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Original Article

Performance Evaluation of Concrete Masonry Units Containing Reclaimed Asphalt Pavement (RAP) Aggregate as Partial Replacement for Natural Aggregate

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Abstract - *Reclaimed Asphalt Pavement (RAP) fragments, featured in Concrete Masonry Units (CMUs), are acquired through the crushing and pulverizing of levelled asphalt pavements. RAP has become an economically prudent and environment-friendly option in lieu of conventional aggregates used in construction. In Qatar, RAP materials are being used in bituminous asphalt mixes; however, there is still a high volume of RAP that is underutilized. Examining how these RAP-containing CMUs perform is the main thrust of this inquiry. Natural aggregates and RAP are mixed in six (6) varying proportions (0%, 10%, 20%, 30%, 40% and 50%), with RAP serving as a partial replacement to 5mm nominal size natural coarse aggregates. The evaluation focuses on the performance of two critical parameters, namely compressive strength and water absorption of the CMUs. According to the Qatar Construction Specifications 2014, CMUs are permitted to be composed of up to 50% recycled aggregates for the target compressive strength of 7.0 MPa or higher, with average water absorption not exceeding 7% and no individual block having greater than 7.5%. Results of the study revealed that while compressive strength significantly declined, there was a slight decrease in water absorption for samples with Reclaimed Asphalt Pavement (RAP) particles. Internal and external non-load-bearing walls, roof blocks and protective skin foundations are examples of structures that can utilize concrete masonry units with up to 50% RAP replacement; however, these cannot be used as load-bearing walls, soakaways and manholes.*

Keywords - *Reclaimed Asphalt Pavement (RAP), Concrete Masonry Unit (CMU), Recycling, Water absorption, Compressive strength.*

1. Introduction

Qatar was awarded the hosting of the FIFA World Cup 2022. In preparation for this sporting event, the government began construction of massive infrastructure projects such as seven football stadiums, high-rise buildings, residential buildings, commercial buildings, and bridges, as well as the rehabilitation of existing utilities, improvement of asphalt road pavements, and expansion of landscaping works, among others, putting particular stress on the use of green materials. As part of Qatar's push for more environment-friendly building practices, the tenets of the Global Sustainability Assessment System (GSAS) were espoused in the Qatar Construction Specifications (QCS) 2014. Furthermore, the country believes that it is advantageous to salvage and repurpose materials from torn-down structures [1].

The Public Works Authority (Ashghal) has led the use of recyclable demolished materials and industrial wastes, including Reclaimed Asphalt Pavements (RAP). The use of waste materials from road improvements and developments has gained attention to highlight the country's sustainability efforts in addressing waste disposal issues. Existing asphalt pavements are being milled to enable the construction of new flexible pavements. RAP aggregates come from the milling and removal of asphalt from demolished pavements. Milling is the first step in the asphalt recycling process, where the upper stratum of the existing asphalt roads and carparks is stripped, leaving the lower layer unaffected. Following milling, the asphalt is taken to a factory for further processing, after which it is ready to be employed for paving. In the country, there is still a high volume of unutilized RAP stockpiled in dumping sites. Therefore, innovative ways are necessary to optimize the use of this excessive waste material. To support the country's environmental sustainability initiative, this research looks into the suitability of partially employing RAP aggregates instead of natural aggregates in manufacturing Concrete Masonry Units (CMUs).

2. Literature Review

In a study, Roja and Masad [2] observed that in recent years, road engineers in Qatar constructed the base course of asphalt roads with RAP fragments. They were used to substitute Virgin Aggregates (VA) and binders, and by incorporating old asphalt binders, the asphalt mixture's all-around stiffness was enhanced. In light of the financial and ecological advantages, RAP materials were prepared in varying proportions based on a composition scheme devised for asphalt composites in the study, and the resulting RAP aggregate asphalt mixes were evaluated based on how well they performed. With the resources acquired, optimally using RAP aggregates in the asphalt pavement base course was attempted. Three distinct RAP levels (15, 25, and 35%) were added to asphalt mixtures, and their performance was contrasted with that of a conventional mix (0% RAP). Several experimental techniques were used to test the RAP-blended asphalt mixtures. First, the AASHTO test method was used to measure the stiffness modulus of RAP mixes. Then, to establish how the mixtures cope with high and low temperatures, the semi-circular beam bending test and the Hamburg wheel tracker were employed. The resulting stiffness and performance measurements were used to propose an appropriate RAP proportion and strategies for enhancing RAP aggregate application.

QCS 2014 Section 13 Part 4 [3] recognizes the value of using recycled aggregates in making Concrete Masonry Units (CMUs). Up to 50% of natural aggregates in CMUs with a target average compressive strength of 7.0 MPa (N/mm2) or above are allowed to be substituted with recycled materials. On the other hand, replacement with recycled aggregates may be up to 100% if the target compressive strength is below 7.0 MPa (N/mm2). Furthermore, CML Method 9-97 requires that no single block must have a water absorption of more than 7.5% and that the water absorption of the evaluated samples must not average above 7%.

Endale et al. [4] concluded that RAP was a long-lasting, cost-effective, and environmentally beneficial material that could be reused with care. The asphalt recycling classification in place in Ethiopia is presented in Figure 1. It identifies cold in-plant recycling, cold in-place recycling, and full-depth reclamation as the most successful recycling techniques in use in the country. Contingent on the scale and nature of the undertaking, recycling could save between 20% and 80% of project costs. Asphalt paving is completely recyclable and can be reused multiple times as needed since RAP aggregates retain their original quality and can be used in the same way as virgin aggregates. To seamlessly enforce the selected recycling techniques, a conceptual strategy must be developed.

Nguyen and Le [5] reported that in Vietnam, the web of roads and highways spanned 20,000 kilometers in its entirety and materials for paving construction and rehabilitation amounted to millions of cubic meters every year. Asphalt binders had to be imported into Vietnam, the supply of good quarry resources was rapidly dwindling, and the area was far from major cities. With cost concerns and environmental welfare under consideration, RAP's innovation became the welcome critical solution to lowering costs and maintaining the environment. The technology had been studied for almost ten years, but the country had only a small number of practitioners. RAP, a cold in-place recycling product, is commonly used in Vietnam today. In contrast, central plant recycling is unutilized in pavement experimental sections since they do not meet the necessary standards. Similarly, as Figure 2 signifies, research regarding hot in-place recycling has yet to be undertaken.

To advocate for a broader application of Portland Cement Concrete (PCC) that contained RAP particles in pavement construction, Shi et al. [6] proceeded with a life cycle inventory analysis. A trio of unique pavement types—plain single-lift PCC block, single-lift RAP-PCC block, and dual-lift concrete slab, which has RAP-PCC providing the bottom lift material—were developed and later subjected to the economic input-out life cycle assessment (EIO-LCA) for a thorough analysis of sustainability. The EIO-LCA findings amply illustrated how RAP-PCC adoption in pavement application had impactful advantages on the economy, society and the environment; the single-lift RAP-PCC slab boasted superior potential economically while the two-lift concrete block with the bottom lift being RAP-PCC claimed outstanding promise societally and ecologically.

