

Research Article

Evaluation of Natural Aggregate Performance for Strength Optimized Concrete without Chemical Admixtures

Bunyamin Bunyamin^{1*}, Heru Pramanda¹, and Muhajjir Muhajjir¹¹ Department of Civil Engineering, Faculty of Engineering, Universitas Iskandar Muda, 23234, Banda Aceh, Indonesia

* Correspondence: Bunyamin Bunyamin (bunyamin@unida-aceh.ac.id)

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Abstract

Concrete is one of the most widely used construction materials due to the availability of its constituent materials and its ability to withstand structural loads. Aggregate characteristics play a crucial role in determining concrete performance, and natural aggregates continue to be the primary source of aggregate in concrete production. However, their capability to achieve the desired compressive strength without the use of chemical admixtures requires further investigation. This study aimed to evaluate the ability of natural aggregates to produce concrete with target compressive strengths of 17, 20, 23, and 26 MPa and to examine changes in the water–cement ratio (W/C) resulting from additional mixing water. The target compressive strengths were selected to represent commonly used normal-strength concrete grades for general construction. An experimental program was conducted using concrete mixtures designed for specified compressive strengths of 24, 27, 30, and 33 MPa. The target slump was set at 75–100 mm without incorporating chemical admixtures; therefore, workability was adjusted by increasing the mixing water content by approximately 7–13% of the initial design requirement. Five specimens were prepared and tested for each concrete mixture to evaluate compressive strength. The results showed that the achieved slump values ranged from 75 to 80 mm, while the corresponding compressive strengths reached 19.85, 22.74, 25.16, and 28.74 MPa, respectively. The addition of water increased the W/C ratio from 0.62 to 0.69, from 0.58 to 0.65, from 0.54 to 0.61, and from 0.49 to 0.56, representing increases of approximately 10.14–12.50%. Despite the increase in W/C ratio, the compressive strengths obtained exceeded the target values in all mixture variations. These findings indicate that natural aggregates possess sufficient quality to produce concrete with compressive strengths surpassing the specified targets, even without the use of chemical admixtures. The natural aggregates used in this study were natural river aggregates obtained from Jantho, Aceh Besar Regency, Indonesia. The investigation covered normal-strength concrete with target compressive strengths of 17, 20, 23, and 26 MPa. Statistical significance testing was not performed; however, all measured compressive strengths consistently exceeded the specified target strengths and remained within the expected acceptance margin of the adopted mix-design approach.

Keywords: Natural Aggregate; Concrete; Compressive Strength; Water Cement Ratio; Workability.

1. Introduction

Concrete is one of the most extensively utilized construction materials in infrastructure development due to its versatility, durability, and ability to meet a wide range of structural requirements. Its applications include buildings, roads, bridges, ports, and water resources

infrastructure [1]. The popularity of concrete as a construction material can be attributed to its numerous advantages, including its versatility in shaping and casting, high compressive strength, excellent durability under various environmental conditions, and the relatively abundant availability of its constituent materials [2]. As construction activities continue to expand, greater demands are being placed on the quality and performance of concrete, particularly in achieving compressive strength levels that satisfy structural design requirements [3], [4].

Concrete compressive strength is a key indicator of concrete quality and structural performance. Its value is governed not only by the properties of the cementitious materials but also by aggregate characteristics, mix proportions, the water–cement ratio (W/C), mixing and compaction practices, and the effectiveness of the curing process [5]. Among the constituent materials of concrete, aggregates represent the largest volume fraction, typically comprising about 60–80% of the total concrete volume. Consequently, aggregate properties have a significant influence on the mechanical performance and long-term durability of concrete [6]. Natural aggregates continue to be the primary source of aggregate in the construction industry because of their abundant availability, ease of procurement, and cost-effectiveness compared with other alternative materials [6]–[8]. Natural aggregates are typically formed through the weathering of parent rock and subsequently undergo natural transportation and deposition processes. Their physical characteristics, such as particle shape, surface texture, specific gravity, porosity, and water absorption, significantly affect the water demand of concrete mixtures and the quality of the bond between the cement paste and aggregates, thereby influencing the overall performance of concrete. Therefore, it is essential to evaluate the capability of natural aggregates to produce concrete that meets the target compressive strength specified in structural design requirements.

In practical construction applications, the attainment of target compressive strength is frequently challenged by the requirement to maintain sufficient workability, enabling effective placement, consolidation, and compaction of concrete during construction operations. The slump test is widely used to assess the workability of fresh concrete. In order to attain the required slump, additional water is frequently added to the concrete mixture during construction activities. While this approach can enhance the workability and placement characteristics of concrete, excessive or uncontrolled water addition may increase the water–cement ratio (W/C), leading to a less dense microstructure and consequently reducing the strength and overall performance of the hardened concrete. Advancements in concrete technology have led to the widespread use of chemical admixtures, particularly superplasticizers, to enhance the workability of concrete without increasing the mixing water content. Numerous studies have demonstrated that such admixtures can significantly improve workability while preserving or even enhancing the compressive strength and overall performance of concrete [9]. Despite these advancements, the use of chemical admixtures is not always feasible in every construction project because of economic constraints, limited material availability, and technological challenges encountered in practice. Consequently, conventional concrete without chemical admixtures remains commonly employed, especially in small- and medium-scale construction applications [10], [11].

The relationship between the water–cement ratio and concrete compressive strength has long been explained by Abrams' law. This theory states that compressive strength is inversely proportional to the water–cement ratio, such that an increase in mixing water content results in the formation of a greater volume of capillary pores following cement hydration. The resulting increase in porosity reduces the density of the hardened concrete matrix, thereby adversely affecting its strength and overall mechanical performance [12]. Consequently, the concrete microstructure becomes less compact, reducing the material's capacity to resist compressive stresses. For this reason, maintaining an appropriate water–cement ratio is a critical consideration in concrete mixture design, as it directly influences the strength and overall performance of the hardened

concrete [13]. Apart from the water–cement ratio, the quality of aggregates plays a crucial role in determining the compressive strength of concrete. Aggregates characterized by high mechanical strength, suitable surface texture, and low porosity generally enhance the bond between the cement paste and aggregate particles. The interfacial transition zone (ITZ) surrounding the aggregates is recognized as a critical component of the concrete microstructure, as it largely governs stress transfer mechanisms and influences the overall mechanical performance of concrete [14]. A stronger bond within the interfacial transition zone (ITZ) enhances the capacity of concrete to resist applied loads, thereby contributing to improved mechanical performance [15].

