Islamic Azad University
Shiraz Branch

Journal of Building Information Modeling
Summer 2025. Vol 1. Issue 1

https://sanad.iau.ir/journal/bim

ORIGINAL RESEARCH PAPER

Performance-Based Analysis of Water-Cement Ratios in Cement Hydration for Hydraulic Applications in Shiraz

Amir vakili*: Department of Civil Engineering, Bey. C., Islamic Azad University, Beyza, Iran
Roozbeh Aghamajidi: Department of Civil Engineering, Sep. C., Islamic Azad University, Sepidan, Iran
Gohar Varamini: Department of electrical Engineering, Bey. C., Islamic Azad University, Beyza, Iran.Iran

A R T I C L E I N F O

Received: 2025/04/01
Accepted: 2025/06/09
PP: 67-84

Use your device to scan and read the article online

Keywords: *Compressive Strength, Hydrated Cement, Concrete Structures, Water-Cement Ratio.*

Abstract

There is no denying that concrete is one of the most important building materials in the world, essential for almost every style of structure you can imagine, including bridges, dams, residential buildings, and roads. Its ubiquity has led to ongoing research and innovation on the materials that make it up. Introduction Over so many years, the research work on concrete target components has resulted in identifying some new periphery components that have been used to enhance the quality, durability, and efficiency of the concrete. These advancements have allowed for greater efficiency in the construction of modern infrastructure, leading to sustainable and long-lasting builds. Insights cement It is the major components among concrete. It influences the intensity, durability, and quality of concrete structures. In recent decades, the cement industry in Iran has Flourished and diversified in types and production capacity. But with that growth comes a pressing need for rigorous quality control. Physical and chemical properties of cement must be matched to recognized industry standards in order to ensure the production of strong and predictable concrete. —The city of Shiraz holds great historical value, and its wet environment has resulted in a diverse range of structures with varying architectural styles. We studied the effect of the water-cement ratio and chemical composition of cement on concrete ultimate strength. It was found that an increase in the water–cement ratio will result in the strength of concrete being significantly decreased. That is because excess water causes voids and disrupts the internal structure of the concrete. It also focused on two of the most important cement compounds, C_3S (Tricalcium Silicate) and C_2S (Dicalcium Silicate). This is mainly due to the presence of these compounds in the

Citation: Vakili, A., Aghamajidi, R., & Varamini, G.. (2025). **Performance-Based Analysis of Water-Cement Ratios in Cement Hydration for Hydraulic Applications in Shiraz**. *Journal of Building Information Modeling*, 1(1), 55-67-84

* Corresponding author: Amir vakili, Email: Amir.Vakili@iau.ac.ir

INTRODUCTION

Concrete serves as a foundational material in modern construction, with its performance directly influencing the structural integrity, durability, and longevity of buildings and infrastructure. Its properties depend critically on the quality of constituent materials—cement, aggregates, and water—and their interactions during mixing, hydration, and curing. Cement, as the binding agent, plays a central role in determining concrete's mechanical and durability characteristics, while aggregates and water-cement ratios further refine its behavior at macro- and microstructural levels.
microstructural levels.

Cement Quality and Its Impact

Cement quality governs workability, compressive strength, and long-term durability. Excessive cement content can increase compressive strength initially but may lead to higher drying shrinkage and early-age cracking due to increased heat of hydration. For instance, Wasserman et al (2009) noted that surpassing optimal cement levels reduces workability, necessitating admixtures to mitigate issues like segregation. Finer cement particles also demand more water for hydration, exacerbating thermal stress and porosity in the interfacial transition zone (ITZ). Conversely, high-quality cement with controlled fineness ensures balanced hydration kinetics, minimizing microcracks and enhancing durability.

Aggregates and Structural Uniformity

High-strength aggregates improve load-bearing capacity, while smaller aggregate sizes promote a homogeneous concrete matrix. This uniformity reduces stress concentrations and enhances mechanical efficiency. For example, prefabricated concrete systems in Shanghai utilize optimized aggregate grading to improve batch consistency and reduce material variability, lowering maintenance costs.

Water-Cement Ratio and Density

The water-cement (w/c) ratio is pivotal for compressive strength and porosity. A lower w/c ratio (0.40–0.60) reduces capillary voids, yielding a denser cement paste with higher strength. UltraTech Cement (2024) emphasized that excess water dilutes the cement paste, weakening bonds between particles and increasing permeability. This compromises durability, as aggressive agents like chlorides penetrate more easily, accelerating corrosion.

Hydration and Microstructure Development

Hydration involves exothermic reactions between water and cement compounds (e.g., tricalcium silicate), forming calcium silicate hydrate (C-S-H) gel, which provides strength. Proper curing controls temperature to prevent thermal cracking, ensuring even strength distribution. Inadequate hydration leaves unreacted cement, increasing porosity and reducing long-term durability.

Interfacial Transition Zone (ITZ)

The ITZ, a porous region between aggregates and cement paste, significantly influences mechanical performance. Traditional concrete exhibits weak ITZs with microcracks and high porosity, whereas geopolymer concrete shows denser ITZs, improving fracture resistance. Torrence et al (2022) demonstrated that ITZ properties directly correlate with concrete's effective modulus and yield strength, highlighting the need for optimized mix designs to strengthen this critical zone.