Fakhri and Amoosoltani [7] conducted an experiment to evaluate Roller-Compacted Concrete Pavement (RCCP) that incorporated RAP and crumb rubber. As encouraging parameters for RCC samples containing waste material mix, energy absorbency and toughness were examined. The samples featuring recycled particles exhibited increased toughness and energy absorbency. This standing was further bolstered by the regression findings, of which the addition of as much as 10% rubber and 50% RAP prolonged the lifespan of the pavement because they boosted the mixes' toughness and energy absorbency, potentially cutting costs and preserving the environment.

Mathias et al. [8] studied how incorporating RAP affected the compressive strength, tensile strength and E-modulus of cement mixture. Based on their data, the RAP dose rate appeared to reduce these attributes. Currently, efforts are being undertaken to accommodate these innovative concrete mixes in Laboratoire Central des Ponts et Chaussées (LCPC) mix-design modeling. These breakthrough mixes expand present-day mix-design techniques, and they endorse RAP application in cement concrete as infrastructure stakeholders profit scientifically, fiscally, and ecologically. The impact of how varied sizes of RAP aggregates, both coarse and fine, and featured as natural aggregate substitutes, behaved mechanically and in terms of durability in Roller Compacted Concrete (RCC) was explored by Settari et al. [9]. They determined that RCC could be manufactured using up to 50% RAP materials. Thus, conferring value to RAP promotes its use in concrete, and it is, in the long run, ecologically sound as it contributes to waste reduction.

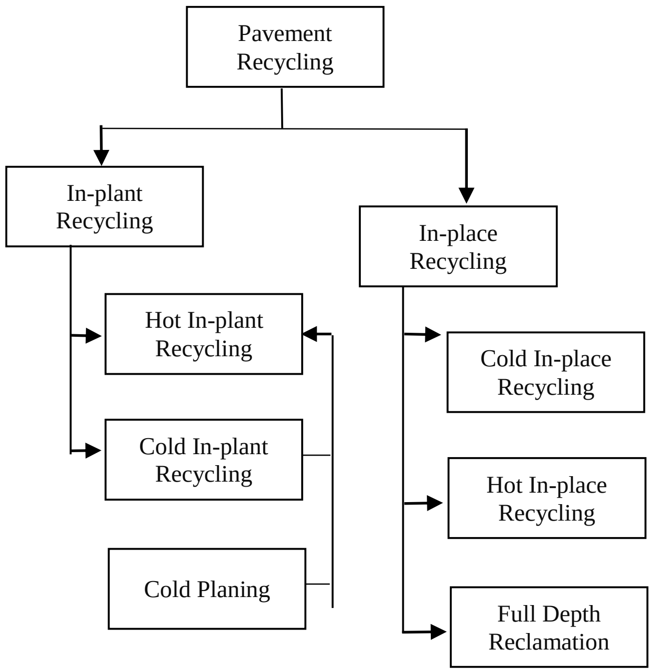


Fig. 1 Ethiopia's asphalt recycling classification

In Italy, Masi et al. [10] examined the performance of RAP as a concrete aggregate. Specimens were gathered from five distinct collecting locations. Their study surveyed the following: dimensional stability, which is the dimensional extent retained as mortar and concrete comprising 10% RAP as aggregates dry and shrink; microstructure by microscopy; physical characteristics, which included particle size distribution, water absorption, porosity, and wettability; and durability by freezing-thawing cycles.

Having both pros and cons, RAP and natural aggregates in concrete are noted to behave differently in several ways. Although RAP is a promising recycled material for concrete, rigorous analysis is necessary to guarantee concrete durability and performance. Erdem et al.'s study [11] on structural concrete made entirely of recycled aggregates focused on verifying concrete's mechanical behavior and ecological impact.

The investigation made use of either waste asphalt design, i.e., RAP, or waste precast concrete, i.e., Recycled Aggregate Concrete (RAC), as an aggregate replacement for virgin ones. The four concrete combinations that were created all possessed identical overall water-to-cement ratios (w/c = 0.74), and natural aggregate either became a benchmark or was completely substituted with reused resources. In all mixtures, a mineral called Ground Granulated Blast Furnace Slag (GGBS) was added in the amount of 35%. The results of the tests established that concrete with recycled materials could function satisfactorily in terms of strength characteristics as long as the aggregates are derived from waste precast concrete. The concrete with RAP aggregates' mechanical characteristics, however, exposed its unsuitability for structural use. Furthermore, the findings indicated that as far as seepage and ecological impact go, RAC was comparable to natural aggregate concrete.

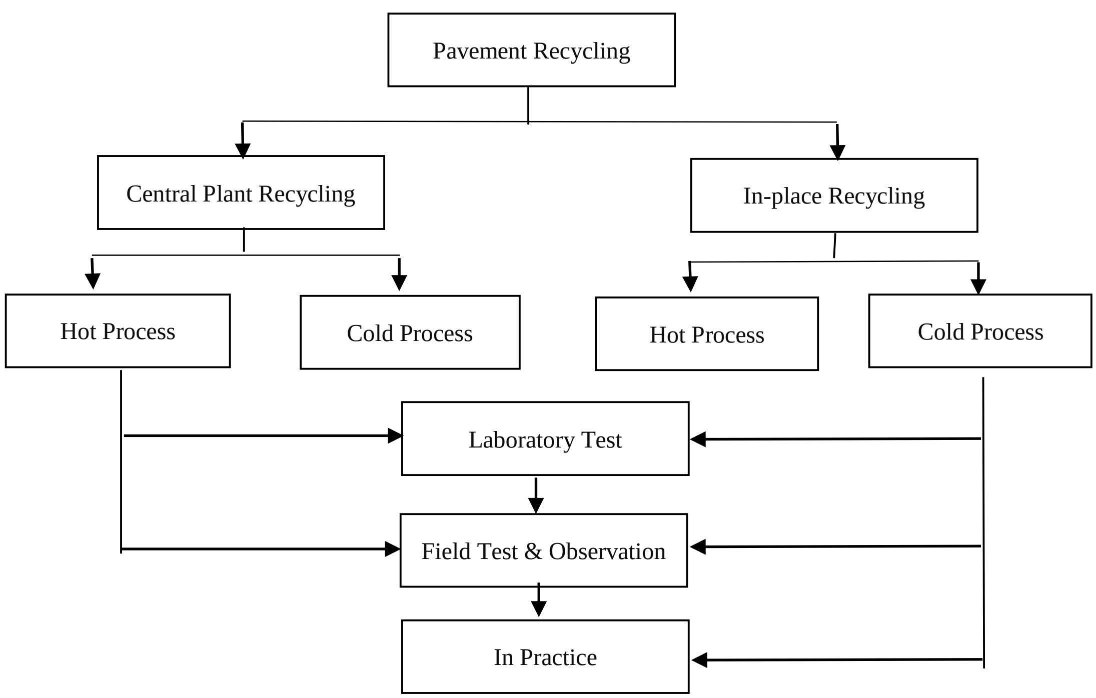


Fig. 2 Flow chart of the current practice of RAP in Vietnam

In another study, Shi et al. [12] examined the feasibility of using coarse RAP to substitute a portion of virgin coarse aggregates in preparing Portland Cement Concrete (PCC) paving mixtures. It was determined that using coarse RAP that contained adequate midsized fragments instead of virgin coarse aggregates could hold the same advantages of dense mixed aggregate gradation. After conducting a series of tests for pertinent mechanical properties, this research developed a method to identify the ideal quantities of RAP replacement. It provided recommendations and instructions for developing PCC that contained RAP. In the process, they discovered that surplus RAP stocks might be cut down when the aggregate in PCC was switched to RAP.