The workability of fresh concrete is generally assessed using the slump test. Achieving a slump value that meets construction requirements facilitates casting and compaction operations, thereby minimizing the risk of segregation and excessive entrapped air voids. Nevertheless, any increase in slump through the addition of water should be carefully controlled, as it may modify the originally designed mix composition and adversely affect the mechanical properties of the hardened concrete [16]. Therefore, a comprehensive understanding of the interrelationship between water demand, slump value, water–cement ratio, and the resulting compressive strength of concrete is essential for achieving the desired performance of concrete mixtures. Despite the widespread use of natural aggregates in the construction industry, their effectiveness in achieving target compressive strengths across various concrete strength classes remains insufficiently understood and warrants further investigation. Previous research has predominantly focused on the incorporation of chemical admixtures, supplementary cementitious materials, and alternative aggregate sources to improve the performance of concrete [17]–[20]. However, relatively few studies have specifically examined the effectiveness of natural aggregates in achieving target compressive strengths in concrete mixtures produced without chemical admixtures.

Conversely, achieving a required slump level in practical concrete production frequently necessitates modifications to the mixing water content. These adjustments inevitably change the water–cement ratio and may consequently influence the compressive strength of the hardened concrete. Nevertheless, there is limited information regarding the ability of natural aggregates to maintain the attainment of target compressive strengths when variations in the water–cement ratio occur due to additional water. The lack of comprehensive understanding in this area constitutes a significant research gap and forms the basis for the present investigation. The research gap addressed in this study specifically concerns the ability of natural river aggregates to consistently achieve specified compressive strengths without chemical admixtures while maintaining the required workability through controlled water adjustment.

The objective of this study is to evaluate the effectiveness of natural aggregates in achieving the desired concrete compressive strengths without the incorporation of chemical admixtures. More specifically, the study assesses the attainment of target compressive strengths of 17 MPa, 20 MPa, 23 MPa, and 26 MPa in concrete produced with natural aggregates. Furthermore, the influence of additional mixing water on variations in the water–cement ratio and the consequent effects on concrete compressive strength are systematically investigated. The target compressive strengths of 17, 20, 23, and 26 MPa were selected because they represent normal-strength concrete grades commonly used for residential buildings, low- to medium-rise structures, and general infrastructure in Indonesia, including the Aceh region. These strength levels also match the scope of this study, which aims to evaluate the performance of locally sourced natural river aggregates in conventional concrete without chemical admixtures.

This study focuses on natural river aggregates, which are characterized by smooth, rounded particles produced through natural weathering and water transport. In contrast, crushed aggregates have angular and rough surfaces that generally provide higher interlocking but may reduce workability. The results of this study are expected to contribute to a better understanding of the

capability of natural aggregates to produce concrete that satisfies or exceeds the specified target compressive strengths across various strength classes. Furthermore, the study seeks to elucidate the interrelationship among additional mixing water, variations in the water–cement ratio, achieved slump values, and the resulting compressive strength of concrete. By providing this information, the research is expected to enhance current knowledge regarding both the potential and limitations of natural aggregates in conventional concrete production without the use of chemical admixtures, thereby supporting more effective mix design and quality control practices. Furthermore, this study is expected to provide experimental evidence that can support concrete mix design decisions, particularly for construction projects that depend on locally sourced materials and conventional concrete production practices without chemical admixtures. The findings may also serve as a valuable reference for assessing the efficiency and suitability of natural aggregates in attaining specific concrete strength requirements.

2. Materials and Methods

The binder used in this study was commercially available Portland Pozzolan Cement (PPC). PPC is produced by blending Portland cement clinker with pozzolanic materials and is widely used in concrete construction because of its good workability, improved long-term strength development, reduced permeability, and enhanced durability. These characteristics make PPC suitable for conventional concrete applications. The study was conducted using an experimental approach in accordance with ASTM (American Society for Testing and Materials) standards for the testing of concrete materials and hardened concrete properties, while the concrete mixtures were designed following the procedures recommended by the American Concrete Institute [21]. The study was conducted through a systematic experimental program designed to evaluate the properties of the constituent materials and the performance of the produced concrete. The experimental stages included material preparation, physical property testing of the raw materials, concrete mix design, specimen casting, fresh and hardened concrete testing, and subsequent data analysis. The collected data were then used to evaluate the capability of natural aggregates to achieve the specified target compressive strengths. The research methodology adopted in this study is described in the following sections.