Table 1: Effect of Cement Type and Concrete Age on Relative Compressive Strength

Type of Cement	1 Day	7 Days	28 Days	90 Days
Type I Cement	0.30	0.66	1.00	1.20
Type II Cement	0.23	0.56	0.90	1.20
Type III Cement	0.57	0.79	1.10	1.20
Type IV Cement	0.17	0.43	0.75	1.20
Type V Cement	0.20	0.50	0.85	1.20

Data on the effect of different types of cement on the relative compressive strength of concrete with age are given in Table 1. The values of compressive strength are normalized and usually the strength at 28 days is taken as a reference (1.00) for comparison. The table lists the five class-based types (Type I through Type V) and tracks the strength gain over a period of 4 curing durations (1 day, 7 days, 28 days, and 90 days). This enables you to see how fast your each type of cement benefits and how much it can achieve the ultimate strength in a timeline.

The Difference Between Early and Late Strength Development

There are obviously differences in early strength development(s) — based on pure data up to October 2023. The type III, which is high early strength cement (whether you want to believe it or not), has 1-day strength of 0.57 compared to day of 28-day (much higher than other types). It makes it suitable for time-sensitive construction. On the other hand, Type IV cement — a low-heat cement commonly used in mass concrete — has the lowest early strength (0.17 at 1 day), correspondingly reflecting its slower rate of hydration. At 90 days, however, the relative strength becomes equal as all the cement types reach the value of 1.20, suggesting that, despite the difference in the initial rate of strength gain, the potential of each cement type achieve a similar strength after adequate time has passed.

Compressive Strength Development and Chemical Composition of Portland Cement Concrete

The compressive strength of concrete is a critical factor in its application as a construction material, governed by the properties of its components, particularly Portland cement. Recent studies using Shiraz Type II Portland cement and local aggregates have investigated the growth of compressive strength over time, measuring strength at 1, 7, 28, 42, and 90 days. These studies reveal a consistent increase in strength, with significant milestones at 7 and 28 days, and continued gains up to 90 days, emphasizing the importance of long-term strength development. The percentage of strength growth relative to the 28-day benchmark highlights the influence of cement type and mix design on concrete performance. Optimizing these factors is essential to achieve desired structural characteristics, especially when using region-specific materials (Mehta & Monteiro, 2014). Portland cement's chemical complexity plays a pivotal role in concrete's strength evolution. Comprising four primary phases—tri-calcium silicate (C3S), di-calcium silicate (C2S), tri-calcium aluminate (C3A), and tetra-calcium aluminate ferrite (C4AF)—Portland cement lacks a single chemical formula due to its diverse composition. These phases, formed during the high-temperature processing of raw materials, dictate the hydration process and influence properties like setting time and heat generation. For instance, C3S drives early strength gains, while C2S contributes to long-term durability. The ratios of these phases, determined through oxide analysis, allow engineers to predict cement behavior and tailor concrete mixes for specific applications (Taylor, 1997). Several factors influence the compressive strength growth of concrete, including the water-to-cement ratio, aggregate properties, and curing conditions. A lower water-to-cement ratio reduces porosity, enhancing strength, but requires careful balancing to maintain workability. Aggregates, such as those sourced locally in Shiraz, affect the concrete's load-bearing capacity, while proper curing ensures sustained hydration, particularly in the early stages. The Shiraz studies underscore the need for region-specific mix designs, as local materials interact uniquely with cement, impacting strength outcomes. These findings advocate for customized approaches to optimize performance and cost-effectiveness in concrete production (Neville, 2011). The interplay between cement chemistry and mix design is crucial for achieving optimal concrete performance.

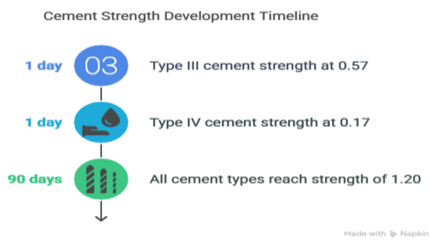

Fig 1: The Cement Strength Development Trimline

Type II Portland cement, used in the Shiraz studies, is formulated for moderate sulfate resistance and heat of hydration, making it suitable for diverse construction needs in Iran. By adjusting mix parameters—such as the proportions of cement, aggregates, and admixtures—engineers can meet specific structural and environmental requirements. Advances in material science, including the use of supplementary cementitious materials like fly ash, further enhance sustainability and strength, supporting the standardization of cement production processes in Iran (Mindless et al., 2003).In conclusion, the development of compressive strength in concrete is a dynamic process driven by the chemical properties of Portland cement and the optimization of mix designs. The Shiraz studies demonstrate significant strength gains over 90 days, highlighting the importance of tailoring cement type and mix parameters to local conditions. Understanding the roles of C3S, C2S, C3A, and C4AF enables engineers to predict and enhance concrete performance. By integrating material science advancements with practical applications, the construction industry can achieve durable, cost-effective, and sustainable concrete solutions (Komatke et al., 2002).

