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Original Article

The Impact of Water-Cement Ratio on Concrete properties made with Hand Crushed and Machine Crushed Aggregates

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Abstract

This study seeks to provide insight into how varying water cement ratios (0.40, 0.45 and 0.50) influence the properties of fresh and hardened concrete made with aggregates prepared using two different preparation methods (manual and mechanical) both experimentally and statistically. Concrete properties evaluated included workability, density, compressive and flexural strengths at 7, 14, 21 and 28 days of curing. Results revealed that varying the water-cement ratio impacted both fresh and hardened concrete properties while concrete having low water cement ratio performed better for both aggregates. Although hand-crushed aggregates had slightly higher percentage gains in compressive strength over time, the machine-crushed aggregates started at a much higher strength. The flexural strength increased over time, with machine-crushed aggregates exhibiting a faster rate of gain while early-age differences were minimal, the disparity became more pronounced at 21 and 28 days. For all w/c ratios, machine-crushed aggregates consistently demonstrated lower water absorption compared to those with hand-crushed aggregates at later ages. ANOVA and the independent samples *t*-Tests were employed to statistically verify these effects. A significant impact of water cement ratio and curing age was observed on the compressive strength, flexural strength and density while water absorption was significantly less impacted. The independent samples t-Test showed a significant difference between the mean values for compressive strength, flexural strength and density ($p < 0.001$), with machine-crushed concrete consistently outperforming hand-crushed concrete. Water absorption, however, showed no statistically significant difference ($p = 0.689$), suggesting that both aggregate types absorb water at comparable rates.

Keywords: *Concrete*; *water-cement ratio*; *hand crushed aggregates*; *machine crushed aggregates*; *fresh and hardened concrete.*

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1. Introduction

Concrete is the most widely used construction material globally due to its versatility and cost-effectiveness. It is primarily composed of cement, aggregates, water, and admixtures [1]. The performance of concrete is largely dependent on the intricate interplay among these constituents. Among the various factors influencing concrete properties, the water-cement ratio (w/c) is regarded as the most critical parameter affecting both its fresh and hardened states.

In many developing regions, especially rural and peri-urban areas, the use of manually produced (hand-crushed) aggregates remains prevalent due to limited access to mechanical crushers and the high cost of machine-produced aggregates. While this practice reduces construction costs and supports local economies, it introduces variability in aggregate quality, which can affect the structural integrity and durability of concrete.

Concrete properties such as compressive strength, flexural strength, and water absorption are known to be significantly influenced by the water-cement (w/c) ratio—a critical parameter controlling the workability and strength development of concrete. Water-cement ratio, defined as the ratio of the weight of water to the weight of cement in a concrete mix. This ratio governs the hydration process of cement and significantly influences the strength and durability of the resulting concrete [2]. The strength of structural concrete is largely a function of the hardened cement paste, which in turn is strongly affected by the water-cement ratio [3]. An optimal w/c ratio is essential for ensuring adequate hydration—typically between 0.22 and 0.25 is required for complete hydration of the cement. The additional water is usually to improve workability [4].

However, excess water in the mix dilutes the cement paste, leading to reduced strength, while insufficient water may prevent full hydration of cement particles, also compromising strength. A high w/c ratio results in a more porous structure, reducing strength, increasing permeability, lowering durability, and accelerating carbonation [5], [6], [7]. It also increases the spacing between aggregates, reduces compaction, and creates voids that are later filled with air as moisture evaporates [8].

Conversely, a low w/c ratio, although beneficial for strength and durability, can lead to poor workability, making the concrete difficult to mix, place, and compact. It may also cause high hydration heat, self-desiccation, and thermal stresses, potentially resulting in early-age cracking

[4], [9], [10]. Therefore, maintaining an appropriate water content is essential for achieving the desired concrete properties.

Workability, a key property of fresh concrete, is highly influenced by the water-cement ratio. It refers to the ease with which concrete can be mixed, transported, placed, and compacted. A low w/c ratio can lead to poor workability and compaction issues, while an excessively high ratio can cause segregation, bleeding, and reduced strength [11].

Water-cement ratio affects the setting time of concrete. Increased water content delays setting, while reduced water content accelerates it—an important consideration in projects where timing and efficiency are critical [2]. It is one of the factors that influences the occurrence of cracking and bleeding in concrete. Low water content reduces bleeding but may cause more severe cracks, while a higher water content slows the drying process, allowing the concrete to gain tensile strength during its plastic state [12].

Aggregates, which make up between two-thirds and three-quarters of concrete volume [13], also play a crucial role. Their grading and source influence packing density, water demand and ultimately, the strength and workability of the mix at specific w/c ratios. Denser aggregates generally have lower porosity and absorb less water.

Hand-crushed aggregates are obtained manually and are often more sustainable and affordable, requiring less energy for production. However, they are labor-intensive, time-consuming to produce and tend to have irregular shapes and rougher textures. Machine-crushed aggregates, produced with mechanical crushers, are more uniform and generally may provide better workability and strength.

The size of coarse aggregates also affects concrete strength. While increasing the size of coarse aggregates can improve strength, excessively large aggregates may trap water beneath them, leading to internal bleeding, reduced strength, and early cracking [14].Water-cement (w/c) ratio remains a critical parameter in determining both the fresh and hardened properties of concrete. Extensive research has examined its influence under various mix conditions, materials, and curing regimes, highlighting its centrality to concrete performance.

Adeyemi et al. [15] investigated the effect of varying w/c ratios (0.45, 0.50, and 0.60) on the compressive strength of concrete incorporating palm kernel shell (PKS) at replacement levels of 0%, 25%, 50%, and 100%. Compressive strength decreased with increasing w/c ratio and PKS content but improved with curing age. Optimal strength was achieved at a w/c ratio of 0.45. Similarly, Apebo et al. [5] observed that reducing the w/c ratio from 0.60 to 0.40 increased compressive strength by over 30% in concrete containing gravel and crushed overburnt bricks. The optimal mix was found at a gravel to brick ratio of 2:2 with a w/c ratio of 0.40.

Al Baijawi and Embong [16] studied the behavior of self-compacting concrete (SCC) with w/c ratios of 0.33, 0.34, and 0.36. They reported improved strength at lower w/c ratios, albeit with reduced flowability. Felekoğlu et al. [17] further confirmed the critical role of water content in SCC, finding that lowering free water and increasing superplasticizer dosage improved both fresh and hardened properties, including compressive strength and modulus of elasticity.

Concrete with alternative binders and aggregates has also been studied. Panda et al. [7] observed that replacing sand with copper slag in concrete improved its mechanical strength and density, particularly at lower w/c ratios. Wang and song [18] explored the hydration behaviour of calcium sulphoaluminate (CSA) cement with freshwater and seawater under varying w/c ratios. High w/c ratios accelerated hydration but reduced long-term strength, while low w/c ratios and seawater improved early strength and microstructure.

Mansor et al. [4] examined the combined effect of w/c ratio and different chemical admixtures—Type A (water-reducing), Type D (water-reducing and retarding), and Type F (high-range water-reducing)—on concrete performance. Results showed that the timing and type of admixture significantly influenced slump and strength, with optimal performance varying with both admixture type and w/c ratio.

Olonade [19] evaluated the influence of w/c ratios and water-reducing admixtures (WRA) on the Schmidt rebound number (RN) of hardened concrete. The RN increased with w/c ratio up to 0.50 but declined beyond that point, and the WRAs had minimal effect on the RN. Isfahani et al. [20] also highlighted the impact of nano-silica at different dosages, observing strength improvements primarily at higher w/c ratios, with limited benefit at lower ratios.

Curing conditions have been shown to affect the outcomes of mixes with varying w/c ratios. Jumadi et al. [6] reported that pond curing yielded higher compressive strength compared to burlap curing, particularly at lower w/c ratios. Auta et al. [21] investigated re-vibrated concrete with w/c ratios of 0.65, 0.70, and 0.75, finding that compressive strength improved with higher w/c ratios under controlled re-vibration.

Workability and setting characteristics are also closely tied to w/c ratio. Mehta and Monteiro [11] emphasized that low w/c ratios compromise workability, while excessive w/c can lead to bleeding and segregation. Salain [22] reported that increasing w/c ratio improved slump in concrete containing volcanic stone waste, though it negatively affected strength. Conversely, increasing the aggregate-to-cement ratio improved strength but reduced workability.

