Modulus of rupture and surface morphology of the cement composites with the addition of quarry dust

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Abstract. Quarry dust is widely used as a substitute material in the cement composites because of its strength, and at the same time the re-use of this by-product waste from the rock mining operations has led to the environmental awareness amongst the researchers all over the world. In this research, an experimental study was undertaken to find out the effect of quarry dust for varying percentage replacement of river sand on modulus of rupture of the cement composites. Besides that, this paper also aims at the relationship of the modulus of rupture and surface morphology of the cement composites. Properties of the cement composites are investigated with partial sand replacement with the addition of quarry dust at 10 wt.%, 12.5 wt.%, 15.0 wt.% and 17.5 wt.%.

Cement composites were cured, tested for modulus of rupture and characterized for surface morphology at curing period of 7 and 28 days to obtain the optimal value of quarry dust in the cement composites. The results of this research have indicated that 12.5 wt.% of quarry dust exhibits the optimal value of modulus of rupture and surface morphology in satisfactory condition.

1. Introduction

In civil engineering, cementitious materials have been widely proposed for many decades ago and grow rapidly in present to constructing architectural structures. Unfortunately, the rapid development at the same time producing waste materials that can threaten our natural ecosystems if not properly managed and controlled. Construction industry is a major consumer of non-renewable resources and a massive producer of waste, and the operation of the buildings is responsible for around half of the total CO₂ emissions [1] and depletion of natural resources such as natural sand.

Throughout the history of construction industry, river sand has been used as one of the major components of the construction materials due to ready availability, strength and stiffness to absorb the loads [2]. Lately, the demand of river sand is very high due to its strength properties especially in developing countries to satisfy the rapid infrastructure growth. In spite of this, the intensive river sand mining to fulfil the construction demand eventually will result in environmental failure and the construction industry may come to a halt if there are no alternatives for river sand. For an example, India have facing the shortage of quality natural sand that are being depleted and causing serious threat to environment as well as the society [3]. Mainly the worldwide consumption of fine aggregate in the production of concrete is very high and several countries have encountered the difficulties meeting this need and have adopted for alternative materials [4]. In this regard, renewable energy resources appear to be the one of the most efficient and
effective solutions to promote and achieved towards the sustainable developments. In fact, due to simultaneous awareness increase on the importance of environmental rehabilitation and sustainable development, many by-products or wastes such as silica fume, wood ash, metakaolin, coal ash, quarry rock powder and other recyclable sources can be used as an alternative materials as fine or cement replacement, depending on their chemical and physical properties. Moreover, the use of quarry dust as alternative material has been widely studied by previous and present researchers from the point of strength and value added in the sustainable construction. Through the economic concern, there is 40% saving if quarry dust used instead of sand [5].

Based on the analysis by Balamurugan [6], the escalation in cost of sand due to administrative restrictions in India, demands comparatively greater cost at around two to three times the cost of quarry dust even in places where river sand is available nearby. Many researchers all over the world investigate the potential use of quarry dust either as a partial or as fully replacement of fine aggregates in the cement composites or concrete production. As a matter of fact, the main objective of the study is to determine the effect of quarry dust as partial sand replacement material in the cement composites when subjected to the flexural load, and at the same time investigate the crack profile and surface morphology of the cement composites that influenced by the quarry dust. The successful utilisation of quarry dust in the cement composites become one of the significant sign to the energy rehabilitation and sustainable development in the construction industry.

2. Materials and methods

In this research, the methodology process was classified into four sections, which are raw materials characterisation, sample preparation, mechanical testing and sample characterisation. The raw materials used in the research to produce cement composites consist of ordinary Portland cement, river sand, quarry dust and water. Quarry dust was milled by using ring mill machine and sieved to obtain the powder form in the range of 75 micron and below. Meanwhile, river sand was cleaned up by using rough screen to remove any impurities, dried up under room temperature and sieved to obtain the size of 2mm and below. These raw materials were weighed according to the planned proportion as tabulated in Table 1 and mixed together in a mechanical mixer to obtain a homogeneous mixing of the cement composites.