2.1 Physical Properties of Aggregates

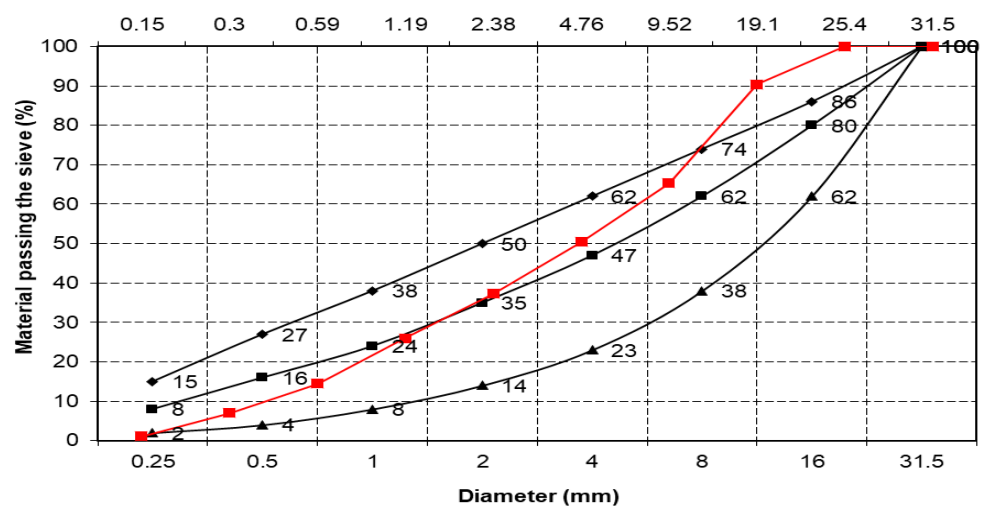
Aggregate characterization was performed through a comprehensive series of physical property tests on fine sand, coarse sand, and gravel in accordance with ASTM standards [22]. The fine aggregate used in this study comprised fine sand with a maximum particle size of 4.75 mm and coarse sand with a maximum particle size of 9.52 mm, whereas the coarse aggregate consisted of gravel with a nominal maximum particle size of 25.00 mm. All aggregates were obtained from Jantho City, Aceh Besar Regency, Indonesia. The physical characterization was undertaken to assess the compliance of the aggregate properties with the requirements for concrete constituent materials. The evaluated parameters included bulk density, determined in accordance with ASTM C29/C29M-97 [22], along with other relevant aggregate properties required for concrete mix design and performance evaluation [22], specific gravity and water absorption, determined in accordance with ASTM C127-88 [23], and particle size distribution (gradation), determined in accordance with ASTM C136/C136M [24]. The experimental results were analyzed and evaluated against the requirements specified in the applicable ASTM standards to assess the suitability of the aggregates for concrete production. The results of the aggregate physical characterization are summarized in Table 1.

Table 1. Physical Properties of the Aggregates

No	Aggregate	Bulk Density (Kg/l)	Specific Gravity (SSD)	Absorption (%)	Fineness Modulus (FM)
1.	Fine Sand	1.596	2.468	1.156	3.16
2.	Coarse Sand	1.609	2.442	1.537	2.94
3.	Coarse Aggregate	1.660	2.674	2.691	6.62

Table 1 presents the results of the aggregate physical property tests, including bulk density, specific gravity, water absorption, and fineness modulus (FM). Based on the test results, the bulk density values of all aggregates used in this study satisfied the standard requirements, exceeding 1,400 kg/m³. The specific gravity test results indicated that both fine aggregates (fine sand and coarse sand) and coarse aggregates had values within the range specified by ASTM standards, namely between 2.00 and 2.70. The water absorption test results showed that the fine aggregates (fine sand and coarse sand) exhibited absorption values below 2.0%, thereby complying with the ASTM requirements. In contrast, the water absorption value of the coarse aggregate exceeded the recommended limit. Furthermore, the fineness modulus values of the fine aggregates were within the range of 2.30–3.10, while the coarse aggregate exhibited an FM value within the range of 5.50–8.00. These values are consistent with the limits recommended by the applicable standards. Overall, the evaluation of the aggregate physical properties indicates that the materials generally satisfy the technical requirements for use as concrete constituents. Therefore, the aggregates were considered suitable and acceptable for the production of concrete mixtures in this study.

Based on the aggregate gradation analysis, a combined aggregate gradation curve was constructed and is presented in Figure 1. The curve was used to assess the conformity of the aggregate particle size distribution with the recommended gradation limits. As illustrated in Figure 1, the gradation curve of the combined aggregate mixture, represented by the red line, lies within the gradation envelope categorized as good to excellent. This result indicates that the aggregate blend exhibits a well-graded particle size distribution, which is conducive to improved packing density, reduced void content, and enhanced workability of the concrete mixture. Consequently, the aggregate composition is expected to contribute positively to the mechanical performance and overall quality of the concrete produced in this study.

**Figure 1.** Gradation Curve of the Combined Aggregates

As illustrated in Figure 1, the combined aggregate gradation curve (red line) falls within the recommended gradation envelope, demonstrating compliance with the aggregate gradation requirements for concrete production. The continuous particle size distribution from fine to coarse fractions indicates a well-graded aggregate blend that promotes efficient particle packing and minimizes interparticle voids. Such characteristics contribute to increased mixture density, improved workability, reduced cement paste requirements, and facilitate the achievement of the desired concrete compressive strength. Previous research has established that aggregate gradation is a key factor governing the fresh and hardened properties of concrete, as it significantly affects workability, porosity, packing density, and ultimately the mechanical performance of the material [25]. Therefore, the combined aggregate blend was deemed suitable for use as a constituent material in concrete mixtures.

2.2 Concrete Mix Design

In this study, concrete mixtures were designed to achieve target compressive strengths of 17 MPa, 20 MPa, 23 MPa, and 26 MPa. The aggregates consisted of natural river aggregates that were washed and screened through a 25.00 mm sieve prior to use. Given that natural aggregates generally exhibit different mechanical characteristics from crushed aggregates, a design strength margin was incorporated into the mix design process. This approach was adopted to account for potential variability in aggregate performance and to ensure that the specified target compressive strengths were attained [26], [27]. Accordingly, the following equation was employed to determine the required design compressive strength:

$$f'_{cr} = f'_c + k.s \quad (1)$$

Where:

f'_{cr} = achieved compressive strength, achieved f'_c (MPa)

f'_c = target compressive strength, target f'_c (MPa)

k = safety factor, taken as 1.64

s = standard deviation, assumed to be 4.50 MPa, the standard deviation of 4.50 MPa was adopted from the recommendations of ACI 214R-11 [26] rather than being determined from preliminary testing.