The impact of fine fraction RAP aggregates when employed at 25%, 50%, 75%, and 100% in lieu of natural fine aggregates (NA) on the cement mortar's mechanical behavior, permeability, and durability was scrutinized. Mortar mixtures with 25% and 50% RAP were able to meet the necessary characteristic compressive strength at 28 days. According to the Mercury Intrusion Porosimetry (MIP), RAP concentration leads to increased porosity, proving the strength-porosity models that have been established by Hasselman D.P.H, Balshin M.Y, Ryshkewitch E., and Schiller K.K. accurate. Under sulfate assault, partly substituted mixtures (25% and 50%) increased compressive strength; however, RAP mortar mixtures exhibited irregular shrinkage during drying [13]

According to Brand and Roesler [14], when bulk concrete was incorporated with RAP as a coarse aggregate, its strength and modulus lessened. Part I of their investigation focused on individually assessing the Interfacial Transition Zone (ITZ) of mortar containing RAP particles and mortar comprising dolomite fragments based on images taken using backscattered electron micrographs. Then, the observations were laid vis-à-vis each other, and the RAP mortar ITZ appeared to be more sizeable and permeable than the dolomite mortar ITZ. It also showed lesser calcium hydroxide (CH) and calcium silicate hydrate (C-S-H) along the asphalt interface. The shape of CH was not substantially changed, although CH growth might have been impacted by the asphalt layer's presence. Furthermore, including silica fume in the RAP mortar ITZ decreased the perviousness as well as CH fragment size, albeit still not on the level of the mortar with dolomite ITZ. The study concluded that the bigger and more permeable ITZ of RAP mortar played a major role in the perceived decrease in the concrete's strength and modulus.

In Part II of the study, Brand and Roesler [15] highlighted the connection between cement and asphalt. An increase in bond energy at the cement-asphalt interface was observed to be triggered by some chemical procedures that oxidize asphalt, though the size and porosity of the ITZ were retained. According to the calculation on surface free energy, asphalt cohesion was estimated to be the failure mode instead of the failure of cohesion between the cement and asphalt or cohesion at the ITZ. Debbarma et al. [16] laid the blame on the RAP's embedded asphalt coating and clumped shards for its strength limitations. However, because the minimum strength requirements were satisfied, coarse and fine RAP particles could each be incorporated up to 50%. Regarding endurance, coarse RAP has freeze-thaw durability and up to 50% resistance to chloride ion penetration. At the same time, the addition of RAP offered advantages like improved workability and toughness, and a porous microstructure might be anticipated, allowing hostile ions from surroundings to seep through and seriously degrade the concrete.

Despite the possibility of a little improvement in durability, the asphalt cohesion failure associated with the aforementioned amalgamations meant that additional cementitious components failed to boost mechanical performance.

Reclaimed Asphalt Pavement (RAP) was investigated by Dubey et al. [17] in rigid pavement as the Pavement Quality Course (PQC). However, there has been a dearth of research that has dealt with how RAP gradation affects Dry-Lean Concrete (DLC) layers. This study detailed how RAP aggregates affected the density and strength characteristics of DLC. RAP ratio was calculated according to black curve gradation and True Curve Gradation (TCG). In an attempt to establish the impact created by RAP via the fractionation method, mixed parameters like density and compressive strength were examined. It was discovered that Fractionated Reclaimed Asphalt Pavement (FRAP) significantly affected how DLC behaved.

Sixty percent (60%) Fractionated RAP (FRAP) proved the first to satisfy the 7-day DLC compressive strength requirement, after which came lesser proportions. As revealed by the data analysis, RAP, like water content, substantially impacted how the DLC composites performed structurally. Conversely, RAP had minimal impact on density. Further research demonstrated that FRAP is an economically sound option for constructing DLC layers in stiff pavements. A clear economic analysis was employed to back up this claim. It is also crucial to incorporate RAP as a waste material when building subbase layers like DLC because it raises a number of environmental issues, including disposal.

Al-Ghalibi and Mohamad [18] credited the extremely porous nature of the erstwhile product, which blanketed the virgin aggregate that was bituminous in RAP and mortar in RCA and strengthened the ITZ, as a factor that could improve the performance and durability of pavements containing RAP or RCA. Water absorption data at the aggregate level were investigated. Results suggested that when saturation was achieved, the change became continuous, and the results were highly connected with time throughout the absorption period. The obtained recycled had a saturation time of almost twenty-four (24) hours.

Saboo et al. [19] also endeavored to investigate how permeable paving slabs would function and how suitable they would be as a construction material using aggregates from RAP. They gathered virgin aggregates as well as RAP, proportioned them into 0-100, 50-50, and 100-0 combinations, and mixed them with aggregates graded G1-coarser and G2-finer in order to create chamfered previous paver blocks. The specimens were produced using three distinct water-cement ratios, to wit, 0.25, 0.30, and 0.35. Porosity, density, and dynamic elasticity using UPV were appraised, as well as compressive strength and abrasion using Cantabro loss, to gauge PPB characteristics, CL. Findings showed that with the RAP incorporation at 10%, 30%, and 50%, strength dwindled by 4.23%, 14.3%, and 23.6% in the G1 gradation, compared to an average of 10%, 27%, and 43% in the G2 gradation. The values of CL, UPV, and CS were ascertained to be closely linked. The Analysis of Variance (ANOVA) findings indicated that RAP had a substantial impact on several pervious concrete qualities. Overall, the findings demonstrated that pervious concrete paver blocks with G1 gradation could include up to 50% RAP, thereby highlighting their sustainability.