| Cement: Sand: Quarry dust (wt.%) | Quarry dust (wt.%) | Water/cement |
|---------------------------------|-------------------|--------------|
| 1:1.00:0.00                     | 0.00              | 0.45         |
| 1:0.90:0.10                     | 10.0              | 0.45         |
| 1:0.875:0.125                   | 12.5              | 0.45         |
| 1:0.850:0.150                   | 15.0              | 0.45         |
| 1:0.825:0.175                   | 17.5              | 0.45         |

Afterwards, the fresh cement composites were placed into the mould of 40mm x 40mm x 160mm and were allowed to settle down for 24 hours. The cast samples were removed from the moulds and immediately immersed into the curing tank for 7 and 28 days and not to be allowed to become dry until the days of testing. The samples were taken out from the curing tank at the day of testing to determine the modulus of rupture of the cement composites through flexural test. The surface of the samples were wiped off from any loose material, placed centrally and loaded uniformly under Universal Testing Machine (Instron) until the sample failed.

The next step in this research is to investigate the surface morphology of the cement composites after failed under the flexural load. The samples of the broken cement composites were observed by using stereomicroscope with 10 times of magnifications. The significant of this observation is to study the pattern of particles distribution and the appearance of voids in the cement composites. The findings of this study can be used to understand the relationship of both investigations and the effects of quarry dust to the strength development in the cement composites.
3. Results and discussions

3.1. Modulus of rupture

The results of flexural test were calculated and recorded as the modulus of rupture and expressed in MPa. According to Figure 1(a), the modulus of rupture at 7 days of curing showed the cement composites without the addition of quarry dust failed at 10.80 MPa. The graph trend showed the increment pattern after the result gradually increased to 12.72 MPa and 13.96 MPa when the cement composites was respectively added with 10.0 wt.% and 12.5 wt.% of quarry dust. However, when the content of quarry dust was added to 15.0 wt.% and 17.5 wt.%, the cement composites were easily fractured under the flexural load and were expressed with the decreased value of the modulus of rupture to 13.64 MPa and 13.20 MPa respectively.

Generally, the modulus of rupture was influenced by maturity of the cement composites along the curing ages. The result at 28 days of curing in Figure 1(b) showed that the modulus of rupture of the cement composites was failed at 14.16 MPa even though without the addition of quarry dust. The same increment trend like 7 days of curing can be observed when the percentage of quarry dust has increased from 10.0 wt.% to 12.5 wt.%, and the modulus of rupture showed the little differences from 15.41 wt.% to 16.34 wt.% respectively. As can be seen, when the content of quarry dust has been added to 15.0 wt.%, the result slightly decreased to 15.36 MPa, subsequently decreased again to 15.33 MPa, and became the lowest value of modulus of rupture with the addition of 17.5 wt.% of quarry dust.

![Figure 1](image_url)

(a) 7 days
(b) 28 days

Figure 1. Modulus of rupture of cement composites at (a) 7 days and (b) 28 days.

As the discussion, the utilisation of quarry dust as a partial sand replacement material experimentally proved has the beneficial effects in strength improvement of the cement composites. According to the result, the cement composites with the addition of quarry dust at various percentages showed the modulus of rupture was more higher than the conventional cement composites (0 wt.% of quarry dust). The experiment by Tasnia [7] on the mechanical properties of modified mortar by stone dust reported that the replacement of 25 wt.% of fine aggregate is higher than normal mortar containing only sand. Alternatively, the study of cement composites with the addition of limestone dust and wood sawdust at 10 and 20 wt.% provide the better results of the flexural strength [8]. Undoubtedly, the percentage of quarry dust tends to influence the modulus of rupture in the cement composites as well. The higher content of quarry dust, the modulus of rupture has displayed the descending trend.

