as equated to the reference mix. This slight improvement in the compressive strength values might be because of the delayed pozzolanic reactivity of fly ash as indicated by the previous studies [1].

From the above results, it can be clearly observed that the quarry waste replacement had shown comparable results as that of the traditional cement-sand mortars, however, the higher percentage replacements for fly ash have resulted in the significant decrease of compressive strength. In this aspect, another methodology which is becoming quite popular among the concrete researchers i.e. geo-polymerization, was opted to increase the usage of fly ash with fully replacing the traditional cement from the mix. The percentage of fly ash used for geo-polymer mortar mix was 70% in reference to MF0. The detailed mix proportions are shown in Table 4. The detailed procedure of preparation of geo-polymer mortar (GM) can be referred to another a recent study of same author [12].
Figure 1. Compressive strength values for MQ series

Figure 2. Compressive strength values for MF series

Table 4. Mix proportions and mechanical strengths for geopolymer mortar used in this study

| Binder Type | Sand | Na$_2$SiO$_3$/NaOH | Liquid/Solid | Compressive Strength (MPa) | Bond Strength (MPa) |
|-------------|------|-------------------|-------------|---------------------------|-------------------|
| Cement      | FA   | 0.5               | 2           | 36.5                      | 74.6              |
| ---         | 0.5  | 0.4               | 1 day       | 28 days                   | 3.25              |

The geopolymer mortar has shown immense increase in the compressive strength as compared to the MF series and has appeared to be a strong candidate for repair concrete mortars specifically because of its early strength gain.

3.2. Cost Analysis as Case Study

To analyse the cost effectiveness of the designed mortars, a multi-storey reinforced concrete office building was selected as a case study. The majority of the rooms were used either as offices or meeting rooms. It has 18 offices and 2 rest rooms in each floor. The details of the reinforced building are shown in Figure 3. It has seven stories and flat plate slab was used to lower the total weight of the structure. The dimension of each flat slab was 4.8 m x 3.6 m. The total height of the building is 27.8 m with 49 numbers of columns. The building has been in service for around 50 years and needs some repair and maintenance to extend its service life. Two scenarios were considered i.e. the walls were built by using masonry bricks and second the walls were made by using plain concrete. In first damage
scenario the building requires the tuck pointing or repointing of the brick walls while in second scenario the 50% of the concrete walls in the building has suffered the cracks. The cracks have not penetrated more than 50mm in depth and the maximum crack width is less than 100 mm.

Figure 3. Details of the multi-storey reinforced concrete building

Based on the results of compressive strength, it was suggested to use MQ and MF or the tuck pointing or repointing of the brick walls while the geopolymer mortar was proposed for repair of concrete walls and comparison will be made in both cases with traditional/standard repair mortars. The detailed cost estimation for the tuck pointing or repointing of the brick walls for the whole multi-storey building is shown in Table 5. The office building had a frame structure as the main load carrying system, thus, all the walls were treated as non-load bearing walls. The total surface area of each wall in both directions was calculated and multiplied with respective total number of walls in each floor to estimate the total repair area. The total repair cost using the traditional mortar for tuck pointing and repointing was estimated by the taking the product of total repair area in each direction and the average per square market rate for each technique as shown in Table 5. However, to analyse the cost efficiency of the prepared mortar series, market prices for each constituent were acquired from the different sources in addition to the estimation of the weight percentages of each material used for the preparation of all mortars types as shown in Table 6 and 7 respectively. The average price for each constituent was converted in terms of the unit cement price.

Table 5. Estimated Repair Cost for the multi-story building using traditional mortar

| Avg. Cost per Sq. Ft (USD) | Wall Dimensions (m) | Total Repair area (m²) | Total Repair Cost (USD) |
|---------------------------|---------------------|------------------------|-------------------------|
|                           | (N-S) | (E-W) | (N-S) | (E-W) | Tuck Pointing | Repointing |
| Tuck Pointing             | 12.5  | 9     | 3.2 x 3.6 | 3.2 x 4.3 | 486.8 | 581.5 | 13355 | 9615 |