Hossiney et al. [20] conducted a study to determine whether RAP aggregates could be used in alkali-activated concrete masonry blocks. India has seen a sharp increase in road expansion projects in recent years, resulting in extant bituminous roads being crushed and dismantled to produce a huge quantity of RAP. New bituminous roads recycled RAP, but a significant amount of it remained degraded, particularly in urban areas. As a result, the paving industry must make optimum use of the unutilized RAP. Alkali-activated paver blocks were created using fly ash, GGBS, NaOH solution, Na2SiO3 solution, RAP, and natural aggregates. RAP materials replaced natural aggregates at 0%, 25%, 50%, and 75% weight replacement rates, respectively. Then, the constructed paver blocks underwent testing for abrasion resistance, compressive strength, and water absorption following the ISO 15658: 2006 standard. The laboratory findings revealed that the compressive strength and abrasion resistance of the paver blocks in alkali-activated concrete were weakened by RAP aggregates. Despite a strength reduction, manufactured paver blocks are still categorized for use in pedestrian and outside carriageways.

Concrete paver blocks fabricated from non-beneficial RAP components, remnant derivatives generated from crushed pavement made of asphalt, were analyzed in a laboratory setting by Nandi and Ransinchung [21]. In the study, these materials were systematically examined, and any similarities and disparities were noted. The study employed a two-way ANOVA and several comparison tests to explore the RAP percentage and moist curing age. In the controlled environment, the RAP-based concrete slabs showed considerable promise when applied in scenarios with medium, moderate and extremely high usage. Moreover, boosting the RAP dose as a natural aggregate substitute and the RAP concrete's durability was possible by adopting a compaction system that combines synchronized impact pressure with vibratory compaction energy, along with a staged mixing process. Likewise, reusing RAP components into prefabricated concrete paver blocks highlighted its possible sustainability when viewed from a financial and ecological standpoint.

3. Research Significance

The performance of RAP utilized in concrete masonry units is investigated in this study with respect to critical metrics like compressive strength and water absorption. As a matter of course, the outcomes will illuminate and highlight the advantages of using considerable RAP quantities, which are currently underutilized in precast paving block applications in the State of Qatar. It will also inspire transportation officials and construction industry professionals alike to create appropriate guidelines for this innovation.

Prior studies have appraised the impact of integrating varying amounts of RAP into concrete paving mixes, including Roller Compacted Concrete (RCC) amalgams, Dry Lean (DLC) blends, and Portland Cement Concrete (PCC) mixes. Notwithstanding the varied percentages of RAP usage, the mechanical strength demonstrated by these concrete mixtures consistently suffered a decline in all of these investigations. The culprit in this demotion was understood to be the coat of asphalt enveloping the RAP particles since it hindered the cement mortar matrix and RAP aggregates from bonding at the interface. Nonetheless, the results of these investigations indicate that there are promising mechanical properties in the mixes as a result of incorporating RAP. Other studies concluded that using RAP has significant benefits for both environmental and economic sustainability. In India, different methodologies, testing approaches and empirical experimentations are being employed in existing research on the application of RAP for concrete products such as paving blocks.

The subject of RAP being a replacement aggregate in manufacturing concrete masonry units remains unsupported by any published studies. By using RAP in place of some of the virgin aggregates, the researcher endeavors to assess the efficacy of concrete masonry units. Furthermore, the Qatar Construction Specification 2014 Section 13 Part 4.4.1 (3) and (4) allows the replacement of natural coarse aggregate with recycled aggregates up to 50% if the target mean compressive strength stands at 7.0 MPa (N/mm2) or higher and up to 100% if the required mean compressive strength is below 7.0 MPa (N/mm2).

4. Conceptual Framework

Figure 3 depicts the conceptual framework of this study.

5. Scope and Limitations

This study will concentrate on evaluating the performance of the Concrete Masonry Units (CMUs) that use RAP in varying proportions to partly substitute natural aggregates. The testing parameters shall be limited only to compressive strength and water absorption pursuant to the Qatar Construction Specifications 2014 requirements.

RAP with nominal aggregate sizes of 0–5 mm is used in this investigation. When manufacturing concrete masonry units, RAP aggregates will be utilized in proportions of 10%, 20%, 30%, 40%, and 50% in place of natural aggregates. Natural fine-washed sand with a size of 0-5mm shall be used as fine aggregate.

6. Materials and Methodology

This research is divided into five (5) phases, namely: Phase 1: Sourcing and Preparation of Reclaimed Asphalt Pavement (RAP); Phase 2: Concrete Mix Design and Preparation of Specimens; Phase 3: Testing of Specimens, Result Interpretation and Discussion; Phase 4: Derivation of Mathematical Model; and, Phase 5: Evaluation, Conclusion and Recommendation.