The durability of concrete, including its resistance to cracking, is influenced by the w/c ratio. Sivakumar [12] found that low w/c ratios increased early-age plastic shrinkage cracking due to limited bleed water. Cracks were more pronounced at a w/c ratio of 0.30, peaked at 0.40, and decreased thereafter. Alawode and Idowo [13] noted that compressive strength in both lateritic and conventional concrete decreased with higher w/c ratios, particularly beyond 0.65 in lateritic mixes. Their slump tests also revealed that lateritic concrete exhibited lower workability compared to conventional mixes.

The type and size of aggregates significantly influences the strength and durability of concrete. For example, Rahman and Ullah [14] observed that 19 mm crushed stone produced the highest compressive and split tensile strength compared to 14 mm and 28 mm aggregates. In a similar study, Konitufe et al., [23] found that angular aggregates outperformed rounded ones in strength, with 14 mm size providing optimal results.

Building upon these foundational studies, the present research investigates the effect of varying w/c ratios on the properties of concrete produced using hand-crushed and machine-crushed aggregates. It is based on the hypothesis that manually produced aggregates, due to their variable shape, texture and strength, will respond differently to changes in the water-cement ratio compared to standard machine-crushed aggregates in terms of workability, strength and durability. Investigating this interaction will provide data-driven insights into how mix design can be tailored to maximize concrete performance while minimizing costs in settings where hand-crushed aggregates are the norm. This study distinguishes itself by integrating statistical analysis, particularly analysis of variance (ANOVA), to evaluate the significance of observed differences in the properties of concrete as the use of statistical tools enhances result reliability and provides a quantitative basis for comparison. The outcomes are expected to inform best practices in material selection and mix design, particularly in contexts where resource constraints necessitate the use of hand-crushed aggregates. Ultimately, the study seeks to advance sustainable and performance-based approaches in concrete technology.

2. Materials and Methods

2.1. Materials

The materials used in this study include Portland Cement of grade 32.5N, locally available in 50 kg bags while fine aggregate was obtained from river sand sourced in Bauchi State, Nigeria. Two types of coarse aggregates were employed, hand-crushed aggregates, manually sourced from local quarries, and machine-crushed aggregates, mechanically produced from quarrying operations in Bauchi State. Clean potable water, suitable for drinking, was used in all concrete mixtures and curing processes.

Figure 1. a) Machine crushed aggregates b) Hand crushed aggregates

2.2. Methods

2.2.1 Material Characterization

The physical properties of the aggregates, including particle size distribution, bulk density, and specific gravity, were determined in accordance with relevant British Standards. The aggregate impact value (AIV) and aggregate crushing value (ACV) were evaluated following BS 812:110 [24]. These tests were conducted to assess the quality and mechanical behaviour of the aggregates used.

2.2.2 Concrete Mix Design and Preparation

Concrete mixes were prepared using water-cement (w/c) ratios of 0.40, 0.45, and 0.50. The selection of these ratios was based on their practical application and their expected influence on concrete workability and mechanical properties. For each w/c ratio, separate batches were prepared using hand-crushed and machine-crushed aggregates. Concrete employed in this research had a mean target characteristic strength of 20 N/mm^2 at 28 days curing. Cube specimens of dimensions 150 mm × 150 mm × 150 mm were cast for compressive strength testing, while beam specimens measuring 150 mm × 150 mm × 600 mm were prepared for flexural strength evaluation. After 24 hours of casting, all specimens were demoulded and cured by immersion in water at ambient room temperature until the specified testing ages of 7, 14, 21, and 28 days. Three (3) number of specimens was prepared for each test and an average of the obtained values was taken. Table 1. below shows the quantity for the materials used for the study.

Table 1. Quantity of the materials used for the study

w/c	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)
0.40	170	420	530	1240
0.45	190	420	530	1240
0.50	210	420	530	1240

2.2.3 Testing Procedures

Compressive strength tests were conducted in accordance with BS EN 12390-3 [25]. Cubes 150 mm in dimension was cast and cured under standard conditions until the time of testing. The cubes were then removed, cleaned and their dimensions measured accurately. The cubes were placed centrally in a compression testing machine. Load was then applied continuously and without shock until failure occurred. The maximum load at failure (in N) was recorded. The compressive strength was then calculated using the formula:

$$f_c(N/mm^2) = \frac{F}{A} \qquad (1)$$

Where:

fc = Compressive strength (N/mm²),

F = Maximum load (N),

A = Cross-sectional area (mm²).

Flexural strength tests followed BS EN 12390-5 [26]. Prismatic specimens measuring 150 mm × 150 mm × 600 mm was cast and cured under standard conditions. A flexural testing machine capable of applying force uniformly through two loading rollers placed at third points of the span. The load is applied through two symmetrical points, creating a three-point bending test setup. The specimen was placed centrally on two supports spaced 400 mm apart. Load is applied vertically at a constant rate and the maximum load at failure is recorded. The flexural strength (fs) is calculated using the formula:

$$f_s(N/mm^2) = \frac{F.L}{b.d^2} \quad (2)$$

Where:

fs = Flexural strength (N/mm^2)

F = Maximum load (N)

L = Span between supports (mm)

b = Width of the specimen (mm)

d = Depth of the specimen (mm)

Water absorption tests were carried out in line with BS 1881-122 [27], to evaluate the porosity-related durability characteristics of the concrete. The water absorption test was carried out using concrete cylinders cured for 28 days. The specimen was dried in an oven at 105°C ±5°C until the weight change between successive 24-hour weighings was less than 0.5%. The specimen was weighed as the dry specimen (denoted as W_{dry}). It was then immersed in water at room temperature after which the specimen was removed, the surface water was wiped with a damp cloth, and weigh it (denoted as W_{wet}). The resulting water absorption measured as a percentage was calculated using the formula:

$$Water\ absorption\ (\%) = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100 \quad (3)$$

Test for density was carried out in accordance with BS EN 12390-7 [28]. Concrete density was determined using hardened concrete cube specimen with known dimensions cured and surface dried. The dimensions (length, width and height) was used to estimate the volume (V) based on the measured dimensions. The surface-dry specimen using a calibrated balance to obtain its mass in kilograms (kg). The density (ρ) was calculated using the formula:

$$Density\ (kg/m^3) = \frac{Mass\ (kg)}{Volume\ (m^3)} \tag{4}$$

2.2.4 Data Analysis

Data obtained from the tests were analyzed using the Statistical Package for the Social Sciences (SPSS). Descriptive statistics, including mean, standard deviation, and range, were computed to summarize the results. Analysis of Variance (ANOVA) was performed to assess the statistical significance of the effects of water-cement ratio and curing age on the mechanical properties of concrete. Additionally, an independent samples t-test will be conducted to compare the mean performance of concrete made with hand-crushed versus machine-crushed aggregates.

2. Results and Discussions

Table 2. Material characterization results

S/No	Parameters	FA	Machine crushed aggregate	Hand crushed Aggregate
1	Specific gravity	2.91	2.82	1.8
2	Fineness modulus	2.7	4.16	3.5
3	Water absorption (%)	13.98	1.47	2.1
4	AIV	-	16.1	11.4
5	ACV	-	21.1	17.2
6	Loose bulk density (kg/m^3)	1581	1477	1063
7	Compacted bulk density (kg/m^3)	1615	1558	1263

Table 2. presents the physical properties of the materials used. The higher specific gravity of machine crushed aggregates as compared to the hand crushed aggregates indicate that stronger and denser concrete can be produced from machine-crushed aggregate. However, hand-crushed

aggregate has a lower Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) than machine-crushed aggregate, suggesting that concrete produced using hand crushed aggregates will be more impact-resistant and perform better under compressive loads.

Figure 2. shows the grading curve for fine aggregates and coarse aggregates. The smooth and continuous curve of the fine aggregates indicates a material having a consistent gradation with a significant proportion of medium sized particles. Nearly all particles pass through the 4.75 mm sieve, showing this material is primarily fine. A minimal amount of material passes through the 150 µm sieve, indicating low fines content, which is beneficial for workability and reduced water demand. The curve demonstrates a gradual reduction in the percentage passing as the sieve size decreases. Most of the material is retained on the larger sieves, indicating a dominance of coarse particles. For the coarse aggregates, at 37.0 mm, 100% of the material passes, below 5.0 mm, there is minimal material, showing the aggregate contains very few fines. The aggregate is well-graded, with a wide range of particle sizes from coarse to fine, ensuring good packing density and minimal voids in the concrete mix.

