Low Density, High Compressive Strength: Experimental Investigation with Various Particle Sizes of Sand for Different Mix Designs of Cement Mortar Manufacturing

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Abstract. Concrete density was optimised by substituting part of the normal-density aggregates (fine aggregate, coarse aggregate, or both) with that of comparable quantities of low-density aggregate, which enhanced structural efficiency (strength to density ratio), improved hydration and decreased transportation costs. These days, focus is given on enhancing the characteristics of concretes in order to make them more efficient. A factor associated in compressive strength, packing particle, water absorption and density is concrete proportioning. A good proportioning mix results in greater strength for concrete at optimum density and specified age. The filler effect is regarded as a physical feature pertaining to small particles for a concrete material since it allows generating extra compressive strength by filling voids by making mortar or concrete more homogeneous. This behaviour allows conferring additional compressive strength as well as optimise or minimise the concrete’s density without having to use a pozzolanic reaction or a chemical reaction. Mainly, this objective has been implemented through using three different lightweight particle sizes of sand group a-(1.18 mm ≤ Sand size < 2.00 mm), b-(2.36 mm ≤ Sand size < 1.18 mm) and (5.0 mm ≤ Sand size < 2.36 mm). The parameters that are taken consideration during the investigation were sand particle size, water/cement ratio, cement/sand ratio. In general, the results demonstrated that there was a decrease in compressive strength when the sand’s particle sizes increased. In case the particle size group (b) and (c) used the decrease rate in compressive strength was 7.97% and 12.39% respectively in comparison with particle size group (a) where the optimum values of the water/cement and cement/sand ratio were used. On the other hand, low density was achieved at the point of the higher compressive strength, whereas 4.4% and 3.66 % increase in the density was recorded over the particle sizes of sand (b and c) respectively. Meanwhile, we put forward the relationships existing between the compressive strength as well as density of concrete mixtures with various proportions of the lightweight aggregates as given above. The conducted experimental studies showed that there were tendencies to possibly utilise various quantities of fine lightweight aggregates as well as their combinations to yield concrete mixtures based on the requirements in practical application. As per the study conclusion, the considered mixtures could be used to yield structural elements that need high compressive strength and lower density.
1. Introduction

The characteristics and proportions with regards to the aggregate, water, cement and even the use of admixtures determine the total amount of the concrete pertaining to a structure, based on curing of the concrete post placing, mixing and compaction procedure as well as the age at which the concrete is assessed [1]. Especially, the water-cement ratio as well as the water absorption (with regards to the total volume of voids) in the mix cast a high influence on the concrete strength [2]. The overall density pertaining to a concrete mix will rely on the presence of relative amounts of these materials as aggregates, water, cement and voids possess various specific weights [3]. The conventional normal weight pertaining to concrete possessing strength of 20–60 MPa and density of 2,200–2,600 kg/m$^3$ was found to be well established as well as disadvantageous because of its associated heavy weight. To decrease the building weight or the dead load, concrete possessing light-weight aggregate is employed in the construction industry [4-7].