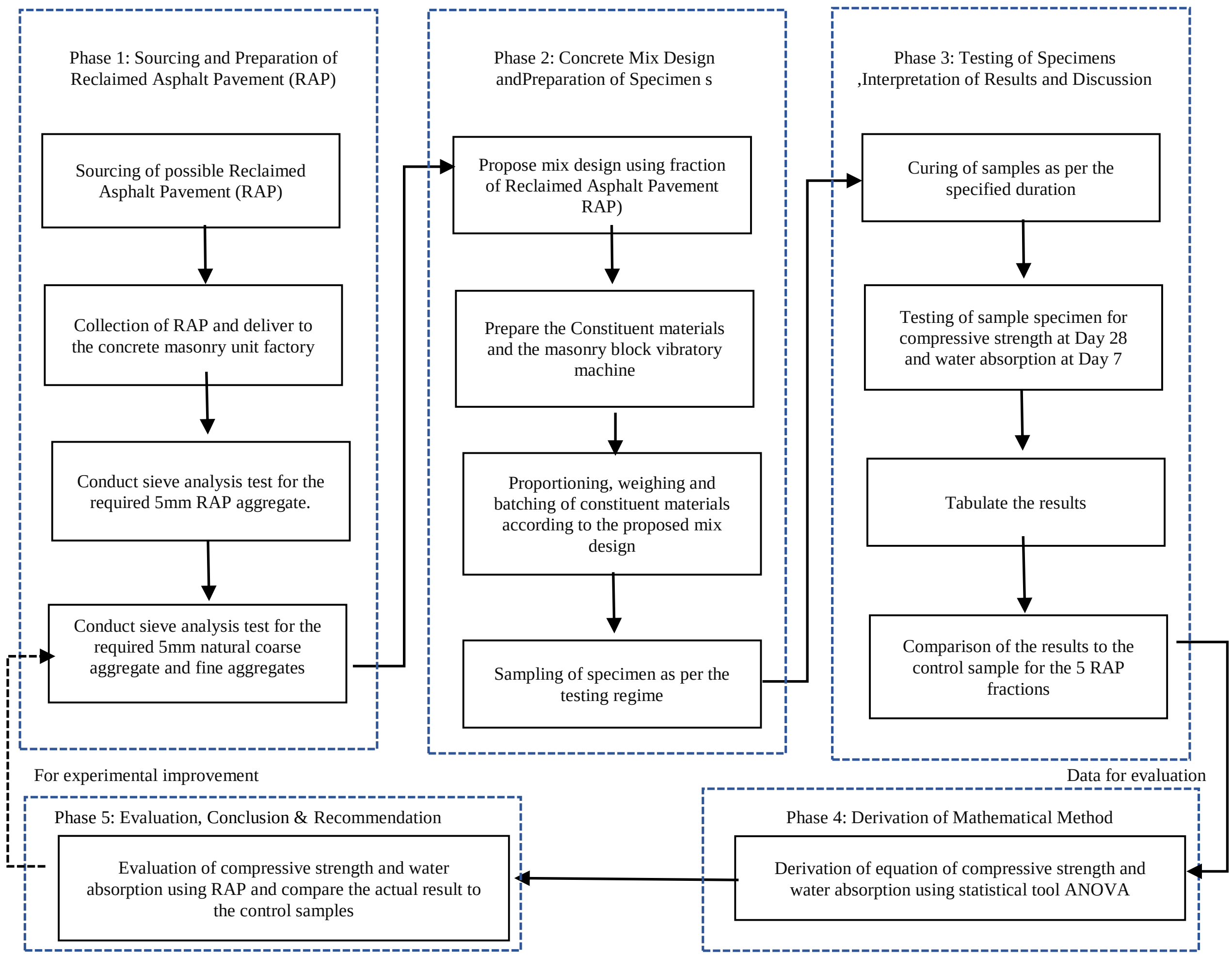


Fig. 3 Conceptual framework of the study

6.1. Sourcing and Preparation of Reclaimed Asphalt Pavement (RAP)

Figure 4 depicts the location where RAP was acquired. Underutilized RAPs were stockpiled by construction contractors at a construction site prior to disposal in government-approved disposal sites. Suitable RAP aggregates were transported from the construction site to the concrete masonry unit production facility for the preparation and sampling of specimens. Next, a sieve analysis test was conducted individually for the RAP aggregate (0-5mm), natural aggregate (0-5mm), and fine sand (0-5mm).

6.2. Concrete Mix Design and Preparation of Specimen

Sampling of specimens for testing used a volumetric ratio of cement, sand, natural and RAP coarse aggregate. Mix Design 1 was the control sample and was designated as

CMU0RAP. It contained 1 part cement, 3 parts 0-5mm fine washed sand, 6 parts 5mm size natural coarse aggregates and 0-part 5mm size RAP coarse aggregates. Mix Design 2, assigned as CMU10RAP, comprised 1 part cement, 3 parts fine-washed aggregates, 5.4 parts 5mm size natural coarse aggregates and 0.6 parts 5mm RAP coarse aggregates. Mix Design 3 was labelled as CMU20RAP and held 1 part cement, 3 parts fine-washed aggregates, 4.8 parts 5mm natural coarse aggregates and 1.2 parts 5mm RAP coarse aggregates. Mix Design 4 was identified as CMU30RAP and included 1 part cement, 3 parts 0-5mm fine-washed aggregates, 4.2 parts 5mm natural coarse aggregates and 1.8 parts 5mm RAP coarse aggregates. Mix Design 5, tagged as CMU40RAP, incorporated 1 part cement, 3 parts 0-5mm fine washed aggregates, 3.6 parts 5mm natural coarse aggregates and 2.4 parts 5mm RAP coarse aggregates. Finally, there was Mix Design 6, marked as CMU50RAP, which combined 1 part cement, 3 parts 0-5mm fine-washed aggregates, 3 parts 5mm natural coarse aggregates and 3 parts 5mm RAP coarse aggregate. Water was added to achieve a zero slump when tested for consistency using a slump cone. Table 1 outlines the six (6) mix designs, along with the number of samples collected for the compressive strength and water absorption tests conducted on Day 28 and Day 7 of curing, respectively.

As shown in Figure 5, all constituent components employed in the research investigation were similar to those materials utilized by the concrete masonry unit factory except for the RAP, as the source was the stockpile area in a construction site. A vibratory masonry concrete block machine was used to compact the specimen into a mold with a size of 400mm x 200 mm x 100mm.

This study made use of ordinary Portland cement (white or gray) that had a minimum grade of 42.5MPa (N/mm2) and a specific gravity of 3.15 to comply with BS EN 197-2 stipulations, as a binder for the concrete masonry unit. This cement complied with QCS 2014 Section 5 Part 3. A natural silica aggregate, approximately 5mm in size and currently in use by the concrete masonry unit factory, was employed. RAP, nominally at 5mm size, was obtained from the RAP stockpile at a construction site and was used as a partial replacement aggregate. Fine-washed sand from the sand treatment plants was utilized as fine aggregates or the same fine-washed sand currently being used by the paving block factory. The fine-washed sand conformed to the provisions of QCS 2014 Section 5 Part 3. Potable water supplied by Kahramaa Water was used and was compliant with QCS 2014 Section 5 Part 4.

Figure 6 illustrates how materials were then measured and proportioned on the basis of the volumetric method. Cement, fine aggregates, coarse aggregates, water, and admixtures were gauged using containers with a defined volume measured by the third-party laboratory. The concrete masonry unit samples were water-cured using and kept in an air-controlled environment for 7 days for water absorption and 28 days for compressive strength, as required by QCS 2014. For each of six (6) mix designs, three (3) samples for compressive strength on Day 28 of curing and three (3) samples for water absorption on Day 7 of curing, for a total of thirty-six (36) samples, were collected and sent for testing at the third-party laboratory, as presented in Figure 7.

6.3. Testing of Specimen, Results Interpretation and Discussion

According to the Qatar Construction Specifications 2014, there are two critical properties required to be evaluated, namely, compressive strength and water absorption, where the acceptance criteria are stipulated in Section 13 Part 4.4.1(6) and Section 13 Part 4.4.1(14), respectively, for five classes of masonry blocks as shown in Table 2.

Illustrated in Figure 8 is the testing being conducted for compressive strength of the concrete masonry units using BS EN 772-1:2011+A1:2015 at day 28 of curing. At Day 7 of curing, specimens underwent water absorption testing using ASTM CML 9-97 in the third-party testing laboratory, as shown in Figure 9. Results were tabulated for statistical analysis, and then those of the control sample and those of the five (5) mix designs containing RAP fractions were compared.

6.4. Derivation of Mathematic Model

The results of water absorption and compressive strength tests for concrete masonry unit samples were scrutinized using the Analysis of Variance (ANOVA) method. Tables and graphical representations of the results have been presented for ease of reference.

6.5. Evaluation, Conclusion and Recommendation

The F-ratio statistic of the ANOVA, which represents the null hypothesis, will approach 1 provided a lack of any observable differences among the evaluated groups. All possible F-statistic values are distributed according to the F-distribution. Two unique sets of numbers-the numerator degrees of freedom and the denominator degrees of freedom-define this group of distribution functions.