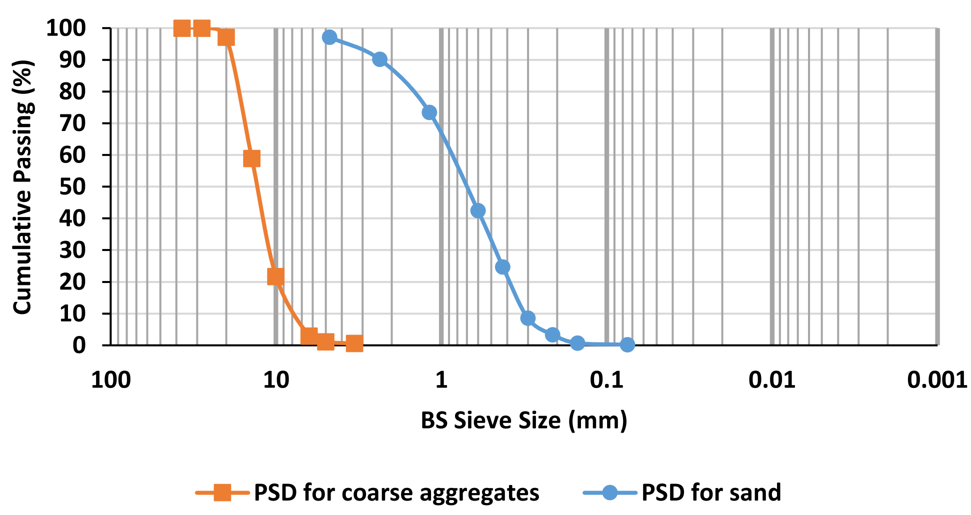


Figure 2. Particle size distribution curve for fine and coarse aggregate.

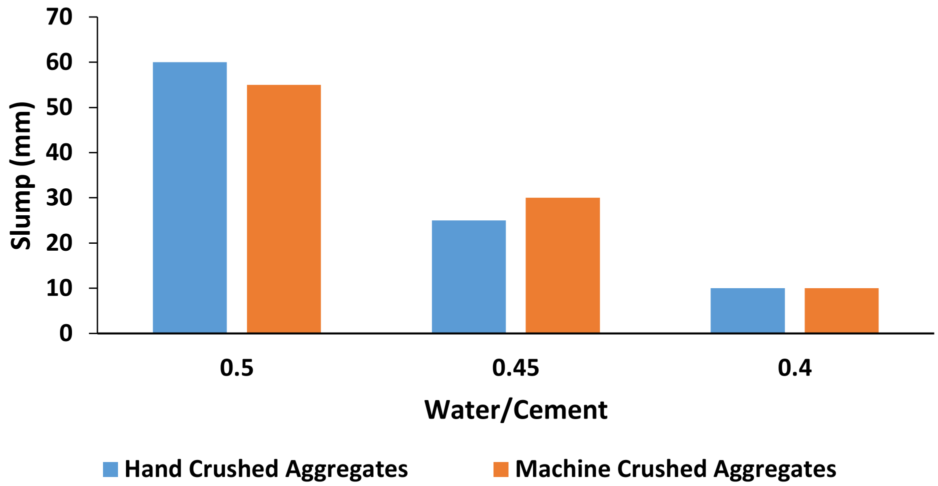


Figure 3. Slump test

3.1. Concrete Workability

Slump is a key measure of workability or consistency of concrete. The workability of fresh concrete was assessed using the slump test, with the results presented in figure 3. It illustrates the slump values (in mm) of concrete mixes prepared using hand crushed aggregates and machine crushed aggregates at three different water-cement (w/c) ratios of 0.5, 0.45, and 0.4.

At a w/c ratio of 0.5, the hand crushed aggregates had a slump value of 60 mm slump, while the machine crushed aggregates had a slump value of 55 mm. Both types of aggregates yielded the highest slump values with the highest w/c ratio, indicating increased workability. Hand crushed aggregates produced a slightly higher slump than machine crushed, possibly due to having more angular or irregular shapes in hand crushed aggregates causing greater water retention and higher surface roughness, improving paste-aggregate bonding and apparent flow.

Hand crushed aggregates had a slump of 25 mm while the machine crushed aggregates had of 30 mm at a w/c ratio of 0.45. A notable drop in slump occurred for both aggregate types as the w/c ratio was reduced. However, machine crushed aggregates yielded a slightly higher slump. This may be due to machine crushed aggregates having more uniform grading and particle shape, which may reduce internal friction and allow easier movement of the paste between particles at lower water contents. Hand crushed aggregates, being more irregular, could increase internal friction and reduce slump more rapidly as water content declines. Both aggregates had a slump of 10 mm. At this lowest w/c ratio, the slump is minimal for both aggregate types, indicating very low workability—unsuitable for unvibrated or hand-placed applications. The small difference in slump is negligible, suggesting that water content dominates the workability when the paste becomes too stiff to flow regardless of aggregate type.

As expected, slump decreases as w/c ratio decreases for both aggregate types. This is consistent with concrete technology principles: lower water content means less lubrication for aggregate particles, resulting in a stiffer mix. At high w/c ratios (0.5), hand crushed aggregates showed slightly better workability. At medium w/c ratios (0.45), machine crushed aggregates gave slightly better workability. At low w/c ratio (0.4), both types exhibited low workability.

Hand crushed aggregates may retain more water due to their texture, benefiting workability when water is abundant. Machine crushed aggregates may behave more predictably and compactly at moderate water contents. For hand-mixed or low-tech construction (often found in rural settings), hand crushed aggregates may perform better at higher w/c ratios due to better slump. For controlled mixing or structural concrete where w/c ratio is kept low, machine crushed aggregates might be preferable due to more consistent behaviour.

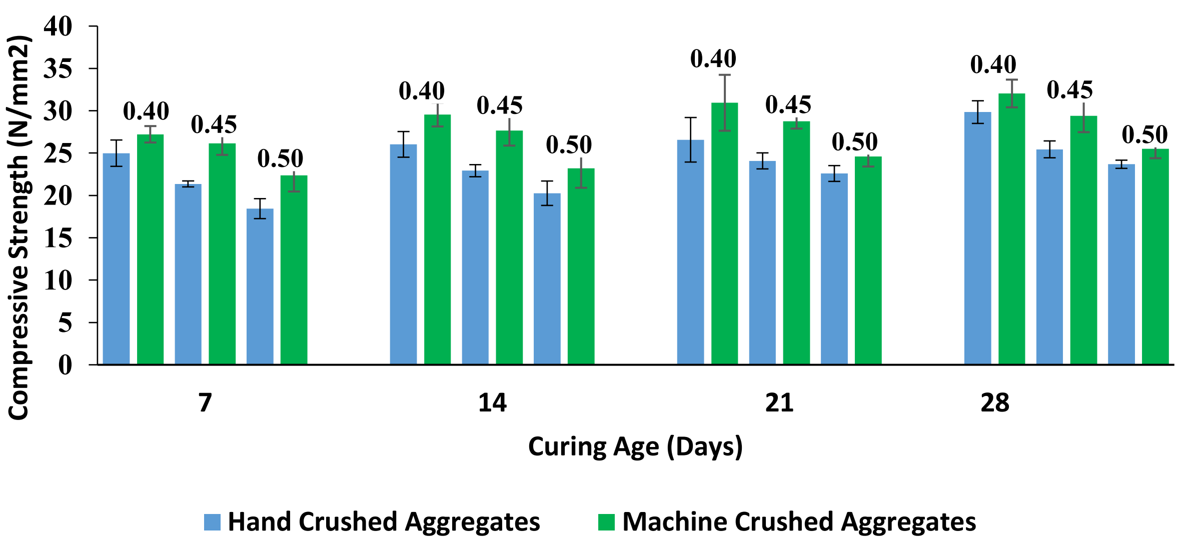


Figure 4. Concrete compressive strength against age for the various water cement ratios for both hand and machine crushed aggregates.