Over the past few decades, the increased use of concrete-light-weight aggregate for the structural elements of tall or long-span buildings has become a more and more important aspect in the modern construction industry. However, despite many advantages, practical application of such concrete in real structures is limited due to its lower mechanical properties and increased brittleness compared to normal weight concrete [8]. A hardened mixture with regards to the appropriate requirements to be tested for evaluating acceptable durability characteristics (compressive strength, density, water absorption, etc.) makes sure that the sufficient service life pertaining to the structural members is yielded from this mixture [9-10]. The characteristics pertaining to the applied aggregate as well as the cement mortar define the density, strength and water absorption with regards to the concrete mixture. Employing a fine aggregate pertaining to a concrete mixture by entirely substituting the coarse aggregate is considered as an approach that allows increasing the concrete strength. This is usually employed to produce concrete mixtures with high strength [11-12]. Employing lightweight aggregate with small diameter (0.5–4 mm) for lightweight concrete enhances the homogeneity pertaining to concrete microstructures as well as minimises the chances of mixture segregation [13]. In generally, fine aggregate is favoured over coarse aggregate because of its smaller distance amongst aggregates. Due to this, providing of the internal curing water is done to a larger volume pertaining to the mortar matrix [14]. The amount of cement employed, water-to-cement (W/C) ratio as well as mortar porosity impact the mortar matrix’s mechanical characteristics [15-17]. Adjustment of the granulometric composition pertaining to the mixture as well as introduction of micro fillers is carried out to minimise the matrix’s porosity. However, sand percentage as well as sand size cast a key impact on the concrete’s mechanical behaviour since they occupy a large volume fraction in the matrix [18]. As per experiment studies, the mortar possessing coarse sand were seen to attain higher density as well as higher compressive strength versus the finer sand when the w/c ratio is less [19-21]. Conversely, research studies have also demonstrated enhanced compressive strength with micro sand [22-24]. Because of this, factors that impact the matrix’s density, strength and water absorption need to be focussed. Sand percentage, sand size, water to cement ratio in the mortar matrix phase are some of the factors within this factor.

In the current research study, concrete lightweight aggregate mixtures possessing various mixes design were evaluated. This study aims to determine the relationships pertaining to the compressive strength, water absorption and density by employing low-fraction (200 μm–1.18 mm) fine aggregates, after which these are compared with the ones that employed aggregates of larger fractions (1.18–2.36 mm and 2.36-5.0 mm) that are usually applied for lightweight aggregate’s structural concrete. Thus, it can be expected that there exists a relation amongst density, strength and water absorption pertaining to a specific concrete mix. If established, this relation could be unique only for those mixes that possess identical cement as well as aggregates, proportions, age at testing, curing and strength testing procedure. After this, aggregates in different proportions are integrated while also preserving the uniform matrix mixture’s composition, as well as to see the effect of proportions on compressive density, strength and water absorption pertaining to the mixture, and then to determine the impact of various mixes design on the characteristics of the hardened state pertaining to concrete with an age of 28 days. The conducted
research study can be regarded as an additional step to develop lightweight concrete mixtures for improving their sustainable application when it comes to the construction industry.

2. Experimental Method Program
The research study aims to determine a broad range of mix design parameters needed to achieve the desirable characteristics (high compressive strength and low density) pertaining to the cement mortar. To attain this, an experimental program was conducted to evaluate the simultaneous impact of mix design factors like water (W) to cement (C) ratio, sand size and cement (C) to sand (S) ratio. A mixture design was employed based on 120 cement mortar mix designs made from various W/C ratio (8 values in every group) that fall between 0.45 to 0.8 along with a step of 0.5, sand in various percentages (five groups) ranging from 1:1 to 1:3 along with a step of 0.5 as well as sand in various sizes (3 groups). The combined impact of factors and the mix designs was determined by conducting water absorption, compressive strength and density tests.

3. Specifications of Materials and Mix Design
As the key binder material pertaining to the production of cement mortar matrix, we employed the Ordinary Portland Cement Type I (Blue Lion Cement) that is usually produced by the cement industries in Malaysia (CIMA GROUP). The classification of the employed cement has been done as BSEN 196 and MS 522. The OPC’s composition falls in the standard range of 70%, 17%, 3.9%, 3.60%, 3.2% and 1.50% and for CaO, SiO₂, Al₂O₃, SO₃, Fe₂O₃ and MgO, respectively. As presented in figure 1, fine aggregate can be segmented into 3 categories (a, b and c); based on the particle size, fine sand (FS) is regarded as natural sand that can pass through 1.18 mm and can be retained on 200 μm IS-Sieves. The second type can pass through 2.36 mm and can be retained on 1.18 mm IS-Sieve, while coarse sand (CS) is the final one that can pass through 5.0 mm and can be retained on 2.36 mm IS-Sieve. The categories are maintained in dry condition. Pipe water is employed for curing cement mortar samples as well as for preparing the mix. The impact of sand size, W/C and C/S on the characteristics of cement mortar was evaluated based on an experimental program. In this experimental study, preparation of 120 cement mortar mix designs was done by considering W/C of 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75 and 0.8 as well as C/S of 1:1, 1:1.5, 1:2, 1:2.5 and 1:3, along with sand of various sizes that fall within 3 groups (a, b and c) pertaining to each specimen.