The reduction of modulus of rupture in the cement composites essentially same with the strength concept in the concrete production. The finding revealed that the flexural strength of concrete decreases with increase in percentage of fine aggregate replacement with quarry dust. Sakthivel [9] stated that the partial sand replacement by quarry dust in the concrete mixed at 10, 20, 30 and 40 wt.% resulted in the lessening trend of flexural strength at 28 days from 11.20 to 10.60, 9.38 and 9.23 MPa respectively. The research by Lohani [10] showed that the reduction of flexural strength occurred at 28 days of curing when the content of quarry dust constantly increased from 20, 30, 40 and 50 wt.. Before that, Radhikes [11] studied the
effect of crushed stone dust as fine aggregate in paving blocks, and found that the flexural strength decreases when the percentage of crushed dust increased from 25, 50, 75 and 100 wt.%. In addition, the high content of quarry dust also increases more amounts of dust particles, which influence the fineness and particles distribution in the cement composites. The previous research revealed as the crushed stone dust content exceeds 15 wt.%, the flexural strength decreases due to the inability of the cement paste to coat all fine and coarse particles [12]. Moreover, according to BS 882:Part 2:1983 allows the content of dust or particles passing 75 µm BS test sieve up to 15 percent by mass for crushed rock fine aggregates [13]. Beyond the limits, the cement–aggregate bond face the weak phenomenon and consequently led to a loss in strength for higher filler amounts than the optimal value [14].

In this research, the optimal value of quarry dust indicates at the addition of 12.5 wt.% compared to the another percentages. The suitable content of quarry dust at 12.5 wt.% caused the dust particles distributed evenly that acted as a filler and helps to reduce the total voids in the cement composites. In other words, water cement ratio, the type of fine aggregate, and the cement content were kept constant for all the mixes, and the only variable was the percentage of quarry dust and river sand. Therefore, the voids in fresh cement composites are filled with dust, and the total air in the cement composites has decreased when the percentage of quarry dust content increased. For an example, the fine particles of quarry dust play an important role in filling large voids and internal gaps in the slurry to generate a compact microstructure, which is beneficial for the increase of strength properties [15]. Furthermore, the physical effect of quarry dust that can be utilized as filler in the cement composites due to its fineness and can fit into spaces between cement grains and sand [16].

Besides that, the strength development of cement composites is majorly depending on the properties of the materials and amount of stresses. The factors affecting the strength of the mortar are the cohesion of the cement paste and its adhesion to the aggregate properties [7]. The shape and particle size of quarry dust also tends to influence the packing effect and voids content [17] in the hydrated cement composites. According to Mehta [18], crushed rocks such as granite show a rough texture can affect particularly to the flexural strength during early age. The rougher texture seems to help the formation of stronger physical bond between the constituents, especially in mechanical properties in the cement composites. Additionally, quarry dust imparts very good improvement to mechanical and chemical properties, which develops the durability of the cement composites by reinforcing the microstructure through the filler effect and thus reduces the segregation and bleeding [17].

The further step is to present the crack profile and surface morphology of the cement composites after being loaded by the mechanical pressure and its connection with the obtained result. The both results explain the effect of quarry dust at different percentages and the importance reason to control the inclusion of quarry dust in the cement composites. In this research, the highest and lowest modulus of rupture has been obtained with the addition of 12.5 wt.% and 17.5 wt.% of quarry dust at 28 days of curing. According to the point of mechanical strength, the strength development of the cement composites indicated the best result at the age of 28 days. Since the strength is 99 % at 28 days and consumed as the full strength, the results of cement composites was reviewed as acceptable strength and reliable for safety factor and the design purposes of the structures [19].

3.2. Crack profile
The crack profiles of cement composites are strongly depending on the mechanical properties and closely related to the obtained results. As can be seen from Figure 2 (a-b), the crack have been shearing at the top and ended at the bottom of the cement composites under the pressure load. According to Figure 2(a), the cement composites have been failed in shearing pattern with the addition of 12.5 wt.%, even so still in good condition and not totally crushed under the pressure load. The result influenced due to the bonding and interlocking properties of quarry dust in the cement composites. The addition of quarry dust less than 75 micron meters in the mixture plays an importance role in controlling the properties of the cement composites. The inclusion of quarry dust at 12.5 wt.% will yield a more cohesive mix than the cement composites made with the addition of 17.5 wt.%.
Furthermore, the result of cracking pattern is depending on the physical effects of quarry dust such as surface texture and shape of the dust particles. Quarry dust has a rough surface texture and angular in shape as displayed in Figure 3, which makes the propagation of crack more difficult and influenced the crack patterns. In fact, the crack propagates along the weak points such as interface zones of ‘cement paste-aggregate’ and since the quarry dusts are characterised by its high angularity that leads to a good tangle of granular structure, the crack length is longer and more zigzagging. The previous experiments shown that the rough-textured aggregate has to increase in contact area between the constituents and develops higher bond strength than the smooth textured [19].