7. Results and Discussion

7.1. Compressive Strength

A concrete masonry unit’s compressive strength has a crucial role in impacting both its performance and longevity. As per Table 3, the compressive strength of the specimens was as follows: control sample 0% RAP (CMU0RAP) reached 15 MPa; 10% RAP (CMU10RAP) rated 9.5 MPa; 20% RAP (CMU20RAP) measured 9.1 MPa; 30% RAP (CMU30RAP) registered 8.7 MPa; 40% RAP (CMU40RAP) set 8.5 MPa; and 50% RAP (CMU50RAP) was 8.4 MPa when tested at 28 days. According to the results plotted in Figure 10, the use of additional RAP fractions to the mixes drastically reduced the compressive strength between 37% and 44% when compared to the control samples. The findings corroborate those of earlier research by Brand and Roesler [14, 15] which found that concrete strength and elastic modulus appeared to diminish when RAP was introduced into the concrete mixtures as an aggregate. This was due to the bitumen that surrounded the aggregates, hampering the aggregate and cement from adhering to one another effectively, and the ITZ shared by the Portland cement mortar and RAP happened to be weaker. Similarly, prior research [7-10, 12, 14-17, 19, 21] supported the observation of reduced compressive strength of concrete containing RAP fractions.

Permissible values for compressive strength of CMUs are stipulated in Qatar's construction specifications [3]. Of the non-load bearing kind, CMUs should be able to withstand compression of at least 7 MPa for external non-load bearing walls and no less than 4 MPa for internal non-load bearing walls, roof block and protective skins to foundations.

In contrast, the compressive strength should be no less than 10.4 MPa for load-bearing walls, a minimum of 17.4 MPa for load-bearing walls below ground, and not lower than 14 MPa for soakaways and manholes. In line with the findings, incorporating RAP into the mixes substantially lowered the compressive strength of the concrete masonry units.

7.2. Water Absorption

A critical factor affecting concrete strength and durability is the CMUs' ability to absorb water. Proper water absorption helps achieve the desired concrete properties and thereby impacts sustainability, while excessive water absorption can lead to cracking and deterioration. The average water absorption for concrete masonry units after 7 days is shown in Table 3 and plotted as a graph in Figure 11.

Control sample 0% RAP (CMU0 RAP) shows a water absorption of 3.7%, 10% RAP (CMU10RAP) was found to be 2.6%, 20% RAP (CMU20RAP) was 2.4%, 30% (CMU30RAP) was 2.3%, 40% RAP (CMU40RAP) was 2.1% and 50% RAP (CMU50RAP) was 1.9% at 7 days. The findings of the previous study are supported by the result, which indicates that the water absorption for concrete containing RAP materials is statistically comparable to or does not differ significantly from the control samples [9].

In comparison to recycled concrete aggregates, reclaimed asphalt pavement absorbs less water; when measured against natural aggregates, it takes up less water and possesses a lower specific gravity [18]. The reason for the decrease in water absorption is that aged asphalt was present in RAP aggregates when the asphalt was mixed at 110°C resulted in filling the gaps in the solidified paste; it lowers porosity and enhances water absorption [20]. Pursuant to Section 13 Part 4.4.1(14), the mean water absorption of the examined specimens must not be more than 7%, and no single block must top 7.5%. The findings of the water absorption test suggested that adding RAP to the mixes enhanced the CMUs' water absorption capacity, albeit the difference was statistically insignificant.

7.3. Correlations

Compressive strength remains among the testing criteria of utmost urgency and significance in evaluating the efficiency of concrete masonry units apart from the water absorption property. Figure 12 presents the correlation established between compressive strength and water absorption. It is evident in the evaluation findings from all six (6) mix designs that as the compressive strength decreases, so does the water absorption. Though it enhanced the water absorption capacity, a feature advantageous for the concrete masonry unit's durability, the higher quantity of RAP drastically reduced the compressive strength.

7.3.1. Analysis of Variance

Tables 4 and 5 present the result of ANOVA to compare the compressive strength and water absorption of the samples. It was noted that only the compressive strength test result of the control sample, 0% RAP (CMU0RAP), are statistically significant differences when compared to those of the samples containing RAP replacements, namely CMU10RAP, CMU20RAP, CMU30RAP, CMU40RAP, CMU50RAP since their p-value less than 0.05. The pairwise comparison between the mix designs containing RAP shows that the compressive strength results were observed to be statistically insignificant.

Furthermore, Tables 4 and 5 ANOVA show the results of the water absorption test, with no significant difference in test results when comparing each of the mix designs individually. Based on the recorded test results, which show minimal differences, the water absorption capacity of the CMUs is not substantially affected by the incorporation of RAP components.

8. Conclusion and Recommendations

8.1. Conclusion

This investigation examined the viability of employing RAP aggregates in the production of concrete masonry units. The key conclusions and findings from the research investigation are as follows:

- Upon analyzing samples on the 28^{th} day of curing, the compressive strength of concrete masonry units reduced as the RAP content in the mixture rose. The possible explanation for the decreased strength is that RAP aggregates contain softer bitumen; this decreases the aggregates' toughness and weakens the overall matrix, leading to the concrete masonry units' reduced compressive strength.
- The water absorption of concrete masonry units decreased as the RAP concentration in the mixture grew. A possible explanation for such behavior is the inclusion of old asphalt in RAP aggregates since it fills the spaces in the cured cement block, reducing the porosity and, consequently, lowering the water absorption. On day 7 of curing, water absorption slightly dropped among specimens with 10% to 50% RAP replacements in

comparison with the control samples.

- Concrete masonry units up to 50% RAP replacement can be a reliable choice for building internal and external non-load bearing walls, roof blocks and protective skins to foundations since the compressive strength and water absorption satisfactorily achieved the minimum requirements stipulated in the Qatar Construction Specifications 2014 Section 13 Part 4.4.1(6) and Section 13 Part 4.4.1(14), respectively, where acceptance criteria are shown in Table 2. However, the CMUs with RAP are not appropriate for load-bearing walls, soakaways and manholes.
- The feasibility of using CMUs with the inclusion of RAP in non-structural applications will contribute to reducing the excessive amount of milled asphalt piled up in construction sites and authorized disposal areas. This will help authorities and contractors manage the waste materials from construction.

8.2. Recommendation

In order to assess the suitability of the concrete masonry units incorporating RAP for various areas of applications, further research would investigate additional performance metrics like thermal conductivity, durability against weathering, and resistance to chemical attacks.

It is recommended that future research would focus on exploring new knowledge, ideas, and concepts regarding the use of Reclaimed Asphalt Pavement (RAP) as a constituent material in the manufacture of various concrete products.

A review of the benefit-cost ratio of using RAP in concrete masonry units is also suggested for future research to assess its economic feasibility. Additionally, in support of the UN Sustainable Development Goal, an assessment of the environmental impact of implementing RAP in CMUs will be conducted.