![Micrograph of particle size of sand range (a, b and c).](image)

(a) (b) (c)

**Figure 1.** Micrograph of particle size of sand range (a, b and c).

4. Preparation of Specimens and Experimental Procedure
The current study employed specimens with 50 × 50 × 50 mm cubic mortar, which were exposed to compressive strength test conforming to ASTM C109 [25]. For specimen preparation, a mixer was employed to proportionally mix the materials as specified based on the mix design conforming to ASTM C305 [26]. Until a uniform consistency was achieved, mixing was allowed to continue, after which casting of the resulting cement mortar into moulds was done. Post 24 hours, specimens were taken out from their moulds to be placed into a water tank that was maintained at a temperature of 22 ± 2°C until
it was time for the test. For every mix design, testing was done for the three specimens with 28 days’ age (for every mix design, 6 specimens in total), while obtaining of the mean values pertaining to their results was done with regards to water absorption, compressive strength and density tests.

5. Results and Discussion
Post the production of cement mortar, the impacts of cement/sand ratio, water/cement ratio and particle size distribution pertaining to sand on the selected mechanical and physical characteristics were analysed and discussed in this section. The following figures show the composition pertaining to the mixtures that have been considered as well as the water absorption, compressive strength and density pertaining to concrete post 28 days of curing, which helps to decide if any relation exists amongst the density, strength and water absorption pertaining to particular mortar mixes.

5.1. Compressive Strength
Figure 2 presents the compressive strength pertaining to cement mortar with diverse cement (C) to sand (S) ratio and water (W) to cement (C) ratio. It was observed that the C/S ratio and W/C ratio cast considerable impact on the mortar’s compressive strength for all samples possessing various particle size distribution of sand. When the W/C ratio was increased from 0.45 to 0.8, the compressive strength decreased by 45.5%, 44% and 57.7% for C/S ratio (1:1.5) pertaining to particle sizes (a, b and c), respectively. However, when the C/S ratio was changed from 1:1.0 until 1:3.0, it was optimised at a ratio of 1:1.5 pertaining to the W/C below than 0.6. It was also observed that the C/S ratio was optimised at 1:2.0 when the W/C ratio was increased beyond 0.6.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Relationship between water to cement ratio and compressive strength at different particle sizes of sand: (a) range from 1.18 mm to 200 μm, (b) range from 2.36 mm to 1.18 mm and (c) range from 5.0 mm to 2.36 mm.
As presented in figure 2, the compressive strength was seen to rely on the difference in the W/C ratio for the mortar mixes. A distinct trend was seen pertaining to decrease in compressive strength with increase in the W/C ratio applicable to all mortar mixes. The results were comparable with the results highlighted by some researchers [27-30]. The increase in the W/C ratio suggests that more water is present amongst solid particles and accordingly more voids are present in hardened condition, while increasing the porosity will subsequently result in reduction of the compressive strength.

Moreover, introducing sand to the cement matrix results in growth of the strength of the cement mortar; however, if sand (C/S ratio beyond 1:1.5) is added in higher quantities, it results in decrease in cement mortar’s compressive strength. As presented in Figure 3, at C/S (1:1.5) particle size (a) and (1:2) particle size (b), higher values pertaining to the compressive strength were achieved at 67.462 MPa and 64.947 MPa, respectively, at W/C ratio of 0.45.