3.2. Compressive Strength

Figure 4. shows the concrete compressive strength results. A general trend was observed in the compressive strength values obtained. Concrete compressive strength values generally increased with increase in age indicating a positive relationship while a negative relationship was observed between compressive strength and w/c ratio. The increase in compressive strength with increase in age is expected, as concrete typically gains strength over time as hydration progresses. As the w/c ratio increased, the compressive strength decreased. The decrease is more pronounced in the concrete made with machine-crushed aggregates. This can be attributed to the increased porosity and impaired interfacial bonding between the cement and aggregates associated with high water-cement ratios. Moreover, a high-water cement ratio may cause some further dilution of the cement paste, reduce its bonding capacity and result in weaker interparticle bonds.This finding is consistent with previous studies that have reported a negative correlation between water-cement ratio and compressive strength.

The 0.4 w/c ratio consistently produced concrete with more compressive strength. Conversely, with an increase in w/c ratio between 0.45 and 0.50, a decline in the compressive strength was observed. The machine-crushed aggregates had higher compressive strength at every w/c ratio compared to hand-crushed aggregates. The highest compressive strength is observed at a 0.40 w/c ratio for machine-crushed aggregates of about 32 N/mm².

Concrete having machine-crushed aggregates generally exhibited higher compressive strength compared to concrete with hand-crushed aggregates, particularly at lower w/c ratios. This indicates that a better compaction and bonding can be achieved using machine-crushed aggregates. The compressive strength of hand-crushed aggregates, though slightly lower, still shows significant strength, especially for lower w/c ratios. For the w/c of 0.40, the hand crushed showed a 19.40% increase from day 7 to day 28. The machine crushed aggregates showed a 17.71% increase. The samples with a w/c of 0.45 showed the hand crushed aggregates having a 19.10% increase, while the machine crushed aggregate had a 12.42% increase. The w/c of 0.50, the hand crushed aggregates showed a 28.46% increase, while the machine crushed aggregates showed a 14.00% increase. This shows overall a strength increase with time to range between 12 – 29% from 7 to 28 days with the hand-crushed aggregates having slightly higher percentage gains in strength over time. However, the machine-crushed aggregates start at a much higher strength.

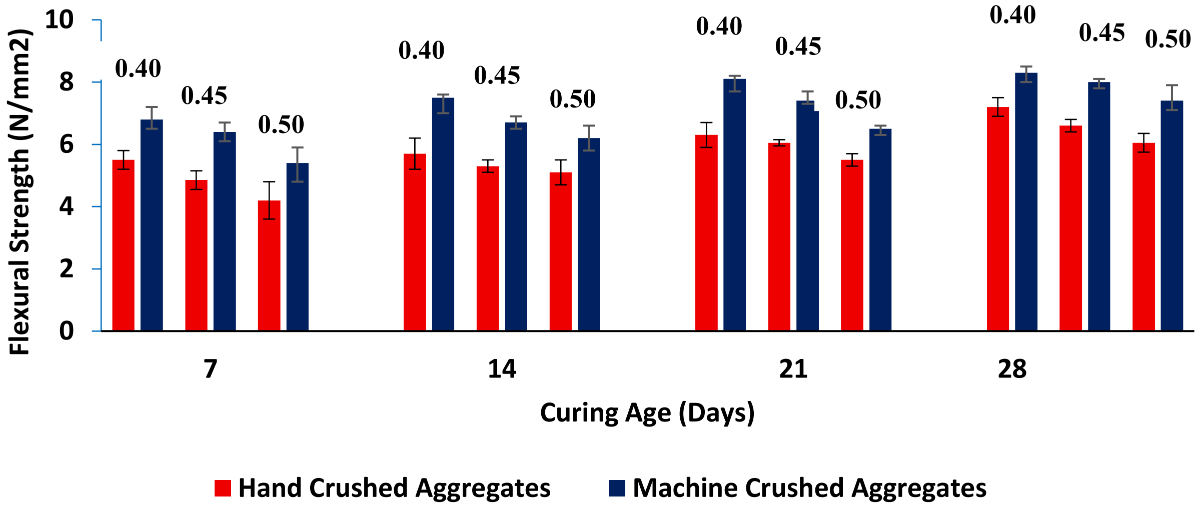


Figure 5. Concrete flexural strength against age for the various water cement ratios for both hand and machine crushed aggregates.

3.3. Flexural Strength

The values of the flexural strength with age and type of aggregate are shown in figure 5. Both hand-crushed and machine-crushed aggregates show an increase in flexural strength with age. Concrete made with machine-crushed aggregates consistently outperformed concrete with hand-crushed aggregates at all ages and w/c ratios. This can be attributed to the uniformity in particle shapes and sizes, which could have led to better compaction and improved interlock between the concrete particles. The highest recorded flexural strength is achieved with machine-crushed aggregates at 28 days. While hand-crushed aggregates also show strength gains, the rate of increase is generally slower compared to machine-crushed aggregates. The difference in flexural strength between hand-crushed and machine-crushed aggregates is less pronounced at earlier ages but becomes more noticeable at 21 and 28 days.

A general decrease in flexural strength was observed with an increase in water-cement ratios confirming that higher water content weakens concrete. The percentage decrease is more pronounced in hand-crushed aggregates compared to machine-crushed aggregates. At 7 Days, the hand crushed and machine crushed aggregate concrete decreased by 13.40 and 6.25% respectively from a water ratio from 0.40 to 0.45 and 15.47 and 18.52% from 0.45 to 0.50. The 14 days results indicated a 7.55 and 11.94% decrease for a water cement ratio from 0.40 to 0.45 for hand crushed and machine crushed aggregates, while a decrease of 3.92 and 8.07% was observed for a w/c ratio from 0.45 to 0.50. At 21 days, from a 0.40 to 0.45 increase in w/c ratio, a 4.13 and 9.46% decrease was observed, while from 0.45 to 0.50, 10.00 and 13.85% was observed for hand crushed and machine crushed aggregates respectively. The 28 days, 9.09% and 3.75% for the increase of w/c ratio from 0.40 to 0.45 and from 0.45 to 0.50 a decrease of 9.09% and 8.11% for hand crushed and machine crushed aggregate concrete respectively. This also shows that the rate of decrease slows as curing progresses, meaning the effect of w/c ratio is stronger at earlier ages. Machine-crushed aggregates appear to be a better choice for achieving higher flexural strength in concrete compared to hand-crushed aggregates. This advantage is particularly evident at later ages.

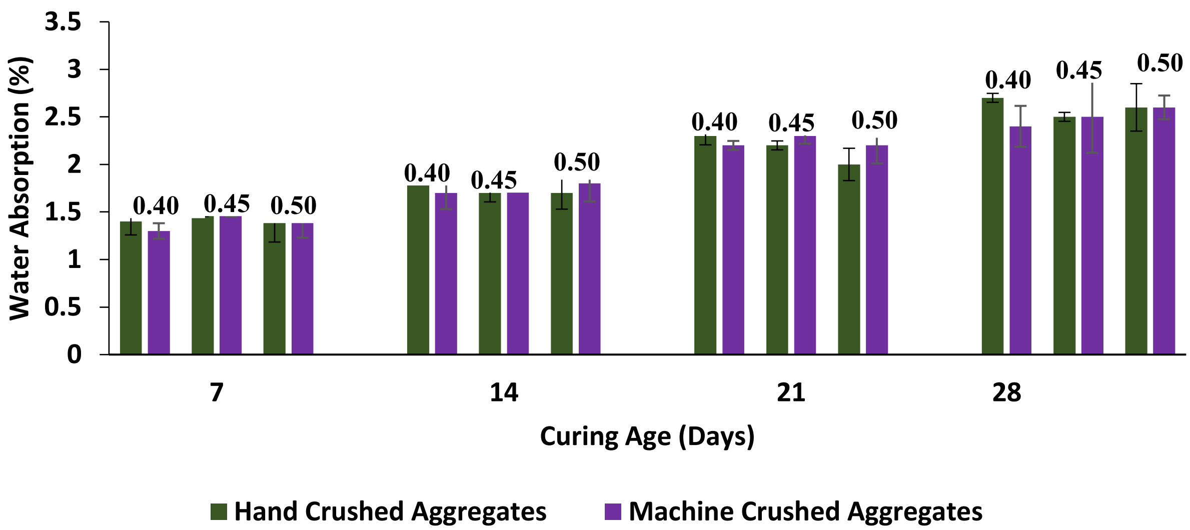


Figure 6. Water absorption against age for the various water cement ratios for both hand and machine crushed aggregates.