The concrete mixtures were proportioned following the procedures recommended by ASTM standards [28] and ACI PRC-211.1-22 [29]. The concrete mix design was established using the following initial parameters: a target slump of 75–100 mm, Portland Pozzolan Cement (PPC) as the binder, design compressive strengths of 24 MPa, 27 MPa, 30 MPa, and 33 MPa, and a nominal maximum coarse aggregate size of 25.00 mm. In accordance with the ACI mix design procedure, the required water content was determined in kg/m³, whereas the water–cement ratio (W/C) was selected based on the specified design strength. The proportions of all constituent materials were then calculated to produce 1 m³ of concrete and expressed on a mass basis. The final mix proportions corresponding to each design compressive strength are summarized in Table 2.

Table 2. Concrete Mix Proportions for 1 m³ of Concrete

NO	Mix	Achieved f'_c (MPa)	W/C	Target f'_c (MPa)	Fine Sand Content (Kg)	Coarse Sand Content (Kg)	Coarse Aggregate Content (Kg)	Cement Content (Kg)	Water Content (Kg)
1	NC-17	24	0.62	17	223.12	573.91	1079.27	310.70	193.00
2	NC-20	27	0.58	20	216.41	556.65	1079.27	334.67	193.00
3	NC-23	30	0.54	23	210.04	540.28	1079.27	357.41	193.00
4	NC-26	33	0.49	26	200.43	515.56	1079.27	391.73	193.00

Table 2 presents the concrete mix proportions designed for target compressive strengths of 17 MPa, 20 MPa, 23 MPa, and 26 MPa. As the target compressive strength increased, the required average compressive strength increased from 24 MPa to 33 MPa, while the water-cement ratio (W/C) decreased from 0.62 to 0.49. The water content was maintained constant at 193 kg/m³ for all mixtures; therefore, the reduction in W/C was achieved by increasing the cement content from 310.70 kg/m³ to 391.73 kg/m³. Meanwhile, the amounts of fine and coarse sand were gradually reduced, whereas the gravel content remained constant at 1079.27 kg/m³. These results indicate that the improvement in concrete quality was planned through a reduction in the water-cement ratio by increasing the cement content without altering the water demand. Previous studies have reported that increasing the water content in concrete mixtures significantly reduces compressive strength. Therefore, achieving higher concrete strength is more effectively accomplished by maintaining a constant water content while controlling or reducing the water-cement ratio [30].

The specimens used in this study were cylindrical, with a diameter of 15 cm and a height of 30 cm. Five specimens were prepared for each concrete mixture, resulting in a total of 20 specimens. To ensure sufficient concrete volume for casting and to account for potential material loss during mixing and placement, a 15% safety allowance was applied. Consequently, the required concrete volume for each set of five specimens was calculated as 0.030 m³, including the safety allowance. The concrete mix proportions for five specimens are presented in Table 3.

Table 3. Material Quantities for 0.030 m³ of Concrete

NO	Mix	Achieved f _c (MPa)	W/C	Target f _c (MPa)	Fine Sand Content (Kg)	Coarse Sand Content (Kg)	Coarse Aggregate Content (Kg)	Cement Content (Kg)	Water Content (Kg)
1	NC-17	24	0.62	17	6.80	17.50	32.91	9.47	5.89
2	NC-20	27	0.58	20	6.60	16.98	32.91	10.21	5.89
3	NC-23	30	0.54	23	6.41	16.48	32.91	10.90	5.89
4	NC-26	33	0.49	26	6.11	15.72	32.91	11.95	5.89

Table 3 presents the mix proportions of normal concrete (NC-17 to NC-26) designed to achieve target compressive strengths ranging from 17 MPa to 26 MPa. The increase in target strength was accompanied by adjustments in the mixture parameters, primarily a reduction in the water-cement ratio (W/C) from 0.62 to 0.49 and an increase in cement content from 9.47 kg to 11.95 kg, while the water content was maintained constant at 5.89 kg. In addition, only minor changes were observed in the proportions of fine and coarse sand, whereas the gravel content remained nearly constant at 32.91 kg. These results indicate that the improvement in concrete strength was mainly achieved through controlling the water-cement ratio and increasing the cement content, thereby producing a denser and stronger cement paste. Meanwhile, the aggregate proportions primarily contributed to maintaining the stability and overall structure of the concrete mixture. Previous studies have reported that increasing the water content leads to a reduction in compressive strength, increased porosity, and greater bleeding. Conversely, concrete with a lower water-cement ratio generally exhibits superior quality and higher strength [30].

2.3 Specimen Preparation

This study utilized fine aggregate (sand) and coarse aggregate (gravel) as the primary constituent materials, with cement as the manufactured binder whose properties conform to standardized specifications, and water deemed suitable for use based on visual inspection in accordance with the Indonesian National Standard (SNI). All aggregates were prepared in a

Saturated Surface Dry (SSD) condition based on the results of the physical properties tests. Before concrete mixing, all aggregates were conditioned to a Saturated Surface Dry (SSD) state following ASTM C127/C128 [23] procedures. The aggregates were soaked in water for approximately 24 h, drained, and surface-dried until no visible free water remained while the internal pores remained saturated. The SSD condition was verified by comparing the aggregate mass with the previously established SSD mass from the specific gravity and water absorption tests. The aggregates were used immediately after verification to prevent moisture variation during batching.

Concrete specimens were produced by weighing the constituent materials according to the proportions determined using the ACI mix design method, followed by mixing in a concrete mixer until a homogeneous mixture was obtained. The concrete was mixed in a laboratory drum concrete mixer following a consistent mixing procedure for all batches. The coarse and fine aggregates were first dry-mixed, followed by the addition of cement. Mixing water was then introduced gradually while the mixer continued to operate until a homogeneous mixture with uniform consistency and color was achieved. The total mixing duration was maintained at approximately 3–5 min for all mixtures, and the mixer was operated at its standard laboratory operating speed throughout the mixing process. Five specimens were prepared for each mixture variation. Subsequently, a slump test was conducted using the Abrams cone, and the measured slump values were compared with the target range of 75–100 mm. After casting, the specimens were cured by water immersion for 28 days prior to testing [31]. Following demolding after 24 ± 2 h, the specimens were cured by complete immersion in clean tap water maintained at $23 \pm 2^\circ\text{C}$ until the specified testing age. The curing water was periodically replaced to maintain consistent water quality throughout the curing period. In addition, each specimen was marked with an identification code and the date of casting on the base of the cylinder to ensure proper identification and facilitate the testing process.