![Crack profiles of cement composites.](image)

**Figure 2.** Crack profiles of cement composites.

Nevertheless, the utilization of quarry dust at 17.5 wt.% displayed the different profiles of crack pattern. The cement composites were experimentally broken in shearing and vertical splitting pattern. As the content of quarry dust increased, the cement composites start to shear and split at the breaking point of the load pressure.

3.3. **Surface morphology**

The further result is the surface morphology of the cement composites, which are resolved under stereomicroscope (Olympus SZ61). The images were displayed in Figure 4(a-b), and the results explanation are presented according to the content of quarry dust in the cement composites and its connection with the obtained modulus of rupture.

Based on Figure 4(a), the particle’s arrangement of the cement, river sand, and quarry dust were well distributed with varying sizes and shapes. The surface observed with grainy texture and obviously denser as well as contributed to good interlocking between the constituents in the cement composites. Moreover, the properties of quarry dust almost similar with crushed sandstone that appears in angular shape and rough
surface and it exhibits better mechanical interlocking with cement paste [20]. Besides that, the inclusion of suitable percentage of minus 75 micron in graded form allows for efficient aggregate packing and results in a denser concrete mix [21].

![Figure 4. Surface morphology of cement composites with (a) 12.5 wt.% and (b) 17.5 wt.% of quarry dust.](image)

The appearance of narrow and tiny voids in the cement composites also can be observed in the Figure 4. The figure indicated that the voids present in the cement composites is air voids. According to the definition by Department of Transportation [22], air voids formed in spherical shape and have an internal surface, which is moulded by air bubbles or pockets. However, the voids present in quarry dust mortar were lesser than compared to the sand [23] and not obviously affected the dense package of the cement composites as well. Additionally, the void ratio of quarry dust is 0.42 and less than river sand at 0.55 respectively [6]. The dense arrangement of the constituents in the cement composites influenced the modulus of rupture when the result indicated the highest value with the addition of 12.5 wt.% quarry dust in the cement composites. In spite of this, the addition of quarry dust up to 17.5 wt.% was conversely influenced the surface morphology of the cement composites. The particle’s distribution of the constituents obviously less in uniformity and there has the appearance of various size of air voids in the cement composites as displayed in Figure 4(b).

Moreover, the cross section of the fractured cement composites indicated the rounded bulging of river sand in various sizes, which contributed to the hollow or dent on the surface of the cement composites. The increment percentage of quarry dust was contributed to the lack of the dense package and the appearance of the air voids has contributed to the reduction of modulus of rupture in the cement composites under the flexural load. Additionally, the presence of air voids mostly in the form of large voids or pockets, the effects are generally detrimental such as porous, poorly consolidated concrete with honeycombing and reduced in-place strength [24]. Referring to the presented results of modulus of rupture and surface morphology, it seems both of the results have a close relationship with each other. On the whole, the highest value of modulus of rupture was revealed with the addition of 12.5 wt. % of quarry dust. This is also contributed by an efficient packing factor and dense constituent's arrangement in the mixture with the addition of quarry dust at 12.5 wt. % as well. Undoubtedly, the findings show the parallel relationship between the modulus of rupture and surface morphology of the cement composites.

4. Conclusion

Based on the discussed experimental results, the following conclusion can be drawn. The content of quarry dust in various percentages significantly effects the strength development of cement composites. Briefly, the mechanical strength of the cement composites was found in decreased trend and unsatisfactory when the percentages of quarry dust increased. On the contrary, inadequate content of quarry dust cannot fill all the space between the cement paste and fine aggregate particles, hence also contributed to the unsatisfactory modulus of rupture. Therefore, the content of quarry dust has to be controlled and properly selected as the
substitution of fine aggregate. Besides that, the modulus of rupture has a close relationship with the particles distribution between cement, river sand and quarry dust in the hydrated cement paste. In fact, the good interlocking characteristic of the materials respectively contributed to the dense arrangement of the particles distribution, which is parallel to the strength development in the cement composites. As a conclusion, the quarry dust has a beneficial effect either in environmental issue or value added as an alternative material and potentially introduced as a functional construction materials.

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