3.4. Water Absorption

A higher water-cement (w/c) ratio introduces more water into the concrete mix, which, upon evaporation, leaves behind larger pores between the cement paste and aggregates. These pores create pathways that facilitate water ingress, thereby increasing the concrete's water absorption capacity. Additionally, high w/c ratios hinder proper compaction, resulting in a more porous and less dense concrete structure. Figure 6. illustrates the water absorption trends for the various concrete samples. For concrete made with machine-crushed aggregates, an overall increase in water absorption was observed with higher w/c ratios. However, water absorption decreased over time for both types of aggregates. Hand-crushed aggregates, due to their more angular and irregular shapes and relatively smaller surface areas, generally require a lower w/c ratio. This lower water demand leads to a denser mix with enhanced durability. In contrast, the higher water requirement of machine-crushed aggregates tends to produce a more porous concrete mix, reducing its durability.

All concrete samples satisfied the water absorption requirement of less than 10% as specified by Neville [2]. This may be attributed to the natural drying and hardening processes of the aggregates. At early curing stages, no significant difference in water absorption was found between the two aggregate types. However, at later ages, concrete with machine-crushed aggregates consistently demonstrated lower water absorption compared to those with hand-crushed aggregates. This could be due to the more uniform particle size distribution or lower surface area of the machine-crushed aggregates, indicating their potential for producing more durable concrete.

At 7 days, the water absorption difference between the two aggregate types was minimal. By 14 days, machine-crushed aggregates showed slightly higher absorption than hand-crushed ones. At 21 and 28 days, the values converged, though hand-crushed aggregates exhibited marginally higher absorption at 28 days.

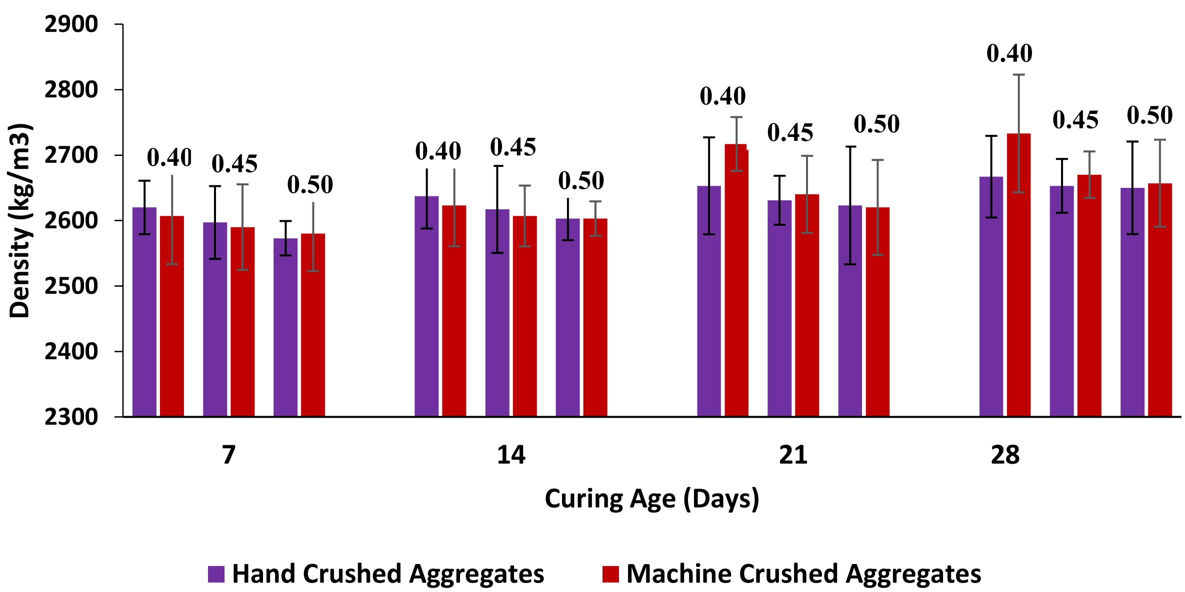


Figure 7. Concrete density against age for the various water cement ratios.

3.5. Density

At a given curing age, a general decrease in concrete density was observed with increasing water-cement (w/c) ratios for both hand-crushed and machine-crushed aggregates Figure 7. This trend can be attributed to the ongoing hydration process, where excess water creates a more porous structure as it is consumed, leaving voids in the concrete matrix. Concrete made with hand-crushed aggregates exhibited slightly higher densities at early ages (7 and 14 days) compared to those made with machine-crushed aggregates. This aligns with the findings of [29], who noted that lower w/c ratios typically result in higher-density concrete. The initial density differences may also be influenced by factors such as particle packing efficiency and the presence of internal voids, particularly within machine-crushed aggregates.

As curing progresses, the density differences between concrete made with hand-crushed and machine-crushed aggregates become less distinct, suggesting that hydration and continued compaction gradually offset initial variations. This implies that while aggregate type can influence early-age density, its impact diminishes over time relative to other factors such as w/c ratio and curing conditions. Overall, density increased with curing age for both aggregate types, indicating continuous hydration and matrix densification. The highest densities were recorded at 28 days, which is consistent with typical concrete development patterns. At 7 and 14 days, hand-crushed aggregates generally showed marginally higher densities across most w/c ratios. However, at 21 and 28 days, machine-crushed aggregates, particularly at a w/c ratio of 0.40, demonstrated a notable increase in density, surpassing that of hand-crushed aggregates. This may be attributed to better particle interlocking and hydration efficiency in the machine-crushed aggregates at lower w/c ratios. In both aggregate types, increasing the w/c ratio consistently led to slight reductions in density. This supports the understanding that higher w/c ratios introduce more voids into the concrete matrix, reducing its overall compactness. The highest density was observed at 28 days in concrete made with machine-crushed aggregates at a 0.40 w/c ratio, suggesting optimal packing and hydration conditions. Lower densities at 7 days further indicate that early-stage concrete lacks full strength and structural compactness.

3.6. Statical Analysis

A multiple linear regression-based model for estimation of compressive and flexural strengths, density and water absorptions of concrete with different water to cement at different ages, is presented in this study expressing the relationship of the concrete properties studied using w/c and CA as variables. Also, the relationship of these properties in both machine and hand crushed aggregates have been presented. The equations with their R^2, R^2 predicted and adjusted values are given as equations (5) – (16) below:

Compressive strength MC (N/mm^2) = 51.27 + 0.1787 CA - 60.25 w/c - - - -(5)

R^2 = 95.5%, R^2 (adj) = 94.5% and R^2 (pred) = 91.8%.

Compressive strength HC (N/mm^2) = 45.24 + 0.2216 CA - 56.15 w/c - - - -(6)

R^2 = 96.5%, R^2 (adj) = 95.73% and R^2 (pred) = 93.3%.

Compressive strength MC (N/mm^2) = Compressive strength HC (N/mm^2)- - - -(7)

R^2 = 99.79%, R^2 (adj) = 99.77% and R^2 (pred) = 99.75%.

Water absorption MC (%) = 0.583 + 0.054 CA (days) – 1.00 w/c - - - - -(8)

R^2 = 97.53%; R^2 (adj) = 96.98 and R^2 (pred) = 95.71%.

Water absorption HC (%) = 1.692 + 0.056 CA (days) – 1.50 w/c - - - - -(9)

R^2 = 97.38%; R^2 (adj) = 96.79 and R^2 (pred) = 95.04%.

Water absorption HC (%) = 1.0078*Water absorption MC (%) - - - - -(10)

R^2 = 99.57%; R^2 (adj) = 99.53 and R^2 (pred) = 99.47%.