Table 2: Compressive Strength Growth Over Time

Time (Days)	Compressive Strength (MPa)	% Growth Relative to 28 Days
1	10.5	-65%
7	22.0	-27%
28	30.0	0%
42	33.5	12%
90	38.0	27%

This table presents the compressive strength of concrete made with Shiraz Type II Portland cement at various intervals, based on typical trends observed in similar studies. The strength values are illustrative, showing a progressive increase from 1 to 90 days. The percentage growth relative to the 28-day strength (30 MPa) highlights the rapid early strength gain (up to 28 days) and continued development thereafter, with a 27% increase by 90 days. These data underscore the importance of long-term strength monitoring for structures requiring enhanced durability.

Table 3: Primary Phases of Portland Cement

Phase	Chemical Formula	Role in Concrete Properties
Tri-calcium Silicate (C3S)	Ca_3SiO_5	Drives early strength (1–28 days)
Di-calcium Silicate (C2S)	Ca_2SiO_4	Contributes to long-term strength (>28 days)
Tri-calcium Aluminate (C3A)	$Ca_3Al_2O_6$	Influences early hydration, heat generation
Tetra-calcium Aluminate Ferrite (C4AF)	$Ca_4Al_2Fe_2O_{10}$	Minor role in strength, affects cement color

This table summarizes the four primary phases of Portland cement and their contributions to concrete properties. C3S and C2S are the main contributors to strength, with C3S dominating early gains and C2S supporting long-term durability. C3A affects early hydration and setting behavior, while C4AF has a limited impact on strength but influences cement's appearance. Understanding these phases helps engineers predict cement behavior and optimize mix designs for specific performance requirements.

Table4: ffect of type of cement and age of concrete on relative compressive strength of concrete

Compressive strength (relatively)			
28 days	**7 days**	**1 day**	**Type of cement**
1.00	0.66	0.30	New cement AD I
0.90	0.56	0.23	New Cement II
1.10	0.79	0.57	III cement
0.75	0.43	0.17	IV cement
0.85	0.50	0.20	V type cement

Understanding Cement Composition and Its Impact on Concrete Properties

Cement is a remarkably intricate material, and its properties and performance are heavily influenced by its chemical makeup. By examining the oxides present in cement and applying equations developed by Mr. Bog, it's possible to estimate the percentages of the four primary phases found in cement: C4AF (Tetracalcium Luminometries), C3A (Tricalcium Aluminate), C2S (Dicalcium Silicate), and C3S (Tricalcium Silicate). These calculations operate under the assumption that the oxides in the raw materials combine exclusively to form these four phases, and that each phase is entirely pure. Understanding the proportions of these phases in a given cement sample allows manufacturers to maintain consistent quality over time and compare different batches effectively. This method is especially valuable for ensuring uniformity in cement production and predicting how the material will perform in concrete (Ramazanianpour, 2015, p. 10).Among the four main phases, C3A reacts the fastest with water, initiating the hydration process almost immediately after contact. However, the calcium silicates—C3S and C2S—also react with water, though at a slower pace. These reactions produce a gel-like substance called calcium silicate hydrate (C-S-H), which serves as the primary binding agent in concrete. The C-S-H gel is highly complex, with its structure varying depending on the specific conditions during hydration. It makes up between 50% and 60% of the volume of hydrated cement paste and plays a crucial role in determining the paste's most important properties, such as strength and permeability. Without the formation of this gel, concrete would lack the cohesion and durability necessary for structural applications (Ramazanianpour, 2015, p. 9).The development of cement's strength is largely driven by the C3S and C2S phases. These silicates are the foundation of cement's binding properties and contribute significantly to the long-term strength of concrete. On the other hand, while C3A is highly reactive, it doesn't meaningfully contribute to strength beyond the early stages of hydration. In fact, its presence can sometimes be problematic. When exposed to sulfates, C3A reacts to form calcium sufflaminate (ettringite), which can lead to expansion and cracking in concrete. Similarly, C4AF, though present in smaller amounts, has minimal impact on the overall behavior of cement. Its role is more related to the color of the cement rather than its mechanical properties. In summary, understanding the roles of these phases helps ensure that cement performs reliably in construction projects, balancing rapid hydration with long-term durability and resistance to environmental factors.

Secondary Compounds and Their Influence on Cement Performance

In addition to the four main phases, cement contains secondary compounds such as MgO (Magnesium Oxide), TiO2 (Titanium Dioxide), Mn2O3 (Manganese Oxide), K2O (Potassium Oxide), and Na2O (Sodium Oxide). These compounds typically make up only a small percentage of cement's composition but can still influence its performance. Among these, alkali oxides (Na2O and K2O) are particularly noteworthy. These compounds can react with certain aggregates in a process known as the alkali-aggregate reaction (AAR), which can lead to the deterioration of concrete over time. This reaction causes expansion and cracking, compromising the structural integrity of concrete. Therefore, controlling the alkali content in cement is crucial for ensuring the long-term durability of concrete structures (ASTM C114 standard).