Table 6. Price ratio for the materials used in the preparation of mortars series

| Materials  | Water | Cement | Sand | Fly ash | Quarry Waste | NaOH | Na₂SiO₃ |
|------------|-------|--------|------|---------|--------------|------|--------|
| Price Ratio| 0.01  | 1      | 0.12 | 0.45    | 0.08         | 3.5  | 1.1    |
To calculate the cost of each mortar type, the weight percentage of each constituent was multiplied with the respective cost ratio. The results for the cost analysis are summarized in Table 8. It was observed that the incorporation of 100% quarry waste led to reduction in the overall price of mortar by 15.4% as compared to the control mortar while, on the other hand, the fly ash has shown relatively higher cost savings i.e. 20.6% and 24.7% at 50% and 60% replacement of saving. This increase in savings is mainly coming from the reduction in the amount of the cement being reduced. However, it should be noted here that, although the replacement of fly ash has reduced the overall cost of the mortar but at the expense of lessened compressive strength. In addition, the geopolymer mortar has shown an increase of about 75% in the overall price of the mortar as equated to traditional mortar; however, its 28 day’s compressive strength is almost 5 times more than MF0. Therefore, in author’s opinion, a clearer picture of the cost-benefit analysis is displayed in terms of cost to strength ratio as shown in Table 8. It was found that the mortar with quarry waste (MQ100) and geopolymer (GM) series have shown the reduction in the cost to strength ratio by 22.1% and 21.5% respectively while the fly ash mortars have shown an immense increase.

### Table 7. Percentage weight for the materials of all the mortars series

| Mortar Type | Water | Cement | Sand | Fly ash | Quarry Waste | NaOH | Na₂SiO₃ |
|-------------|-------|--------|------|---------|--------------|------|--------|
| MQ0         | 0.121 | 0.22   | 0.659| -       | -            | -    | -      |
| MQ100       | 0.121 | 0.22   | -    | -       | 0.659       | -    | -      |
| MF0         | 0.107 | 0.238  | 0.655| -       | -            | -    | -      |
| MF50        | 0.107 | 0.119  | 0.655| 0.119   | -            | -    | -      |
| MF60        | 0.107 | 0.095  | 0.655| 0.143   | -            | -    | -      |
| GM          | -     | -      | 0.38 | 0.38    | -            | 0.08 | 0.15   |

### Table 8. Percentage weight for the materials of all the mortars series

| Mortar Type | Savings (%) | Cost Saving |
|-------------|-------------|-------------|
| MQ0         | Ref-MQ      | Ref-MQ      |
| MQ100       | 15.4        | 22.1        |
| MF0         | Ref-MF      | Ref-MF      |
| MF50        | 20.6        | -69.1⁹⁷     |
| MF60        | 24.7        | -54.6⁹⁷     |
| GM          | -74.7⁹⁷     | 21.5        |

⁹ Negative sign means increase in the cost.

In addition, a comparison for the second damage scenario was also made with a commercial repair mortar. It was assumed that the total amount of mortar required for the repair of concrete walls for the commercial repair mortar and geopolymer mortar prepared in this study will be same. It was found that geopolymer mortars were almost 4.7 times cheaper than the commercially available standard repair mortar. The results found in the current study are consistent with the previous published literature [13, 14 and 15].

4. Conclusions

By products from the quarries and coal fired energy sources have been utilized in the current study to explore their feasibility in replacing the ingredients of traditional cement-sand mortar. Different
mortar series have been prepared and compared with respective control mix. Following are the major conclusions of the current study:

- It was found that the replacement of 100% quarry waste with normal river sand showed an increase of about 8% in 28-day compressive strength. However, the fly ash replacement with cement at 50% and 60% has resulted in a decrease of about 43% and 42% respectively. In addition, the alkali-activated fly ash based geopolymer mortar was also prepared and it showed an increase in the 28 day compressive strength by almost 5 times as compared to control mortar.

- The cost analysis based on two damage scenarios for a multi-story building was also conducted and the comparison among the mortars was made on the basis of cost to strength ratio. It was found that the quarry waste mortar and geopolymer mortars have shown the reduction in the cost by 22.1% and 21.5% respectively as compared to control mortar, however, the cost to strength of fly ash mortars have increase mainly due to their lessened strength at higher replacement levels.

- Overall, the quarry waste and fly ash in light of mechanical properties and cost analysis have shown themselves as potential alternatives for preparation of sustainable green mortars.

5. References

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