Table 1. Mix designs for the concrete masonry unit

Mix Design Designation	Volumetric Ratio (C: FS: NCA: RCA)	No. of Samples, Compressive strength at 28 days	No. of Samples, Water absorption at 7 days
CMU0RAP	1: 3:6:0	3	3
CMU10RAP	1: 3:5.4:0.6	3	3
CMU20RAP	1: 3:4.8:1.2	3	3
CMU30RAP	1: 3:4.2:1.8	3	3
CMU40RAP	1: 3:3.6:2.4	3	3
CMU50RAP	1: 3:3:3	3	3

C: Cement, FS: Fine sand, NCA: Natural Coarse Aggregate, RCA: RAP coarse aggregate

Table 2. Acceptance criteria in accordance with qatar construction specifications 2014

Class	Minimum Compressive Strength, MPa (N/mm^2)		Water absorption, %		Uses for which Blocks are Suitable
	Average of 3 Blocks	Lowest Individual Block	Average of 3 Blocks	Highest Individual Blocks	
1	7.0	5.6	7	7.5	External non-load-bearing walls
2	10.4	8.3	7	7.5	Load bearing walls
3	17.4	14	7	7.5	Load-bearing walls below ground
4	14.0	11.2	7	7.5	Soakaways and manholes
5	4.0	3.6	7	7.5	Internal non-load bearing wall, roof block, protective skins for foundation

Table 3. Results of compressive strength and water absorption tests

Mix Design Designation	Volumetric Ratio (C: FS: NCA: RCA)	Compressive strength at 28 days, (N/mm^2)	Water absorption at 7 days, %
CMU0RAP	1: 3:6:0	15.0	3.7
CMU10RAP	1: 3:5.4:0.6	9.5	2.6
CMU20RAP	1: 3:4.8:1.2	9.1	2.4
CMU30RAP	1: 3:4.2:1.8	8.7	2.3
CMU40RAP	1: 3:3.6:2.4	8.5	2.1
CMU50RAP	1: 3:3:3	8.4	1.9

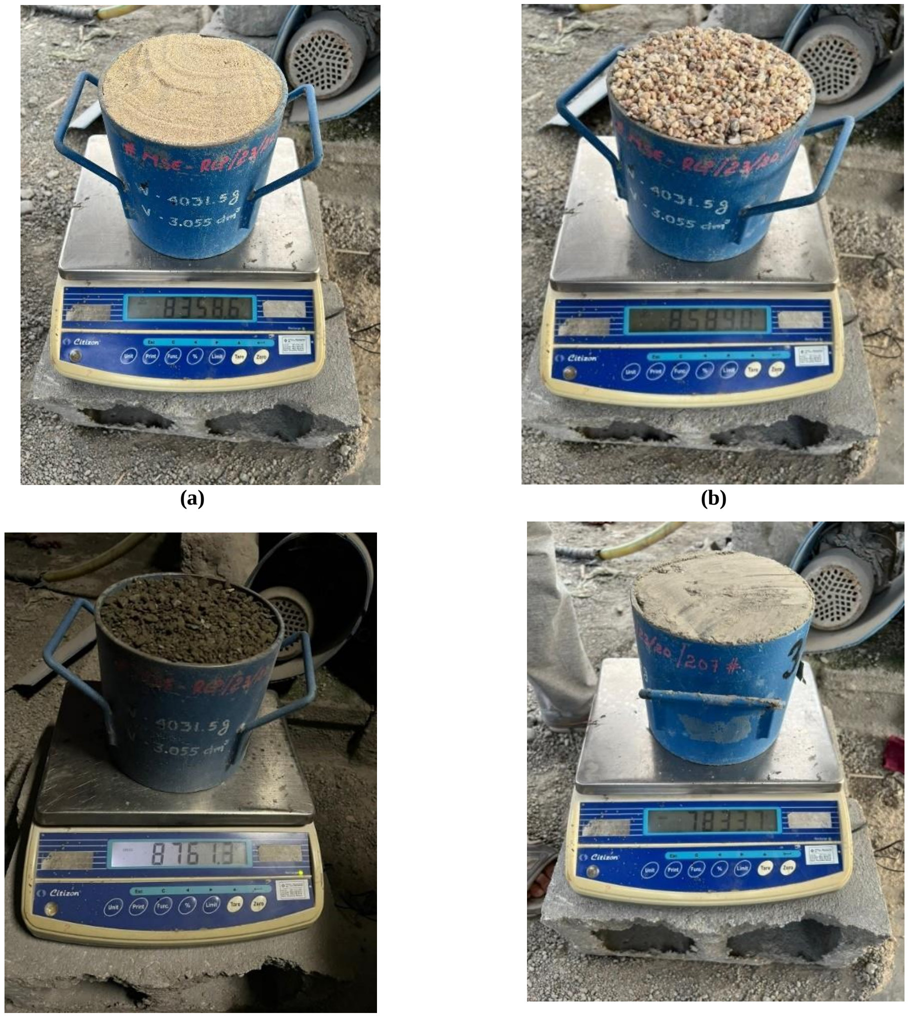
Table 4. One-way Analysis of Variance (ANOVA) for results of compressive strength and water absorption

Parameters		Sum of Squares	df	Mean Square	F	p-value	Significance
Compressive Strength	Between Groups	96.336	5	19.267	26.494	0.000	Significant
	Within Groups	8.727	12	0.727			
	Total	105.063	17				
Water Absorption	Between Groups	5.811	5	1.162	2.345	0.105	Not Significant
	Within Groups	5.947	12	0.496			
	Total	11.758	17				

Table 5. Pairwise comparison (Tukey HSD) of compressive strength

(I) Percentage	(J) Percentage	Mean Difference	Std. Error	p-value	Significance
0%	10%	5.467	0.696	0.000	Significant
	20%	5.867	0.696	0.000	Significant
	30%	6.267	0.696	0.000	Significant
	40%	6.467	0.696	0.000	Significant
	50%	6.567	0.696	0.000	Significant
10%	20%	0.400	0.696	0.991	Not Significant
	30%	0.800	0.696	0.852	Not Significant
	40%	1.000	0.696	0.707	Not Significant
	50%	1.100	0.696	0.625	Not Significant
20%	30%	0.400	0.696	0.991	Not Significant
	40%	0.600	0.696	0.949	Not Significant
	50%	0.700	0.696	0.907	Not Significant
30%	40%	0.200	0.696	1.000	Not Significant
	50%	0.300	0.696	0.998	Not Significant
40%	50%	0.100	0.696	1.000	Not Significant

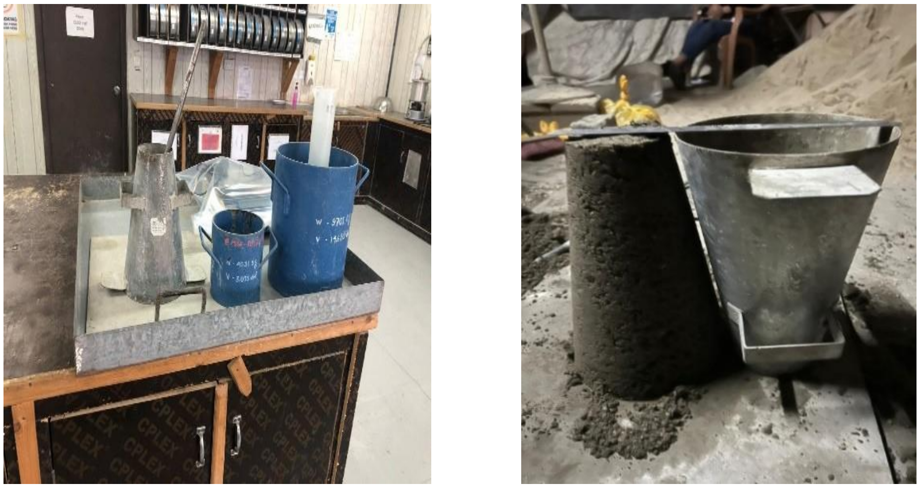
Fig. 4 Stockpile of Reclaimed Asphalt Pavement (RAP) at construction site



(a) (b) (c) (d)

Fig. 5 Constituent materials for concrete masonry units (a) Fine sand (0-5 mm), (b) Course sand (5mm), (c) RAP (5 mm), and (d) Portland cement.