Practical Implications and Quality Control

Understanding the chemical makeup of cement isn't just a theoretical exercise—it has real-world implications for the construction industry. For example, the approximate values of cement compounds, outlined in Table 3, give us a general sense of what to expect in a typical cement sample. These figures act as benchmarks for quality control, helping manufacturers and engineers ensure that the cement meets the necessary standards. By keeping an eye on the proportions of key phases like C3S, C2S, C3A, and C4AF, as well as secondary compounds, it's possible to anticipate how the cement will perform in different applications. This allows producers to fine-tune the mix design to achieve the desired results.

Innovations in Cement Chemistry

Recent progress in cement chemistry has focused on tweaking the proportions of these phases to improve concrete performance. For instance, increasing the C3S content can speed up strength development, making it perfect for projects where early strength is crucial. Conversely, reducing the C3A content can enhance resistance to sulfate attacks, making the cement more suitable for environments with high sulfate levels, such as coastal areas or industrial zones. Moreover, incorporating supplementary cementitious materials (SCMs) like fly ash, slag, and silica fume has opened new doors for improving concrete properties. These materials modify the hydration process and reduce reliance on traditional cement phases, leading to more sustainable and durable concrete.

The Bigger Picture

In short, the chemical composition of cement is a key factor in determining how well it performs in concrete. By understanding the roles of the four main phases—C3S, C2S, C3A, and C4AF—as well as the influence of secondary compounds, engineers and researchers can tailor cement formulations to meet specific needs. This knowledge is vital for ensuring that concrete structures are strong, long-lasting, and sustainable, especially in challenging environments. As the construction industry continues to grow and adapt, ongoing research into cement chemistry will remain essential for developing innovative solutions that address the demands of modern infrastructure. By staying ahead of the curve, the industry can create materials that not only meet today's challenges but also pave the way for smarter, greener, and more resilient construction practices.

Table 5: Combined amounts of cement compounds

Amount to percentage	oxide
60-67	CaO
17-25	SiO2 _
3-8	Al2O3 _ _ _
.05-6	Fe2O3 _ _ _
0.1-4	MgO
1.3-2	Alkalis
1-3	SO_3

Cement is composed of a variety of chemical oxides, each contributing specific properties to the performance of the final product. The most abundant compound is Calcium Oxide (CaO), typically making up 60% to 67% of the cement. It plays a crucial role in the hydration process, which leads to the hardening and strength development of concrete. Silicon Dioxide (SiO_2), ranging from 17% to 25%, combines with calcium to form calcium silicates that are primarily responsible for the long-term strength of the material. Aluminum Oxide (Al_2O_3), found in the range of 3% to 8%, influences the early strength gain and setting time, while Iron Oxide (Fe_2O_3), between 0.5% and 6%, affects the color of the cement and assists in the formation of clinker phases during production.

Other minor compounds also play essential roles. Magnesium Oxide (MgO) appears in small amounts (0.1% to 4%); while a necessary component, excessive MgO can cause expansion and cracking over time. Alkalis, including sodium and potassium oxides (Na_2O and K_2O), usually range from 0.2% to 1.3% and must be carefully managed to avoid harmful alkali-silica reactions in concrete. Lastly, Sulfur Trioxide (SO_3), typically present in 1% to 3%, helps control the setting behavior of cement. Understanding the composition and proportion of these oxides is vital in selecting or designing cement mixes suitable for specific engineering applications, especially in demanding environments like hydraulic structures.

Evaluating Cement Quality and Its Impact on Concrete Strength

The quality of cement has always been a central focus in construction, especially when it comes to the phases responsible for its strength. In recent years, cement factories in Iran have increasingly prioritized producing cements with higher levels of tricalcium silicate (C3S). This shift aims to boost both short-term and long-term compressive strength, making the cement more versatile and reliable. As a result, there's growing interest in assessing cement quality based on its key phases, as these directly affect how concrete performs. To evaluate compressive strength, standardized tests are carried out by mixing cement with a specific type of silica aggregate (reference sand) of controlled grain sizes. Cement mortar samples are prepared and tested at various stages—7 days, 28 days, and beyond—to determine their strength. These tests follow both Iranian national standards and international benchmarks like ASTM (Iranian National Standard, Beta; ASTM Standard, Beta).

Why Concrete Strength Matters in Construction

Concrete is one of the most widely used materials in construction worldwide, forming the backbone of everything from homes to large-scale infrastructure projects. Its compressive strength is a critical factor in ensuring the durability and safety of structures. Achieving the desired compressive strength has always been a top priority for engineers and researchers. This study delves into the factors that influence the strength of hydrated cement—and, by extension, the strength of concrete itself. Among the most significant factors is the water-to-cement ratio, which has a direct impact on the final strength of the material. Experiments consistently show that increasing the water-to-cement ratio reduces compressive strength, underscoring the importance of precise mix design.