Flexural Strength MC (N/mm^2) = 11.883 + 0.0862 CA (days) - 14.00 w/c- - - -(11)

R^2 = 98.64%, R^2 (adj) = 98.34 and R^2 (pred) = 97.55%

Flexural Strength HC (N/mm^2) = 8.556 + 0.0841 CA (days) - 9.63 w/c - - - -(12)

R^2 = 97.34%; R^2 (adj) = 96.75 and R^2 (pred) = 94.79%

Flexural Strength MC (N/mm^2) =1.2426*Flexural Strength HC (N/mm^2)-- - -(13)

R^2 = 99.89%; R^2 (adj) = 99.88 and R^2 (pred) = 99.87%

Density MC (Kg/m^3) = 3002 + 12.22 CA (days) – 1145 w/c - - - - -(14)

R^2 = 94.02%, R^2 (adj) = 92.69 and R^2 (pred) = 89.13%

Density HC (Kg/m^3) = 2913 + 12.09 CA (days) – 1215 w/c - - - - -(15)

R^2 = 80.60%; R^2 (adj) = 76.29% and R^2 (pred) = 66.28%

Density HC (Kg/m^3) = 0.95438*Density MC (Kg/m^3) - - - - -(16)

R^2 = 99.94%; R^2 (adj) = 99.94% and R^2 (pred) = 99.93%

Table 3. Analysis of Variance (ANOVA)

	Source	DF	Adj SS	Adj MS	F-Value	P-Value
Compressive strength (N/mm²) for machine crushed aggregate concrete	Regression	2	96.064	48.032	95.12	0.000
	CA (days)	1	23.463	23.463	46.47	0.000
	W/C	1	72.601	72.601	143.78	0.000
	Error	9	4.544	0.505		
	Total	11	100.608			
Compressive strength (N/mm²) for hand crushed aggregate concrete	Regression	2	99.156	49.578	124.18	0.000
	CA (days)	1	36.100	36.100	90.42	0.000
	W/C	1	63.057	63.057	157.94	0.000
	Error	9	3.593	0.399		
	Total	11	102.749			
Compressive strength (N/mm²)	Regression	1	9017.55	9017.55	5249.26	0.000
Water Absorption (%) for machine crushed aggregate concrete	Regression	2	2.148	1.074	177.92	0.000
	CA (days)	1	2.128	2.128	352.52	0.000
	W/C	1	0.020	0.020	3.31	0.102
	Error	9	0.054	0.006		
	Total	11	2.203			
Water Absorption (%) for hand crushed aggregate concrete	Regression	2	2.327	1.163	167.06	0.000
	CA (days)	1	2.282	2.282	327.66	0.000
	W/C	1	0.045	0.045	6.46	0.032
	Error	9	0.063	0.007		
	Total	11	2.389			
Water Absorption (%) for hand	Regression	1	49.7729	49.7729	2522.43	0.000
Flexural Strength (N/mm²) for machine crushed aggregate concrete	Regression	2	9.380	4.690	327.22	0.000
	CA (days)	1	5.460	5.460	380.94	0.000
	W/C	1	3.920	3.920	273.49	0.000
	Error	9	0.129	0.014		
	Total	11	9.509			
Flexural Strength (N/mm²) for hand crushed aggregate concrete	Regression	2	7.045	3.522	164.74	0.000
	CA (days)	1	5.192	5.192	242.82	0.000
	W/C	1	1.853	1.853	86.65	0.000
	Error	9	0.192	0.021		
	Total	11	7.237			
Flexural Strength (N/mm²) for	Regression	1	612.316	612.316	9706.66	0.000
Density (kg/m³) for machine crushed aggregate concrete	Regression	2	136045	68023	70.71	0.000
	CA (days)	1	109825	109825	114.17	0.000
	W/C	1	26221	26221	27.26	0.001
	Error	9	8658	962		
	Total	11	144703			
Density (kg/m³) for hand crushed aggregate concrete	Regression	2	136882	68441	18.69	0.001
	CA (days)	1	107357	107357	29.32	0.000
	W/C	1	29525	29525	8.06	0.019
	Error	9	32951	3661		
	Total	11	169833			
Density (kg/m³) for hand and machine crushed aggregate concrete	Regression	1	79836599	79836599	19516.11	0.000
	Density	1	79836599	79836599	19516.11	0.000
	Error	11	44999	4091		
	Total	12	79881598			

Table 4. Paired samples statistics

	Mean	N	Std. Deviation	Std. Error
Compressive strength MC (N/mm^2)	27.29	12	3.024	0.873
Compressive strength HC (N/mm^2)	23.85	12	3.056	0.882
Flexural strength MC (N/mm^2)	7.09	12	0.930	0.268
Flexural strength HC (N/mm^2)	5.70	12	0.811	0.234
Water absorption MC (%)	1.98	12	0.449	0.129
Water absorption HC (%)	1.99	12	0.466	0.135
Density HC (Kg/m^3)	2577.33	12	124.255	35.869
Density MC (Kg/m^3)	2700.42	12	114.694	33.109

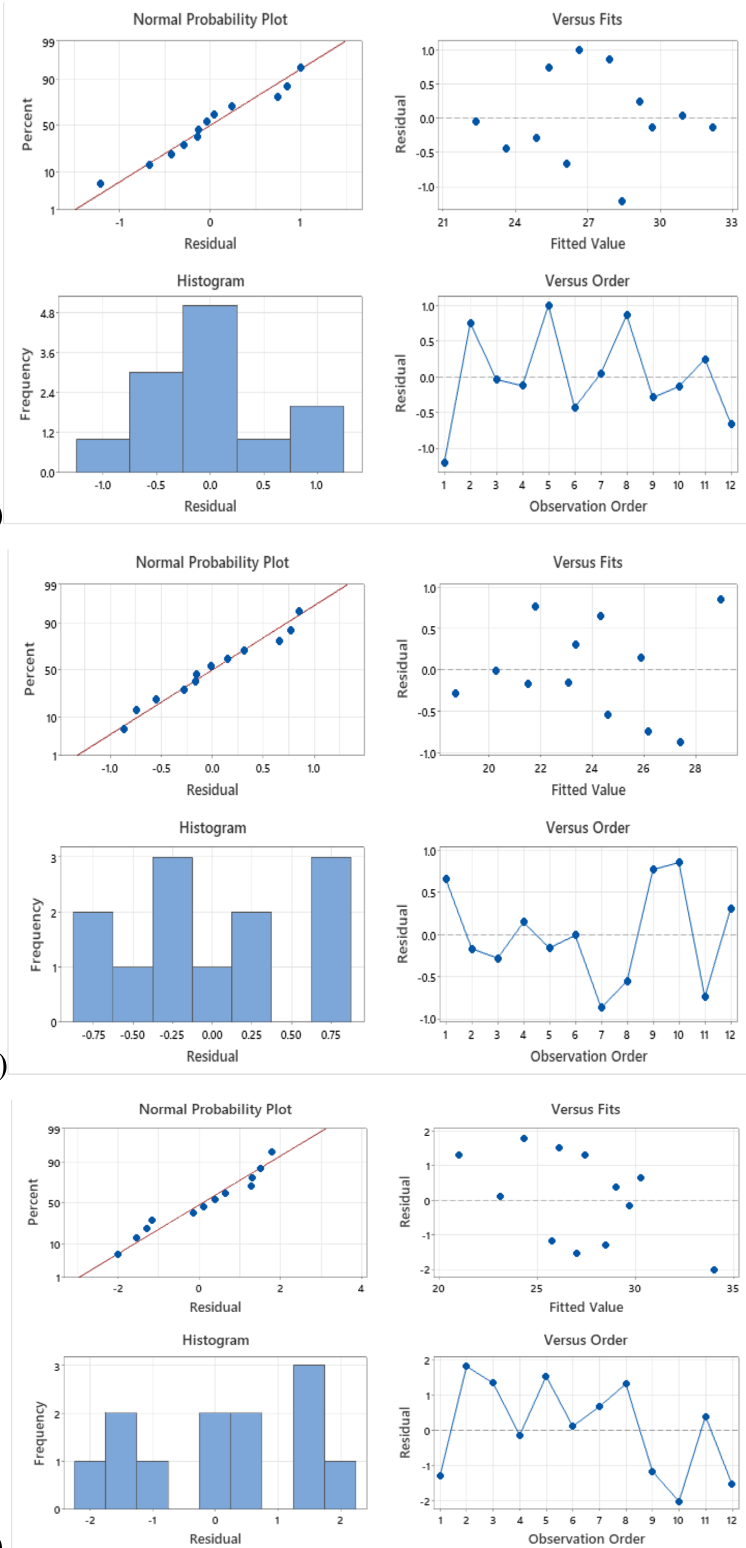
Table 5. Paired samples correlation

	N	Correlation	Sig.
Compressive strength (N/mm^2)	12	0.929	0.000
Flexural strength (N/mm^2)	12	0.970	0.000
Water absorption (%)	12	0.954	0.000
Density (Kg/m^3)	12	0.858	0.000

Table 6. Paired samples test

	Paired Differences					T	Df	Sig. (2-tailed)
	Mean	Std. Dev.	Std. Error	95% Confidence				
				Lower	Upper			
Compressive Strength	3.438	1.146	0.331	2.710	4.166	10.393	11	0.000
Flexural strength	1.396	0.245	0.071	1.241	1.551	19.781	11	0.000
Water absorption (%)	- 0.017	0.140	0.041	- 0.106	0.0725	- 0.411	11	0.689
Density (Kg/m^3)	- 123.08	64.408	18.593	-164.007	- 82.160	- 6.620	11	0.000