2.4 Workability Assessment

The slump test is a standard method used to evaluate the consistency and workability of fresh concrete using the Abrams cone apparatus. The test begins by placing the cone on a clean, moistened, and level base plate. Fresh concrete is then placed into the mold in three equal layers. Each layer is compacted using a steel tamping rod with an equal number of strokes to ensure uniform distribution of the mixture and to minimize excessive air voids. After the mold has been completely filled, the top surface is struck off level, and the cone is carefully lifted vertically in a slow and steady motion, allowing the concrete to subside freely. The slump value is determined by measuring the difference between the original height of the mold and the height of the slumped concrete. The result is expressed in millimeters and serves as an indicator of the workability of the concrete mixture [32].

2.5 Density and Compressive Strength Testing of Concrete

In this study, the properties of hardened concrete were evaluated through unit weight and compressive strength tests. The unit weight was determined by weighing the hardened concrete specimens and comparing their mass to the corresponding geometric volume to obtain the concrete density in kg/m^3 . This parameter reflects the compactness of the concrete, where denser concrete generally contains fewer voids and exhibits a more compact internal structure. Consequently, a higher unit weight is often associated with improved durability and mechanical performance of concrete [4]. In addition, compressive strength testing was conducted to determine the capacity of the concrete to withstand compressive loads. Specimens that had undergone 28 days of curing were tested using a compression testing machine, with the load applied gradually until failure occurred. The compressive strength was calculated as the ratio of the maximum applied load to the cross-

sectional area of the specimen and was expressed in MPa. The results of this test served as the primary basis for evaluating the quality and performance of the concrete produced [33].

3. Results and Discussion

3.1 Workability Test Results

The workability test results indicate that all concrete mixtures achieved slump values within the target range of 75–100 mm. The NC-17 mixture produced a slump value of 75 mm with an additional water content of 7%, while NC-20 achieved a slump of 75 mm with 9% additional water. The NC-23 mixture exhibited a slump value of 80 mm with 11% additional water, whereas NC-26 produced a slump of 75 mm with 13% additional water. These results demonstrate that the desired workability was successfully attained for all mixtures despite variations in water addition. The additional water content (7–13%) was determined through preliminary trial mixes rather than by using a predetermined percentage. Water was gradually added until the target slump of 75–100 mm was achieved without visible segregation or bleeding. Consequently, each concrete mixture required a different amount of additional water depending on its workability characteristics and target strength. A detailed summary of the slump test results is presented in Table 4.

Table 4. Workability Test Results

No.	Specimen	Target Rencana (mm)	Measured Slump (mm)	Additional Water Content (%)
1	NC-17	75-100	75.00	7.00
2	NC-20	75-100	75.00	9.00
3	NC-23	75-100	80.00	11.00
4	NC-26	75-100	75.00	13.00

As shown in Table 4, the relatively uniform slump values obtained for all concrete mixtures indicate that the additional water introduced during the mixing process was effective in maintaining the required level of workability for construction purposes. The measured slump values remained within the target range, demonstrating that the mixtures possessed adequate consistency and ease of handling for casting and compaction without exhibiting excessive segregation or bleeding. Although the achieved slump values were generally similar, the percentage of additional water required increased with the designed concrete strength. The NC-17 mixture required only 7% additional water, whereas the NC-26 mixture required up to 13% to achieve a comparable level of workability. This trend suggests that higher-strength concrete mixtures require greater water adjustment to maintain the specified workability range. Such behavior is consistent with the characteristics of high-strength concrete, which typically contains a higher cement content and a lower water-to-cement ratio, resulting in reduced workability unless appropriate measures, such as water adjustment or the use of chemical admixtures, are implemented to improve the rheological properties of the fresh concrete [34].

Although the NC-26 mixture required the highest additional water content (13%) to achieve the target slump, it also exhibited the highest concrete density. This indicates that the added water did not significantly increase porosity because it primarily improved workability, enabling better compaction and reducing entrapped air. Moreover, the lower design water–cement ratio and higher cement content promoted the development of a denser cementitious matrix during hydration. Consequently, the combined effects of improved consolidation and matrix densification outweighed the potential adverse effect of the limited additional water.

The increase in water demand can be attributed to the characteristics of the concrete mixtures. In mixtures designed for higher target compressive strengths, the cement content is generally

increased while the specified water-to-cement ratio is reduced. As a result, the fresh concrete tends to become stiffer, requiring additional water to achieve a level of workability comparable to that of lower-strength mixtures. Furthermore, the greater surface area of solid particles that must be coated by the cement paste increases the effective water demand of the mixture. The findings of this study also indicate that the natural aggregates used were capable of absorbing a portion of the mixing water, thereby necessitating adjustments to the water content to attain the desired slump values. As the amount of additional water increases, the likelihood of deviations between the actual and designed water-to-cement ratios also becomes greater. Such variations should be carefully considered, as they may influence the mechanical performance of the concrete, particularly its compressive strength at the testing age [35].

Interestingly, although the percentage of additional water increased from 7% to 13%, the resulting slump values did not show a substantial increase and remained within a relatively narrow range of 75–80 mm. This observation suggests that the relationship between water addition and workability enhancement is not necessarily linear. A portion of the added water was likely absorbed by the aggregates or utilized to improve lubrication between particles within the mixture, thereby limiting its direct contribution to an increase in slump. Consequently, not all of the additional water was reflected in higher slump values, as part of it was consumed in overcoming internal friction and maintaining the cohesiveness of the concrete mixture.

The present study was not designed to determine the optimum amount of additional mixing water for each concrete mixture. Instead, water was added incrementally only until the target slump was achieved. Despite the resulting increase in the actual water–cement ratio, all mixtures exceeded their target compressive strengths, indicating that the amount of additional water used was sufficient to achieve the required workability without causing a significant reduction in mechanical performance. Therefore, the water additions adopted in this study may be considered close to the practical optimum for the investigated mixtures. Nevertheless, identifying the true optimum water content would require a dedicated optimization study involving multiple water addition levels while simultaneously evaluating workability and compressive strength.