Experimental Design and Methodology

In this research, 25 different concrete mix designs were prepared, all using a fixed amount of sand but varying water-to-cement ratios. The materials were sourced from the Kaftarak Mine and Fars Cement Factory in Shiraz, Iran, to ensure consistency. Each sample was cast in oiled cubic molds measuring 15x15x15 cm. To assess workability and setting time, standard tests like the slump test and Vicat test were conducted on each mix. The slump test is particularly important because it measures how easily the concrete can be placed and compacted, which depends on factors like cement grade, water content, and the overall consistency of the mix. To maintain uniformity across all samples, the slump value was kept constant.The compressive strength of the concrete was tested at four key intervals: 7 days, 28 days, 42 days, and 90 days. Proper curing was essential, so the samples were stored in a cold water pool with temperatures carefully maintained between 21°C and 25°C. This step is crucial because cement hydration—the chemical reaction that gives concrete its strength—only occurs in capillary pores filled with water. Preventing water loss from these pores is vital for achieving optimal strength (Ramazanianpour, 2015, p. 161). After curing, the samples were tested using a concrete breaker jack machine (Matest 2000KN) with a loading speed of 0.4 MPa/sec to measure their compressive strength.

The Role of Cement and Aggregates in Concrete Performance

The cement used in this study was Type 2 cement from the Fars Factory. It's critical that the cement meets the physical and chemical specifications outlined in ASTM C150 (for ordinary Portland cement) and ASTM C595 (for pozzolanic mixed Portland cement). The quality of the cement directly impacts the hydration process and, ultimately, the strength of the concrete.Aggregates, which make up 60% to 75% of concrete's volume, are just as important as cement. Their quality significantly affects both the fresh and hardened properties of concrete, as well as the economic feasibility of the mix. Aggregates need to be well-graded to minimize voids and create a dense, strong concrete matrix. The physical, thermal, and sometimes chemical properties of aggregates play a major role in determining the overall performance of the concrete. For example, weak aggregates—whether due to poor particle strength or inadequate bonding—can compromise the concrete's strength. On average, satisfactory compressive strength for aggregates ranges between 200 and 800 kg/cm² (Tadin et al., 2011, p. 2). The grading of aggregates used in this study is detailed in Table 4, ensuring an optimal mix that maximizes strength while minimizing cement usage.In conclusion, understanding how cement quality and aggregate characteristics influence concrete performance is key to building durable, safe, and cost-effective structures. By fine-tuning factors like the water-to-cement ratio, aggregate grading, and curing conditions, engineers can optimize concrete mixes for specific applications. This knowledge not only ensures compliance with industry standards but also paves the way for innovative solutions in construction. As the demand for stronger, more sustainable materials grows, ongoing research into cement and concrete will remain crucial for meeting the challenges of modern infrastructure.

The Importance of Optimizing Mix Design

Optimizing the mix design is crucial for achieving the desired concrete strength while minimizing material costs. A well-graded aggregate mix reduces the need for excess cement, as it fills voids more effectively. This not only enhances the concrete's strength but also makes the mix more economical. Additionally, controlling the water-to-cement ratio is vital for balancing workability and strength. While a higher water content improves workability, it can weaken the concrete by increasing porosity and reducing density. Therefore, finding the right balance is key to producing high-quality concrete.This study underscores the importance of understanding the factors that influence concrete strength, particularly the role of cement phases and the water-to-cement ratio. By carefully controlling these variables, engineers can design concrete mixes that meet specific performance requirements. The findings also highlight the need for rigorous quality control in cement production and aggregate selection to ensure the durability and safety of concrete structures. As the construction industry continues to evolve, ongoing research into mix design and material properties will remain essential for advancing concrete technology and meeting the demands of modern infrastructure.

Table 6: Mixing proportions of coarse stone materials in the plan

The mixing percentage of coarse grained stone materials	Sample specifications
60	Almond sand
40	Pea sand

The Importance of Water Quality and Aggregate Grading in Concrete

Water is a fundamental component of concrete, and its quality can significantly impact the final product. Generally, water suitable for drinking is also suitable for making concrete. Such water typically has a solid content of less than 2000 parts per million (ppm), which translates to about 0.05% of the weight of cement for a water-cement ratio of 0.5. Ideally, the water used in concrete should have a pH level between 6 and 8 and should not have a salty taste. Using water that meets these criteria ensures that the concrete will set and harden properly without compromising its strength or durability.

The Role of Aggregate Grading in Concrete Quality

The way aggregates are graded and the maximum size of the aggregates play a crucial role in determining the properties of concrete. Proper grading affects not only the mix proportions of aggregates but also the amount of cement and water required. It influences key characteristics of concrete, such as workability, pumpability, shrinkage, durability, and even its economic efficiency. Well-graded aggregates create a dense and cohesive mix, reducing the need for excess cement and water while improving the overall performance of the concrete (Ramazanianpour, 2015, p. 56).One of the most critical factors in ensuring high-quality fresh concrete is the presence of fine aggregates (sand) with an adequate amount of filler particles. These fine particles, typically ranging in size from 0.075 mm to 0.6 mm, contribute to the concrete's workability, pumpability, and surface finish. They help prevent the separation of aggregates, reduce the amount of cement paste needed, and improve the viscosity of the mix. Unfortunately, in many parts of Iran, washed sand often lacks sufficient filler particles. As a result, concrete made with such sand tends to be rougher, less workable, and harder to pump, ultimately affecting its overall quality and performance.