(a) (b)



(c) **(d)**

Fig. 6 (a) Measuring the amount of water, (b) Mixing of Constituent Materials, (c) Measuring apparatus, and (d) Slump test

(a) **(b)**

(c)

Fig. 7 (a), (b) Samples of CMU for compressive strength and water absorption, curing of samples, and (c) delivery of samples to the 3rd party laboratory for testing.

(a) (b)

(c) (d)

Fig. 8 (a), (b), (c) and (d) Testing for compressive strength of CMU Samples at 28 days.

(a)

(b) (c)

Fig. 9 (a), (b), and (c) Testing for water absorption of CMU samples at 7 days.

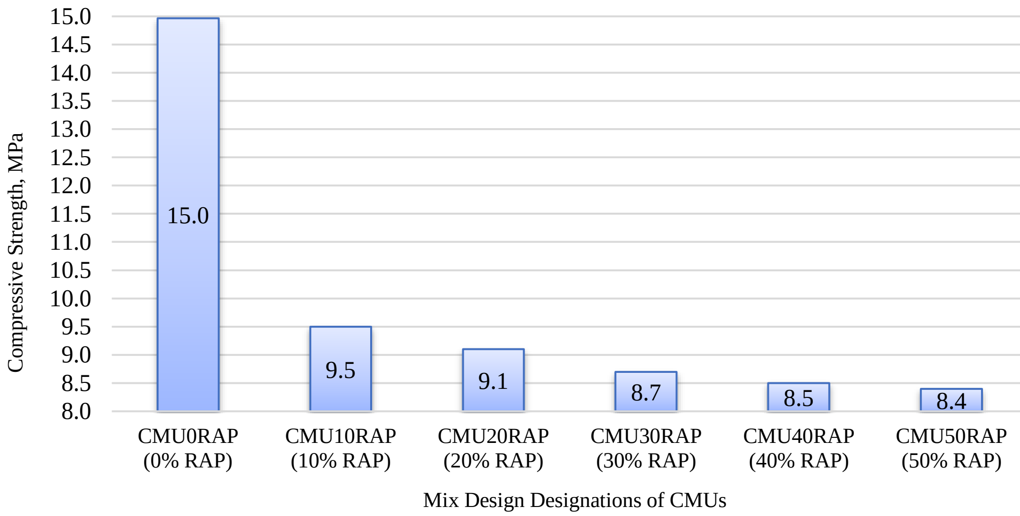


Fig. 10 Compressive strength test results at 28 days of curing

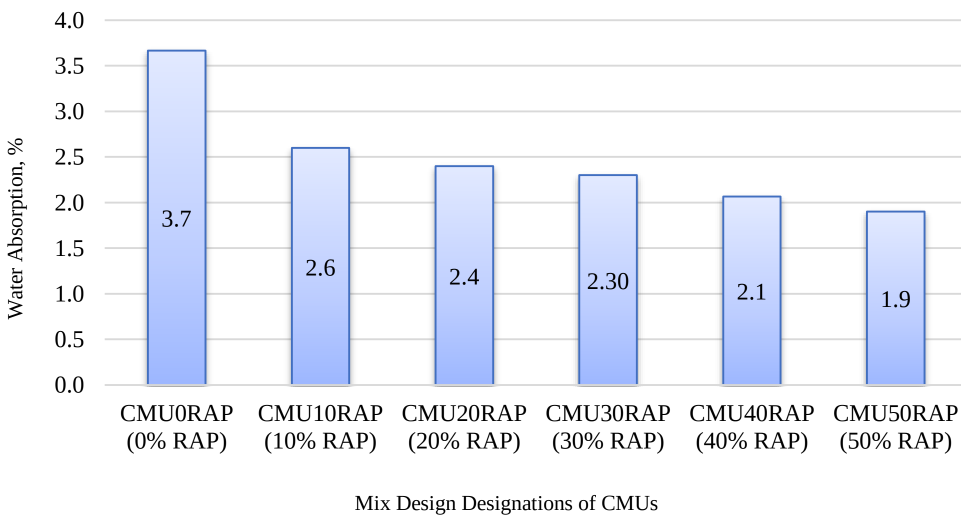


Fig. 11 Water absorption test results at 7 days of curing

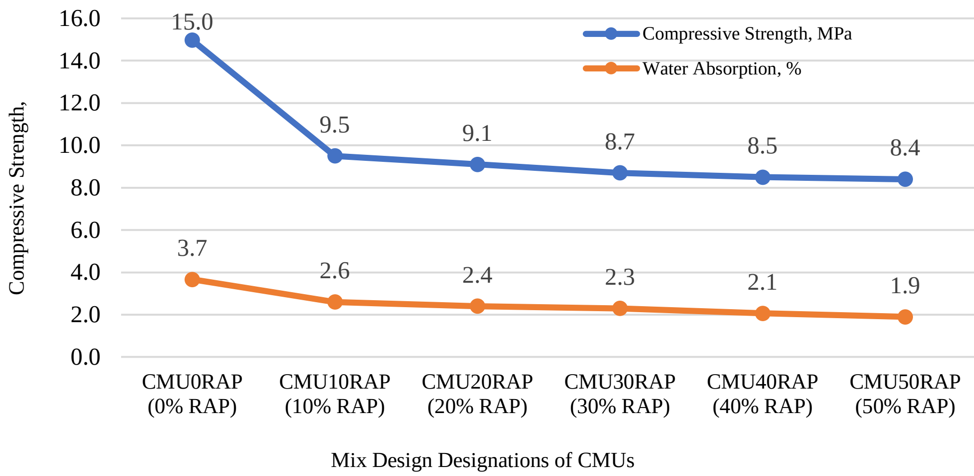


Fig. 12 Relationship between compressive strength and water absorption

Availability of Data and Materials

All data, models, and code generated or used during the study appear in the submitted article.

Author's Contribution

E.F. Domingcil conceptualized this study, carried out experiments and finalized the manuscript. B.S. Villaverde provided advice during the research and has reviewed the manuscript.

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