![Figure 3](image_url)

**Figure 3.** Relationship between sand percentage and compressive strength at different particle sizes of sand: (a) range from 1.18 mm to 200 μm, (b) range from 2.36 mm to 1.18 mm and (c) range from 5.0 mm to 2.36 mm.

This result was found to disagree with the results reported by some researchers. The Authors observed that, mortar matrix of S / C ratio of 2.25/1 obtained higher compressive strength at W/C ratio 0.4, at the age of 28 days [31]. In contrast, an experiment study created out on effect of nanomaterials in cement mortar characteristics, the researchers observed that, Nano cement mortar matrix of sand/cement ratio of 1.5/1 obtained higher compressive strength at W/C ratio = 0.34. Moreover, addition of
sand (C/S ratio beyond 1:1.5) in higher quantities resulted in decrease in the compressive strength [32]. The result demonstrated that a key role is played by C/S ratio and W/C ratio during the hydration process for strongly binding the binder to the sand. On the other hand, too high addition of sand reduced the compressive strength due to the insufficient binder.

On the other hand, in order to identify and verify the internal microstructure and bonding between sand and OPC binder. Microstructure analysis was carried out on cement mortar specimen. The morphological study of cement mortar with 0.45 and 1:1.5 was selected to assess the bonding at interface transition zone. The homogenous bond between the aggregate and cement binder can be seen clearly by SEM micrograph in figure 4, this is due to no cracks were observed along the interface between them or known as the interfacial transition zone (ITZ). The strong bonding at the ITZ was due to the soluble silicate at the surface of the sand and the complete hydration process of OPC.

![SEM micrograph of cement mortar at particle size of sand range](image)

The filling impact of micro-sand is important in order to produce strong transition zone. The microstructure of the transition zone between aggregates and cement paste has been reported to strongly impact concrete’s durability and strength [33].

The high-strength concrete tests demonstrated significant results pertaining to the impact of sand with varying particle sizes on the compressive strength, which suggest that the finer sand mix produces a greater compressive strength versus coarse sand mix. This could be because of the impact of the particle packing, in which the filler impact is regarded as a physical property of small particles in a material that confers extra compressive strength to concrete due to filling of the voids that makes the mortar or concrete more homogeneous and dense [34]. This characteristic could also confer additional compressive strength to the concrete by skipping the need for a chemical reaction, like pozzolanic or hydration reaction.

5.2. Water Absorption

As presented in figure 5, the water absorption pertains to cement mortar at varying W/C ratio and varying particle sizes (a, b, and c) with diverse sand-to-cement ratio. With rise in W/C ratio from 0.45 until 0.8 pertaining to all samples, the water absorption was also increased. Meanwhile, the water absorption is increased with rise in sand percentage from 1.0 until 3.0 for every batch alongside same W/C ratio. In contrast, there is a reduction in water absorption with increase in sand’s particle size. Most of the outcomes were found to conform to ASTM C140 [34], in which the test samples’ average water absorption does not exceed 5% and no individual unit exceeds 7%, particularly when W/C ratio until 0.6 was employed.
Figure 5. Water absorption of cement mortar at different sand percentages, water to cement ratio and particle sizes of sand: (a) range from 1.18 mm to 200 μm, (b) range from 2.36 mm to 1.18 mm and (c) range from 5.0 mm to 2.36 mm.

With regards to the result, higher W/C ratio results in higher water absorption pertaining to the cement mortar samples. Higher porosity because of high water content in the sample defines the cement mortar sample’s water absorption. Post completion of the hydration process, the excess water gets evaporated, which creates the pore that contributes to the mortar samples’ higher water absorption. Meanwhile, there is an increase in overall aggregate surface area when employing the proportion of the fine particle size, thus resulting in increase in water absorption. This result was found to agree with the results reported by some researchers [36-38].