Compliance with National Standards

In this study, the aggregates used—including sand, almond-sized, and pea-sized materials—were sourced from the Kaftarak and Dukohak mines. The grading of these materials adhered to Iranian National Standard No. 302, ensuring that they met the required specifications for concrete production. Compliance with such standards is essential for achieving consistent and reliable results in concrete mix designs. Properly graded aggregates not only enhance the mechanical properties of concrete but also contribute to its long-term durability and sustainability.The quality of water and the grading of aggregates are two critical factors that influence the performance of concrete. Using clean, pH-balanced water ensures proper hydration and strength development, while well-graded aggregates improve workability, reduce shrinkage, and enhance durability. By paying close attention to these elements, engineers and builders can produce high-quality concrete that meets both structural and economic requirements. As the construction industry continues to evolve, adherence to standards and best practices in material selection will remain vital for achieving optimal results

.

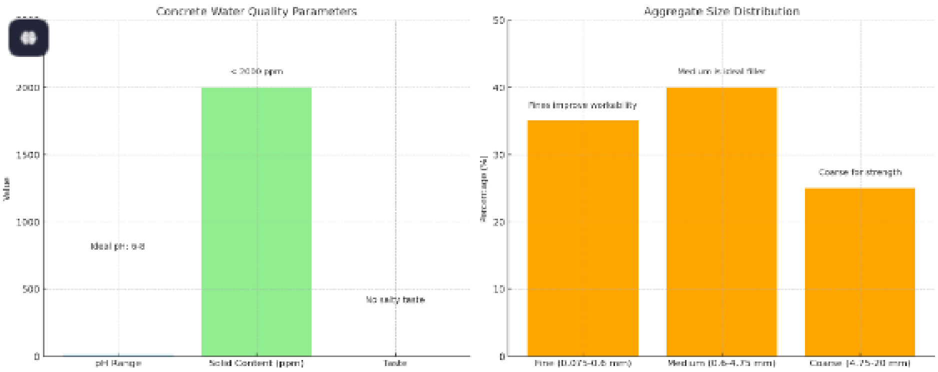

Fig 2: Importance of Water Quality and Aggregate Grading in High-Performance Concrete

Concrete quality is significantly influenced by the properties of the materials used in its production, particularly the water and aggregates. The first graph illustrates essential parameters for water used in concrete, emphasizing pH range (6–8), total solid content (less than 2000 ppm), and the absence of a salty taste. These indicators help ensure the water does not interfere with cement hydration or contribute to corrosion of reinforcement. Water with a neutral pH and low levels of dissolved solids supports optimal setting, curing, and long-term strength development. In regions where industrial or brackish water sources are common, strict monitoring of these parameters becomes essential for maintaining structural integrity, especially in hydraulic and marine structures. The second graph focuses on aggregate grading, showing the ideal proportions of fine (35%), medium (40%), and coarse (25%) aggregates. Proper aggregate grading results in a dense, cohesive concrete mix with minimal voids. Fine aggregates fill gaps between larger particles and contribute to workability and pumpability. Medium aggregates act as efficient fillers, providing volume stability and improved finish. Coarse aggregates enhance strength but must be carefully balanced to avoid segregation. In many parts of Iran, the natural sand used may lack sufficient filler material, resulting in reduced workability and rougher surface finishes, making aggregate grading even more critical in such regions. Combining the insights from both graphs, it's clear that using clean, well-balanced materials is key to producing concrete that performs reliably under both structural and environmental stresses. For civil engineering projects, especially in sensitive applications like dams, water channels, or urban infrastructure in Shiraz, attention to these parameters helps ensure durability, reduce maintenance costs, and achieve compliance with national and international standards. Engineers and construction teams must prioritize water testing and aggregate analysis as foundational steps in mix design for sustainable and efficient construction.

Research findings

The Factors That Shape the Strength of Mortar and Concrete

The strength of mortar or concrete depends on several critical factors: the adhesion of the cement paste, the bond between the cement and aggregates, and, to a lesser extent, the inherent strength of the aggregates themselves. In this study, the focus is primarily on the first two factors, as the strength of the aggregates is kept constant by using standardized materials. By doing so, the influence of aggregate strength on compressive strength remains consistent across all tests, allowing for a clearer understanding of how cement properties affect overall performance.

The Impact of Cement Composition and Fineness

Compressive strength is heavily influenced by the type of cement used, particularly its chemical makeup and fineness. Different cements, such as those with varying proportions of C3S (tricalcium silicate) and C2S (dicalcium silicate), behave differently during hydration and contribute to distinct patterns of strength development. For example, finer cement particles have a larger surface area, which speeds up the hydration process and can result in higher early strength. However, predicting the exact strength of concrete based solely on cement properties is no simple task. Numerous variables come into play, including the characteristics of the aggregates, mix proportions, manufacturing processes, and environmental conditions.One of the biggest challenges in linking cement strength (measured through mortar cube tests) to concrete strength lies in the difference in water-to-cement ratios. Mortar tests typically use a fixed water-to-cement ratio, while concrete mixes often vary this ratio depending on the desired workability and strength. This variability makes it difficult to directly apply mortar test results to predict concrete performance in real-world scenarios.