Results from the ANOVA, Table 3. reveal that both curing age and water-cement (w/c) ratio significantly influence the key properties of concrete made with machine-crushed and hand-crushed aggregates. For compressive strength, both aggregate types exhibited highly significant regression models ($p < 0.001$), confirming that strength development is strongly affected by both curing duration and w/c ratio. Flexural strength also showed extremely significant influence from both factors ($p = 0.000$), with curing age emerging as the more dominant factor, highlighting the critical role of hydration in enhancing tensile resistance over time. Water absorption showed differing trends: for machine-crushed aggregates, curing age was the only statistically significant factor ($p < 0.001$), while the w/c ratio had no significant effect ($p = 0.102$), suggesting that long-term curing effectively reduces porosity regardless of mix water content. In contrast, for hand-crushed aggregates, both curing age and w/c ratio were significant, though the w/c ratio had a weaker influence ($p = 0.032$), indicating a slightly more sensitive absorption response to mix design. For density, both factors were significant for both aggregate types, with machine-crushed aggregates demonstrating a stronger model fit and greater sensitivity to curing age. This suggests that machine-crushed concrete benefits more from prolonged curing and optimized w/c ratios in terms of compaction and densification. The descriptive statistics in Table 4. further support these findings, showing that machine-crushed aggregate concrete had higher mean compressive and flexural strengths, marginally lower water absorption, compared to hand-crushed aggregate concrete. Correlation analysis of Table 5. shows strong positive relationships across all concrete properties between the two aggregate types ($r > 0.85$, $p < 0.001$), indicating that despite material differences, both concretes follow similar performance trends. However, the paired samples t-test in Table 6. confirms that these differences are statistically significant for compressive strength, flexural strength, and density ($p < 0.001$), with machine-crushed concrete consistently outperforming hand-crushed concrete in these areas. Water absorption, however, showed no statistically significant difference ($p = 0.689$), suggesting that both aggregate types absorb water at comparable rates. Overall, these findings indicate that while both curing age and w/c ratio critically affect concrete performance, the type of aggregate also plays a notable role—particularly with regard to strength and density—with machine-crushed aggregates providing a more compact and mechanically superior concrete, especially at lower w/c ratios and extended curing periods.

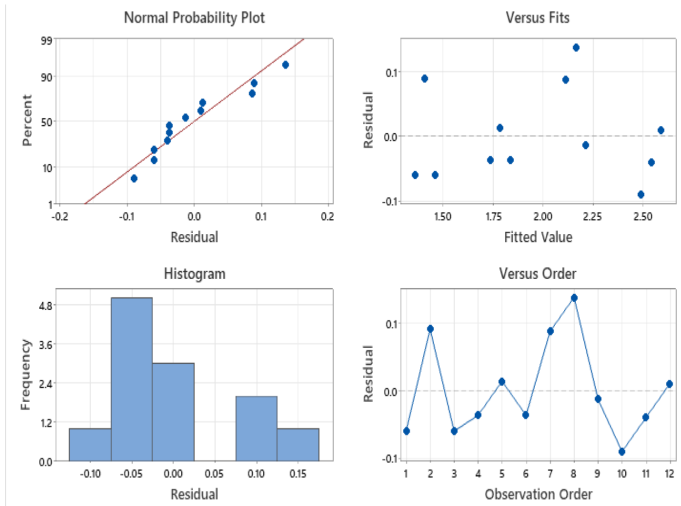


a)

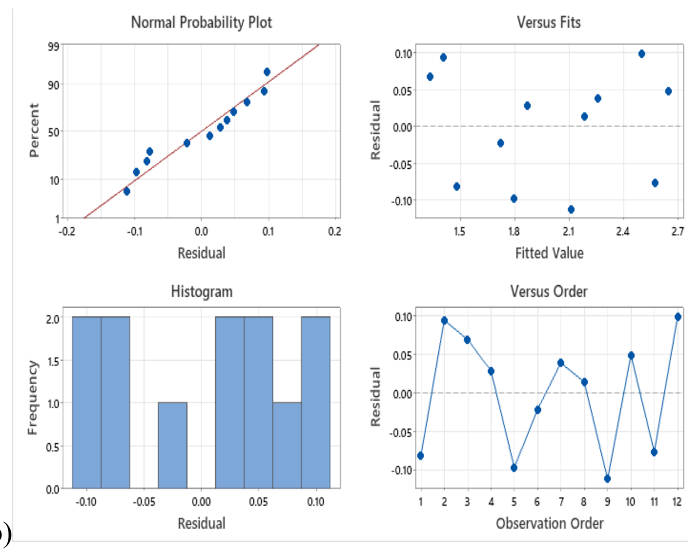
b)

c)

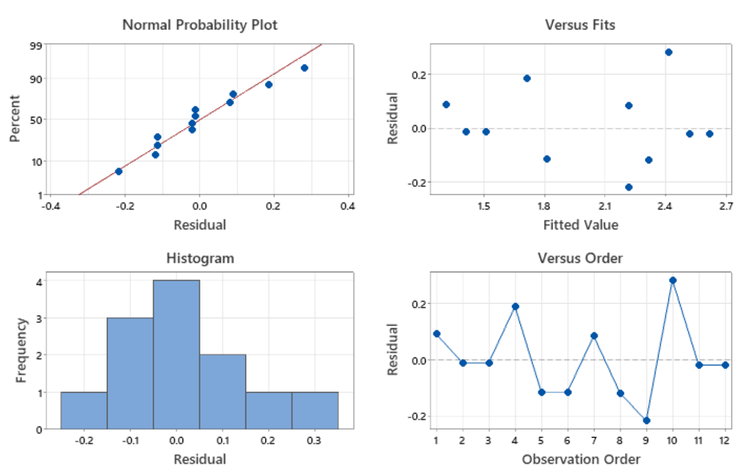
Figure 8. Concrete compressive strength residual plots for a) machine crushed b) hand crushed and c) both machine and hand crushed aggregates



a)



b)



c)

Figure 9. Concrete water absorption residual plots for a) machine crushed b) hand crushed and (c) both machine and hand crushed aggregates