5.2.1. Relations Between Water Absorption and Compressive Strength
As per the experimentally obtained results with regards to the impact of water absorption due to immersion, the compressive strength at 28 days is presented in figures 6 and 7. With regards to the batch, various correlations could be observed. For instance, at C/S ratio 1:1.5, correlations were observed to be high (0.9463, 0.8536 and 0.8431) at sand’s particle sizes of (a, b and c), respectively. Meanwhile, at C/S ratio 1:2.5 with sand’s particle size of (a, b and c), it was found to be (0.7944, 0.8407 and 0.9222), respectively.
Figure 6. Relationship between water absorption and compressive strength at cement(C) to sand(S) ratio 1:1.5 with different particle sizes of sand: (a) range from 1.18 mm to 200 μm, (b) range from 2.36 mm to 1.18 mm and (c) range from 5.0 mm to 2.36 mm.

Figure 7. Relationship between water absorption and compressive strength at cement(C) to sand(S) ratio 1:2.5 with different particle sizes of sand: (a) range from 1.18 mm to 200 μm, (b) range from 2.36 mm to 1.18 mm and (c) range from 5.0 mm to 2.36 mm.
Based on the result, the high correlation coefficients pertaining to R suggested that a significant inverse linear correlation existed between compressive strength and water absorption, in which higher water absorption was associated with higher porosity, thus subsequently decreasing the compressive strength. Else, it is usually known that higher compressive strength attained at C/S ratio of 1:1.5 was 67.462 MPa, 62.083 MPa and 59.101 MPa corresponding to higher water absorption of 4.351%, 3.677% and 3.392, respectively. Because of this contradiction, it can be assumed that the water absorption due to immersion may not be regarded as being very sensitive parameter for determining the compressive strength, while the strength relies on the total porosity as well as more dependency was seen with regards to the pore size distribution. There is also a possibility that the two porous concretes can possess the same porosity even though pore size and distribution varies, wherein a narrower void size distribution demonstrates higher strength [39]. Higher correlations (R) were observed, thus suggesting that the equations could be employed; however, it needs to be noted that these relations are specific as well as unique only for mixes that possess identical cement and aggregates, age at testing, proportions, curing and strength testing procedures.

5.3. Density

Figure 8 presents the density pertaining to cement mortar at various particle sizes that range from (a, b and c), respectively, with varying cement (C) to sand (S) ratio and water (W) to cement (C) ratio. For the entire samples, increase in W/C ratio from 0.45 until 0.8 resulted in density reduction. The results suggest that the density was found to be 2.052 and 1.979 at C/S ratio of 1:2.5 and W/C ratio of 0.45 and 0.8, respectively, and for the particle size group (a), the decrease in density rate was 3.6%. On the other hand, the decrease rate was 4.8% and 7.2% respectively with particle size group (b and c).

![Figure 8](image)

**Figure 8.** Density of cement mortar at different water to cement ratio and particle sizes of sand: (a) range from 1.18 mm to 200 μm, (b) range from 2.36 mm to 1.18 mm and (c) range from 5.0 mm to 2.36 mm.
It was seen that an inverse relationship existed between the density of concrete produced and the W/C ratio. In general, there is a decrease in density with rise in W/C ratio and a decreased rate, when sand with large particle size was employed, which was higher versus smaller particle size. This is maybe due the coarser particle size of sand will lose water faster or more permeable than finer once while the finer absorb more water and less permeable.

Based that result, figure 9 shows the variation in sand percentage in three groups of particle size and its effect on the mortar density. It can be shown that the density was increased with the increase sand percentage and its particle size due to the increase of the weight. On the other hand, the results show that for a given percentage and size of sand, there is an optimum value as example at W/C ratio 0.45 the optimum value was occurred at C/S 1:1.5 with particle size group (a) and 1:2 with particle size group (b and c) respectively.

![Figure 9](image)

**Figure 9.** Density of cement mortar at different sand percentage and particle size of sand: (a) range between 1.18 mm and 200 μm, (b) range between 2.36 mm and 1.18 mm and (c) range between 5.0 mm and 2.36 mm.