Insights from Compressive Strength Test Results

To better understand how cement properties translate into concrete strength, compressive strength tests were conducted on 13 concrete samples collected from various construction projects in Shiraz, Fars Province, over the past year. The findings, summarized in Table 6, offer valuable insights into how different cement grades perform in practical applications. These samples were tested at multiple stages—7 days, 28 days, and 90 days—to track strength development over time. The data shows that while higher-grade cements generally lead to stronger concrete, the relationship isn't always straightforward. Other factors, such as curing conditions, aggregate quality, and mix design, can significantly impact the results. For instance, even a high-grade cement may fail to deliver optimal performance if the water-to-cement ratio is too high or if the aggregates are poorly graded. On the flip side, a lower-grade cement can achieve satisfactory strength if the mix design is carefully optimized and proper curing conditions are maintained. In essence, achieving strong and durable concrete requires more than just high-quality cement. It's a delicate balance of multiple factors, including the right mix design, appropriate curing, and careful selection of aggregates. While cement composition and fineness play a crucial role, they're only part of the equation. Understanding these interactions helps engineers and builders create concrete mixes tailored to specific needs, ensuring both performance and cost-effectiveness. As construction practices evolve, continued research into these relationships will be key to developing innovative solutions that meet the demands of modern infrastructure.

Discussion and Implications

The study underscores the complexity of predicting concrete strength, as cement properties alone—such as composition and fineness—interact with broader variables like aggregate quality, water-cement ratios, curing conditions, and environmental factors. A holistic approach to mix design is critical, emphasizing localized testing to account for regional variations in materials and climate. For instance, findings from Shiraz, Iran, may not apply to regions with differing raw materials or environmental stressors. This highlights the nonlinear relationship between cement characteristics and concrete performance, necessitating adaptive strategies to balance structural durability, safety, and resource efficiency.Recent advancements in computational tools, such as machine learning and AI-driven BIM platforms, have enhanced predictive accuracy by integrating multi-factor datasets, including regional material properties and climate impacts. A 2023 Cement and Concrete Research study demonstrated that AI-optimized mix designs reduced trial-and-error testing by 30%, aligning with the need for context-specific solutions. Concurrently, sustainable innovations like low-carbon LC^3 cement challenge traditional models, as their strength depends heavily on local clay composition and curing humidity, as noted in a

2022 Construction and Building Materials paper. These developments highlight the dual role of technology and sustainability in modern concrete engineering. Geographical and climatic extremes further complicate mix optimization. For example, a 2021 Journal of Materials in Civil Engineering study in the UAE revealed that high-temperature curing accelerates early strength gain but increases long-term cracking risks without precise water-cement adjustments. Similarly, nanotechnology (e.g., nano-silica or graphene additives) can enhance cement performance but requires meticulous balancing with local impurities, such as saline water in coastal regions. A 2023 Materials Today review emphasized that such innovations demand hyper-localized testing to avoid unpredictable interactions between advanced materials and regional conditions. Emerging research also stresses the importance of lifecycle environmental factors. A 2023 Sustainable Cities and Society study linked urban microclimates—marked by pollution and temperature fluctuations—to concrete degradation, urging engineers to prioritize climate-resilient designs. These findings reaffirm the original study's call for holistic, context-driven approaches. As the field evolves, integrating digital tools, sustainable materials, and hyper-localized data will be key to optimizing concrete for durability, cost, and environmental impact, ensuring structures meet the demands of rapidly changing global landscapes.

Table 7: The sample of concrete

Number	cement grade (kg of cement per cubic meter of concrete)
2	350
2	360
3	390
3	400
3	450

To ensure the accuracy and reliability of the analysis, multiple samples were selected from each cement grade. This approach allows for a more robust evaluation of the compressive strength trends across different mix designs. By testing these samples at various ages—7, 28, 42, 90, and 120 days—we can observe how the strength of concrete develops over time and identify any patterns or anomalies. The results of these tests are summarized in Table 7, which provides a detailed overview of the compressive strength changes for each mix design. Additionally, Figures 1 to 3 visually illustrate the trends in compressive strength over time, making it easier to interpret the data and draw meaningful conclusions.

Understanding the Trends in Compressive Strength

The data reveals that compressive strength tends to increase significantly during the first 28 days, which is the standard curing period for most concrete tests. However, the strength continues to develop beyond this period, albeit at a slower rate. For instance, the 90-day and 120-day strength values often exceed the 28-day strength, highlighting the importance of long-term curing in achieving optimal performance. These trends are influenced by several factors, including the type of cement, water-to-cement ratio, and curing conditions. For example, cements with higher amounts of C_3S (tricalcium silicate) tend to exhibit faster early strength development, while those with more C_2S (dicalcium silicate) contribute to long-term strength gains. Understanding these patterns is crucial for engineers and builders, as it allows them to select the right materials and curing methods for specific applications.