The initial slump before water adjustment was not recorded because the objective of the study was to evaluate concrete performance after achieving the specified workability. Additional water was gradually introduced during mixing until the target slump of 75–100 mm was obtained. Therefore, only the final slump values, which satisfied the specified workability requirement, were used for subsequent analysis. Slump loss over time during the casting process was not evaluated in this study. The slump test was performed immediately after mixing and water adjustment to verify that the fresh concrete satisfied the target workability (75–100 mm) before casting. Therefore, comparisons of time-dependent slump loss among the mixtures were beyond the scope of this investigation.

3.2 Density of Concrete Test Results

The test results indicate that the unit weight of concrete increased with the increase in the target compressive strength. The measured unit weights were 2368.11 kg/m³ for NC-17, 2383.58 kg/m³ for NC-20, 2392.26 kg/m³ for NC-23, and 2401.70 kg/m³ for NC-26. All values fall within the typical range of normal-weight concrete, which is approximately 2200–2500 kg/m³. This trend suggests that mixtures designed for higher compressive strengths produced denser concrete, likely due to improved particle packing and a more compact internal structure. A clearer illustration of this relationship is presented in Figure 2.

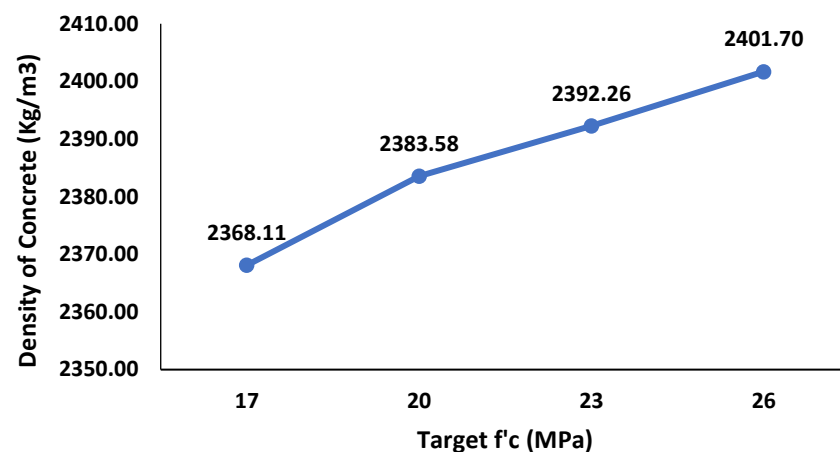


Figure 2. Density of Concrete Test Results

Based on Figure 2, the increasing trend in concrete unit weight indicates that mixtures designed for higher strength grades possessed a denser internal structure. This condition is generally associated with a higher binder content and a reduction in internal voids, resulting in a greater mass per unit volume of concrete. Denser concrete typically exhibits lower porosity and an enhanced capacity to resist compressive loads. Although the differences in unit weight among the mixtures were relatively small, a consistent upward trend was observed from NC-17 to NC-26. This finding suggests that the natural aggregates used in the study provided good particle distribution and effective compaction across all mixture variations. Furthermore, the absence of any reduction in unit weight at higher strength levels indicates that the additional water introduced to achieve the target slump did not lead to excessive void formation in the hardened concrete. These findings are consistent with previous studies reporting that increased concrete density is closely associated with reduced porosity and improved compressive strength [36].

Overall, the test results demonstrate a positive relationship between concrete unit weight and the target compressive strength. As the designed concrete strength increased, the corresponding unit weight also increased, indicating the development of a denser and more compact concrete structure. This condition contributes to the achievement of higher compressive strength and suggests that the natural aggregates used in this study performed effectively in producing normal-weight concrete without the need for chemical admixtures. The findings further confirm that the aggregate characteristics were capable of supporting adequate compaction and particle packing, resulting in concrete with satisfactory physical and mechanical properties.

3.3 Concrete Compressive Strength Test Results

The test results indicate that the compressive strength of concrete increased in accordance with the planned target compressive strength. The NC-17 mixture achieved a compressive strength of 19.85 MPa, while NC-20, NC-23, and NC-26 attained strengths of 22.74 MPa, 25.16 MPa, and 28.74 MPa, respectively. All concrete mixtures exceeded their specified target compressive strengths, which were 17 MPa, 20 MPa, 23 MPa, and 26 MPa, respectively. These results demonstrate the effectiveness of the mix design in achieving and surpassing the desired strength performance. A clearer illustration of the relationship between the target and achieved compressive strengths is presented in Figure 3.

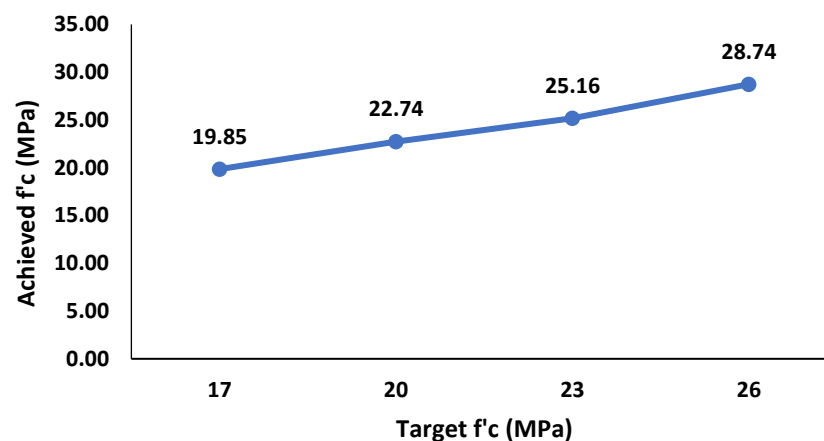


Figure 3. Concrete Compressive Strength Test Results

Figure 3 illustrates that the achieved compressive strengths exceeded the specified target values, indicating that the natural aggregates used in this study possessed adequate quality to support the development of a dense concrete structure capable of effectively transferring applied loads. Furthermore, the bond between the cement paste and the aggregates is likely to have developed satisfactorily, resulting in a relatively strong interfacial transition zone (ITZ). This improved bond quality contributed to the enhanced mechanical performance of the concrete and played a significant role in the observed increase in compressive strength.