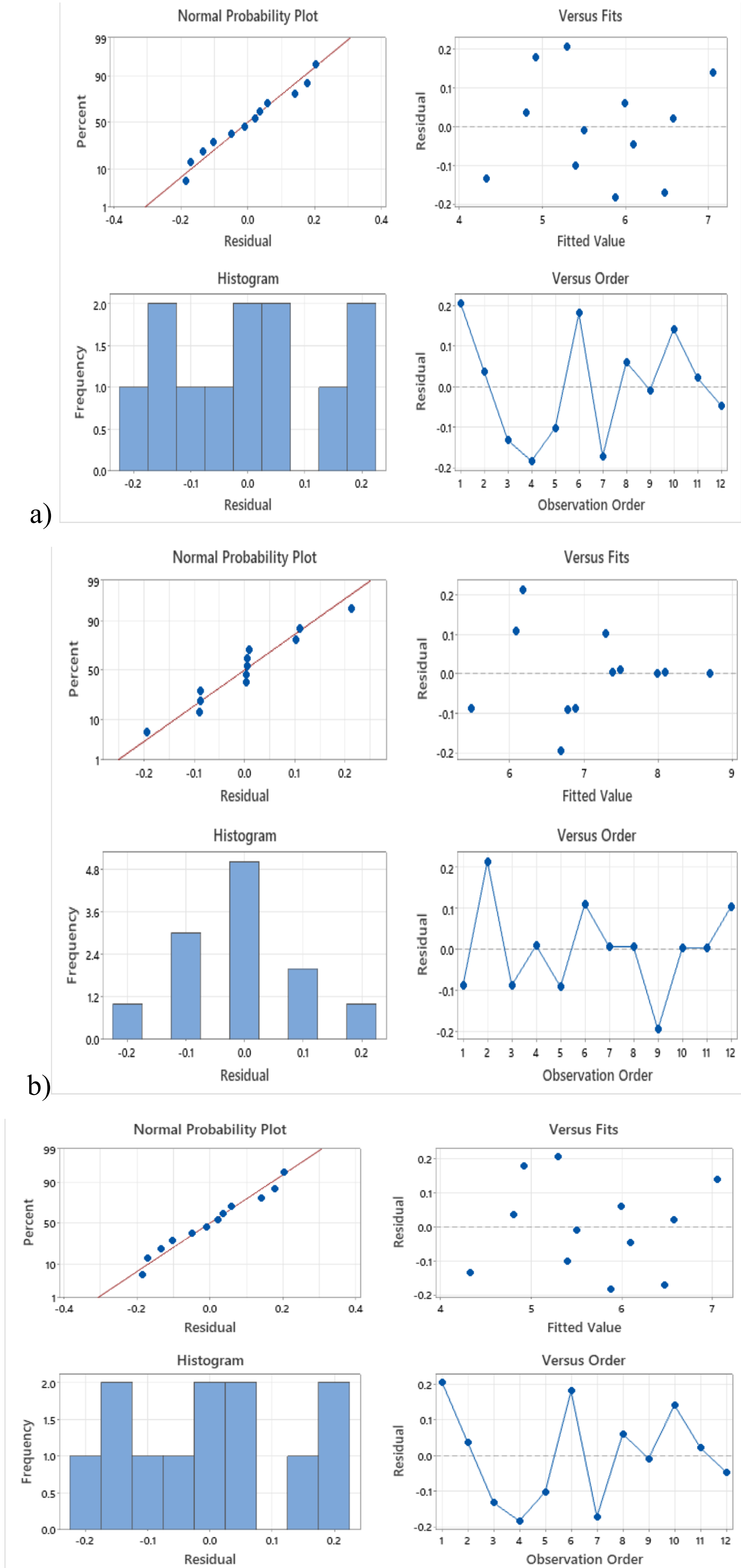
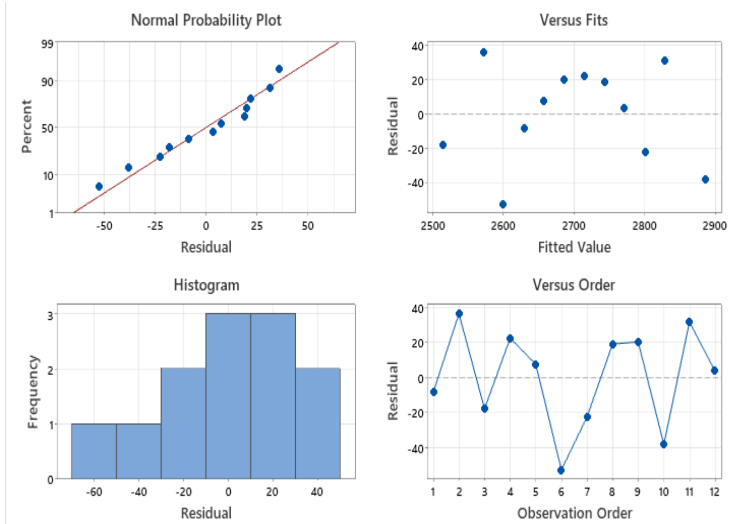
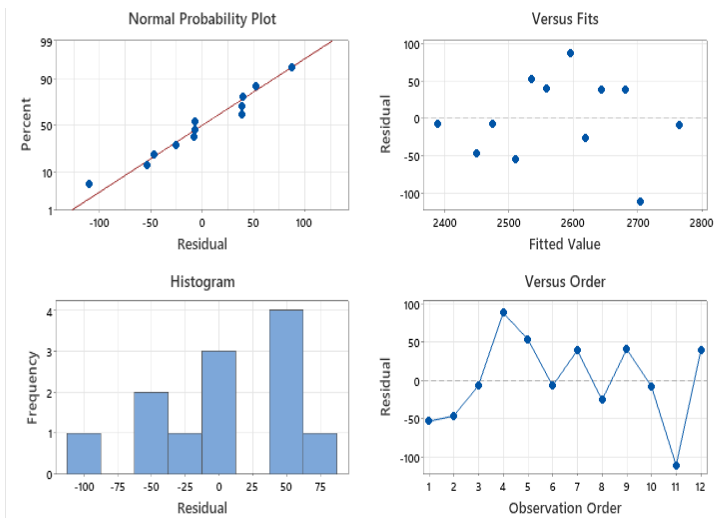


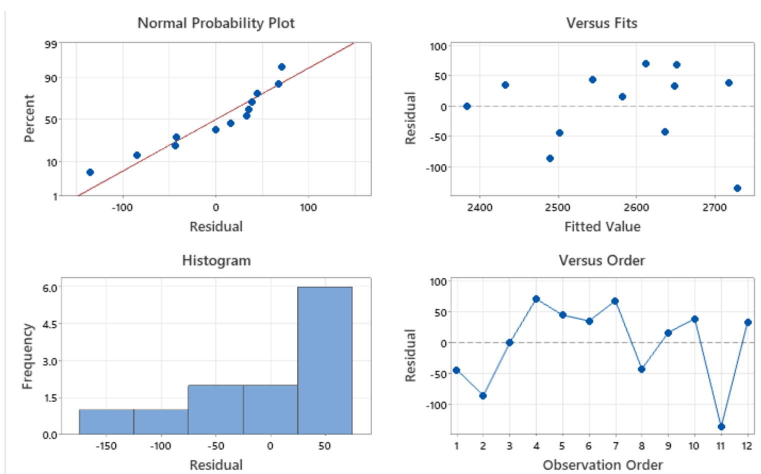
Figure 10. Concrete flexural strength residual plots for a) hand crushed b) machine crushed and c) both machine and hand crushed aggregates



a)



b)



c)

Figure 11. Concrete density residual plots for a) machine crushed b) hand crushed and c) both machine and hand crushed aggregates

4. Conclusion

This study has demonstrated that both the water-cement (w/c) ratio and aggregate type significantly affect the properties of fresh and hardened concrete. Increased w/c ratio enhances workability but reduces strength, aligning with existing literature. Machine-crushed aggregate concrete consistently outperforms hand-crushed aggregate concrete in compressive strength, flexural strength, and density, highlighting its superior compaction and mechanical behavior. While both aggregate types exhibit similar performance trends, as indicated by strong correlations, their differences are statistically significant—except in water absorption, where both types perform comparably.

The results strongly demonstrate that both curing age and water-cement (w/c) ratio significantly affect concrete properties, with ANOVA p-values < 0.001 for compressive and flexural strengths across both machine-crushed and hand-crushed aggregates. Flexural strength was more influenced by curing age ($p = 0.000$) than w/c ratio, reinforcing the importance of hydration over time for tensile behaviour. For water absorption, machine-crushed aggregate concrete showed no significant dependence on w/c ratio ($p = 0.102$), while curing age was significant ($p < 0.001$), suggesting porosity reduction is more time-driven. In contrast, for hand-crushed aggregates, both factors were significant, though w/c ratio showed weaker influence ($p = 0.032$).

Regarding density, both factors were significant for both aggregate types, but machine-crushed concrete showed a stronger model fit ($R^2 > 0.90$), indicating a more pronounced response to curing and mix design. Descriptive statistics further validate this as the mean compressive strength for machine-crushed aggregates was higher (27.29 MPa vs. 23.85 MPa at 28 days), with similarly higher flexural strength (7.09 MPa vs. 5.7 MPa) and slightly lower water absorption (1.98% vs. 1.99%) compared to hand-crushed concrete. Moreover, correlation analysis ($r > 0.85$, $p < 0.001$) across all properties confirms that while the two aggregate types follow similar performance patterns, statistically significant differences in compressive strength, flexural strength, and density ($p < 0.001$), favouring machine-crushed aggregates were observed. However, water absorption was not significantly different ($p = 0.689$), indicating similar pore structures between the concretes.

Construction professionals can apply these findings to optimize mix designs for targeted performance, balancing workability, strength, and material availability. While machine-crushed aggregates offer better structural performance, hand-crushed aggregates may be acceptable in low-load or temporary applications where cost or availability is a concern. The study recommends that

1. A w/c ratio of 0.40 is optimal for achieving maximum strength and workability across both aggregate types.
2. Hand-crushed aggregate concrete at 0.40 w/c can be used where machine-crushed aggregates are unavailable.
3. For temporary structures, hand-crushed aggregate concrete at 0.40 w/c is a viable alternative.

Further research should explore the underlying mechanisms of these effects and investigate the use of additives or supplementary cementitious materials to enhance performance under varying w/c ratios. These findings contribute to the advancement of sustainable and performance-based concrete design.

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