The obtained results suggest that this could be because of the particle packing that relies on the sand particles’ shape. Meanwhile, the percentage as well as size of sand cast a key impact on the mortar density. Particle packing optimisation pertaining to concrete mixtures casts positive impact for both hardened and fresh concrete characteristics. In a particle structure, introducing fine particles aids in filling up the voids pertaining to the particle structure as well as keeping minimum space for water [40].
5.3.1. Relations Between Density and Compressive Strength

Figure 10 presents the impact of mortar density on the apparent compressive strength, which suggests the existence of a significant linear correlation between compressive strength and density. It can be distinctly said that the correlation coefficient relies on the C/S ratio and sand’s particle size, 0.9755, 0.8402 and 0.9362 at C/S ratio of 1:1.5, given the particle size of (a, b and c), respectively. Moreover, variations of the correlation coefficients have been noticed with higher sand ratio.

![Graphs showing correlation between density and compressive strength](image)

**Figure 10.** Relationship between density and compressive strength at cement(C) to sand(S) ratio 1:1.5 with different particle size of sand: (a) range between 1.18 mm and 200 μm, (b) range between 2.36 mm and 1.18 mm and (c) range between 5.0 mm and 2.36 mm.

In general, the results demonstrated that with rise the density, there was an increase in compressive strength. On the other hand, at the same point of density different of compressive strength values have been noted at particle sizes of sand. As example at density value 2.0 g/cm³, the compressive strength was 57.77 MPa, 45.17 MPa and 34.25 MPa at particle size (a, b and c) respectively. This is an indicator that the results from this study were limited to the mix design as well as materials employed in this study. Also, it needs to be noted that the extension of these results to other sizes, types, etc. pertaining to aggregates as well as various mix designs cannot be done.

5.3.2. Relations Between Density and Water Absorption

The experimentally obtained results concerning the relations between density and water absorption at 28 days have been shown in Figure 11, according to its particle size batch, different correlations were noticed as example at C/S ratio 1:1.5 the correlations was high (0.9326, 0.7405 and 0.8952) at particle size of sand (a, b and c) respectively.
Figure 11. Relationship between density and water absorption at cement (C) to sand (S) ratio 1:1.5 with different particle size of sand: (a) range between 1.18 mm and 200 μm, (b) range between 2.36 mm and 1.18 mm and (c) range between 5.0 mm and 2.36 mm.

6. Conclusion
The fact that a denser concrete generally provides higher strength is not completely true, each various batch of mix design has a unique physical and mechanical properties. The substances rely on the characteristics of the constituent material. The optimisation pertaining to the cement mortar production’s mix design considerably impact the characteristics of the materials’ hardened and fresh states. Based on these study objectives, it can be concluded that optimisation was achieved for the water to cement ratio that plays a role in the hydration process as well as the inclusion of sand that behaves as an inert filler in the mortar production process. The highest strength pertaining to cement mortar was achieved at a ratio of 1:1.5. The formation of calcium-silicate-hydrate (C-S-H) chiefly contributed to the OPC-based cement mortar’s strength as well as it impacted the construction materials’ durability. As per the experimental results, high correlation coefficients pertaining to R suggested that a significant inverse linear correlation exists between compressive strength and water absorption, even between water absorption and density. In contrast, there exists a linear correlation between compressive strength and density. The water absorption as well as density pertaining to the mortar matrix clearly demonstrate impact but these cannot be considered as sensitive parameters alone in order to determine the compressive strength, wherein the obtained sample were suggestion of low density as well as high water absorption. In this research work, the best physical and mechanical characteristics were suggestive of considerable potential pertaining to cement mortar, which can be applied for different tasks in the construction industry. To conclude, the impact of cement (C) to sand (S) ratio, water (W) to cement (C) ratio as well as sand with different particle size on the compressive strength, water absorption as well as density pertaining to cement mortar manufacturing was presented.
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