The increasing trend in compressive strength from NC-17 to NC-26 further demonstrates that the adopted mix design was effective in producing concrete with strength levels consistent with the intended design objectives. Although additional water was introduced during mixing to achieve the desired slump values, a consistent increase in compressive strength was still observed across all mixtures. This finding suggests that the amount of added water remained within an acceptable range and did not significantly compromise the quality of the concrete. Consequently, the adjustments made to improve workability were successfully balanced with the requirement to maintain adequate mechanical performance [16].

When correlated with the results of the concrete unit weight test, the increase in compressive strength was accompanied by an increase in concrete unit weight. This relationship indicates that concrete with a higher unit weight tends to possess a denser internal structure and lower porosity, enabling it to withstand greater compressive loads. The observed trend suggests that the densification of the concrete matrix was one of the key factors contributing to the compressive strength development across all mixture variations. As the concrete became more compact, the reduction in internal voids enhanced its load-bearing capacity and overall mechanical performance [37].

Overall, the results of this study demonstrate that the natural aggregates used were capable of producing concrete with compressive strengths that met and even exceeded the specified design targets without the use of chemical admixtures. These findings indicate that the natural aggregates possess considerable potential for application in the production of normal-weight concrete across various strength grades while maintaining satisfactory mechanical performance. The consistent achievement of the target strengths further confirms the suitability of the aggregates for structural concrete applications and highlights their ability to support the development of durable and mechanically reliable concrete.

3.4 Comparison of Design and Actual W/C Ratios

The results indicate that the actual W/C ratios of all concrete mixtures were higher than the corresponding design values due to the additional water introduced to achieve the target slump. The W/C ratio increased from 0.62 to 0.69 for NC-17, from 0.58 to 0.65 for NC-20, from 0.54 to 0.61 for NC-23, and from 0.49 to 0.56 for NC-26. The difference between the design and actual W/C ratios ranged from 10.14% to 12.50%. These findings demonstrate that adjustments in mixing water were necessary to maintain the desired workability, resulting in an increase in the effective W/C ratio of each mixture. A more detailed presentation of the data is provided in Table 5.

Table 5. W/C Ratio Difference

No	Design Parameters					Actual Results				
	Target f_c	k	Standard Deviation	Achieved f_c	Design W/C Ratio	Additional Water Content	Slump Value	Achieved f_c	Actual W/C Ratio	W/C Ratio Difference
	(MPa)		(MPa)	(MPa)		(%)	(mm)	(MPa)		(%)
1	17	1.64	4.50	24	0.62	7.00	75.00	19.85	0.69	10.14
2	20	1.64	4.50	27	0.58	9.00	75.00	22.74	0.65	10.77
3	23	1.64	4.50	30	0.54	11.00	80.00	25.16	0.61	11.48
4	26	1.64	4.50	33	0.49	13.00	75.00	28.74	0.56	12.50

Based on Table 5, it can be observed that the increase in the difference between the design and actual W/C ratios was accompanied by a corresponding increase in the amount of additional water required for higher-strength concrete mixtures. This trend indicates that mixtures designed with lower W/C ratios required greater water adjustments to maintain workability within the desired slump range. The reduced water content associated with higher-strength concrete generally results in a stiffer mixture, thereby necessitating additional water to achieve adequate consistency and ease of placement. Similar observations have been reported in previous studies, which noted that concrete mixtures with lower design W/C ratios often require greater adjustments in mixing water to attain the targeted workability while maintaining acceptable performance characteristics [30]. Despite the increase in the W/C ratio, all concrete mixtures achieved compressive strengths that exceeded their respective design targets. These results indicate that the additional water introduced during mixing remained within an acceptable range and did not cause a significant reduction in compressive strength. Consequently, the natural aggregates used in this study were capable of producing concrete that satisfied both workability and strength requirements without the need for chemical admixtures. This finding highlights the suitability of the aggregates for normal concrete production while maintaining adequate fresh and hardened concrete performance.

To provide a more comprehensive evaluation of the relationship between the target compressive strength and the discrepancy between the designed and actual water–cement (W/C) ratios, the data were presented graphically, as illustrated in Figure 4. This graphical representation facilitates a clearer interpretation of how variations in the target compressive strength influence the difference between the planned and realized W/C ratios across the concrete mixtures.

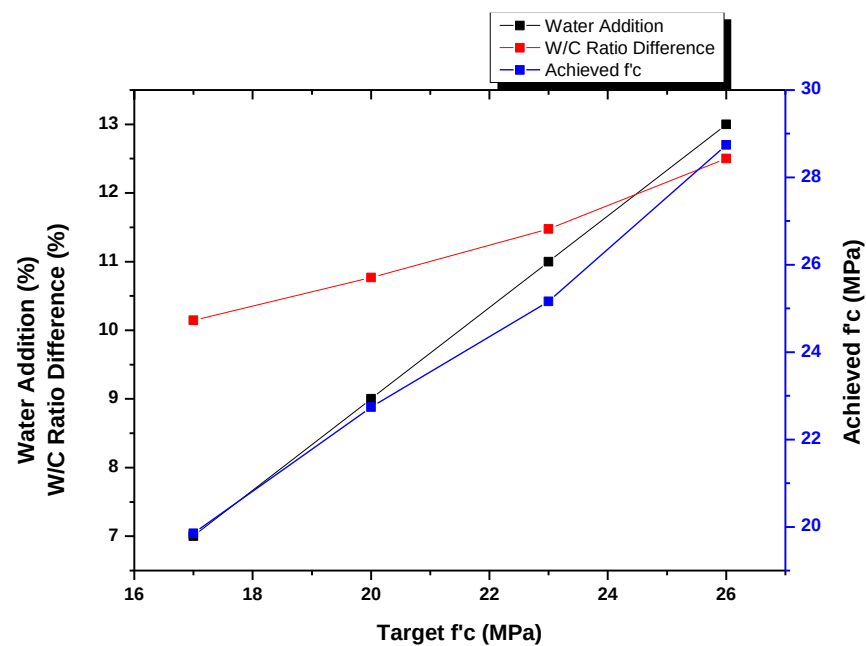


Figure 4. Relationship Between Target f'_c and the W/C Ratio Difference

Figure 4 illustrates a gradual increase in the difference between the planned and actual water–cement (W/C) ratios as the target concrete strength increases. The W/C ratio discrepancy rose from 10.14% for the concrete mixture designed for 17 MPa to 12.50% for the mixture designed for 26 MPa. This trend suggests that higher-strength concrete mixtures require greater adjustments in water content to achieve the desired level of workability while maintaining the specified slump range. Theoretically, higher concrete strength is generally achieved by reducing the water–cement (W/C) ratio. A lower W/C ratio decreases the amount of free water available in the cement paste, resulting in a stiffer mixture with reduced workability and greater resistance to handling and placement. Similar observations have been reported in previous studies, which indicate that concrete mixtures with lower W/C ratios tend to require additional measures to maintain adequate workability during mixing and casting [16]. This behavior was also observed in the present study, where concrete mixtures designed with lower W/C ratios required greater amounts of additional water during the mixing process to maintain the slump values within the specified target range. The findings indicate that as the designed W/C ratio decreased, a larger adjustment in water content was necessary to achieve the desired level of workability while ensuring proper mixing, handling, and placement of the fresh concrete.

The relatively linear increase in the W/C ratio difference indicates that the demand for additional water is closely related to the reduction in the planned W/C ratio. In other words, the lower the designed W/C ratio, the more sensitive the mixture becomes to variations in water content. This phenomenon is commonly observed in medium- to high-strength concrete, where even small changes in the amount of water can have a significant effect on the fresh properties of the concrete. From the perspective of concrete technology, these findings emphasize the difficulty of maintaining conformity between the designed mix proportions and the conditions encountered during concrete production. While the incorporation of additional water can enhance the workability of fresh concrete, it inevitably alters the actual W/C ratio from the value specified in the mix design. Previous research has highlighted that careful regulation of water content during mixing is essential to preserve the intended performance characteristics of both fresh and hardened concrete, thereby ensuring that the concrete achieves the desired engineering properties [38].

Overall, the graph demonstrates that achieving higher concrete strength requires not only a reduction in the W/C ratio but also more rigorous control of workability. The progressive increase in the discrepancy between the planned and actual W/C ratios across the strength classes suggests that concrete mixtures designed for higher target compressive strengths exhibit greater sensitivity to water addition than those with lower strength requirements. This behavior reflects the narrower tolerance of low-W/C mixtures to variations in water content, where even minor adjustments can significantly influence the rheological characteristics of fresh concrete and potentially affect its subsequent performance. Consequently, stricter control of water dosage becomes increasingly important as the target strength level increases to ensure consistency between the mix design assumptions and the properties achieved in practice.

4. Conclusions

The results of this study demonstrate that the natural aggregates employed were capable of producing concrete with actual compressive strengths that met and, in all cases, exceeded the specified target strengths without the incorporation of chemical admixtures. Although the actual water–cement (W/C) ratios increased as a consequence of additional water being introduced to satisfy workability requirements, all concrete mixtures successfully achieved the intended strength classifications. These findings suggest that the aggregates possessed favorable physical characteristics and adequate quality to support the development of concrete with satisfactory mechanical performance.

A key contribution of this study lies in demonstrating the potential of natural aggregates to produce normal-strength concrete in an effective and cost-efficient manner without the use of chemical admixtures. The findings indicate that satisfactory mechanical performance can be achieved through appropriate mix proportioning and the utilization of quality natural aggregates, thereby reducing the reliance on additional chemical constituents. Nevertheless, the scope of the study is limited to concrete strength classes ranging from 17 to 26 MPa, a single source of natural aggregate, and performance evaluation primarily based on compressive strength characteristics. Consequently, the applicability of the results is mainly confined to normal-strength concrete intended for low- to medium-strength construction applications, and caution should be exercised when extending these findings to higher-strength concrete or to aggregates obtained from different geological sources.

For future research, it is recommended to investigate a wider range of aggregate sources, higher concrete strength classes, and additional performance aspects, including durability and other engineering properties of concrete. Such studies would provide a more comprehensive understanding of the influence of aggregate characteristics on concrete behavior and long-term performance, thereby contributing to the development of more reliable and sustainable concrete mixtures for diverse construction applications.

For practical applications, quality control should include moisture correction of the aggregates, verification of aggregate gradation, strict control of additional mixing water, routine slump testing before casting, and regular compressive strength testing. These measures help maintain a consistent water–cement ratio and ensure uniform concrete performance.

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Conflict of Interest

The authors declare no conflicts of interest.

Generative AI Declarations

Not Applicable.

Author Contributions

Bunyamin Bunyamin: conceptualization, methodology, formal analysis, investigation, writing-original draft preparation, writing-reviewing and editing. Heru Pramanda: data validation, data curation, supervision. Muhajir Muhajir: conceptualization, validation, data curation, supervision. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials

All materials, experimental data, and analytical results relevant to this research are reported within the manuscript. The information provided enables readers to assess, interpret, and validate the outcomes of the study.

Abbreviations

W/C	Water Cement Ratio
f'_{cr}	Kuat tekan rencana
f'_c	Kuat tekan target
k	Faktor keamanaan
s	Standar deviasi
FM	Fineness Modulus
SSD	Saturated Surface Dry
ASTM	American Society for Testing and Materials
ACI	American Concrete Institute

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