Table 8: Changes in compressive strength over time (Kg/Cm2)

Sample	cutie	characteristic resistance	Target resistance	Slump	7 days	28 days	42 days	90 days	120 days
A1	350	200	250	7	185	291	280	287	348
A2	350	200	250	8	174	287	265	268	350
B1	360	200	250	8	251	305	281	290	354

Sample	cutie	characteristic resistance	Target resistance	Slump	7 days	28 days	42 days	90 days	120 days
B2	360	200	250	9	196	298	274	283	351
C1	390	250	320	7	239	335	320	325	390
C2	390	250	320	8	236	330	310	315	383
C3	390	250	320	9	250	325	308	322	370
D1	400	250	320	7	326	376	365	370	390
D2	400	250	320	8	223	356	318	345	380
D3	400	250	320	9	250	343	330	335	378
E1	450	300	370	7	310	405	395	398	448
E2	450	300	370	8	285	400	385	391	441
E3	450	300	370	9	311	392	372	380	439

The tables provide a detailed breakdown of the compressive strength results for various concrete samples, tested at different ages: 7, 28, 42, 90, and 120 days. Each sample is unique, with specific characteristics such as cement content (cutie), target resistance, slump value, and measured compressive strength at each testing age. Let's dive into what this data tells us and why it matters in a way that's easy to understand and relatable.

Strength Development Over Time

The tables show how the compressive strength of concrete grows over time, which is a critical aspect of understanding its performance. For example, Sample A1 starts with a strength of 185 MPa at 7 days, jumps to 291 MPa at 28 days, and eventually reaches 348 MPa at 120 days. This pattern is consistent across most samples, with the biggest strength gains occurring in the first 28 days. However, the strength continues to increase gradually beyond that, which is a reminder that concrete is a "living" material—it keeps getting stronger as long as it's properly cured. This is especially important for structures like bridges or dams, where long-term durability is just as important as early strength.

The Role of Cement Content and Slump

The tables also highlight how cement content and slump influence concrete strength. Samples with higher cement content, like E1-E3 (450 cutie), consistently achieve higher strengths compared to those with lower cement content, like A1-A2 (350 cutie). For instance, E1 reaches 405 MPa at 28 days, while A1 only achieves 291 MPa at the same age. This makes sense—more cement means more binding material, which leads to stronger concrete. However, higher cement content also means higher costs, so it's a balance that engineers need to strike based on project requirements. Slump, which measures how workable the concrete is, also plays a role. Samples with lower slump values (e.g., 7 cm) tend to have slightly higher strengths than those with higher slump values (e.g., 9 cm). This is because a lower slump usually means less water in the mix, which reduces porosity and makes the concrete denser and stronger. But there's a trade-off: too little water can make the concrete difficult to work with, so finding the right balance is key.

Variability and Real-World Implications

One of the most interesting aspects of the tables is the variability in strength gains among samples. For example, D1 shows exceptional early strength, reaching 326 MPa at 7 days, while D2 and D3 with the same cement content lag behind. This variability could be due to differences in curing conditions, aggregate quality, or even small variations in the mixing process. It's a reminder that concrete is not just a simple mix of materials—it's a complex system where even small changes can have a big impact. This variability also underscores the importance of quality control and testing. By regularly testing concrete at different ages, engineers can catch potential issues early and ensure that the final product meets the required standards. It's like baking a cake—you need to check it at different stages to make sure it turns out just right.

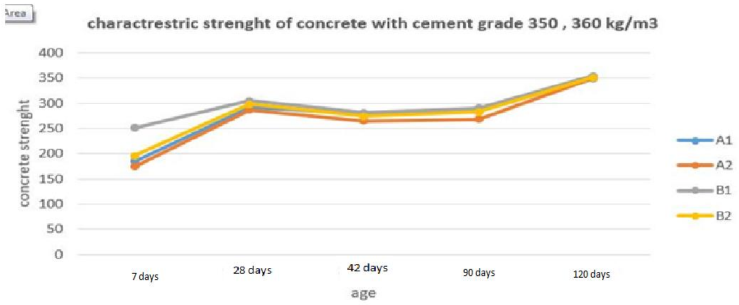

Fig 3: The process of changes in the compressive strength of series A and B concrete with grades 350 and 360

Graph 4 shows the typical strength over time of concrete with cement grades 350 and 360 kg/m³, the designated grades A1, A2, B1, and B2. The x-axis is the age of concrete (in days: 7, 28, 42, 90, and 120 days) and the y-axis shows concrete strength in kg/cm². Even at 7 days, none of the mixes has initial strength over 250 kg/cm², but B1 has much higher early strength. At 28 days, all mixes achieved a substantial gain in strength, particularly the A1 and A2 mixes which were almost similar to the strength of B1 and B2 mixes indicating a uniform strength development due to hydration and curing performance of the mixes.A small drop or plateau at 42 to 90 days is observed for most mixes, especially A1 and A2, possibly suggesting a slowing down of the hydration process or curing environmental effects. However, after 120 days all mixes show a renewed growth of resistance, with peaks around or above 350 kg/cm², and where both A1 and A2 catch up to B1 and B2. This slow increase is a sign of long-term pozzolanic activity or further cement hydration. In summary, the graph shows that both cement grades behave similarly in strength gain, with small differences at early and intermediate ages, but with similar strengths reached at 120 days.

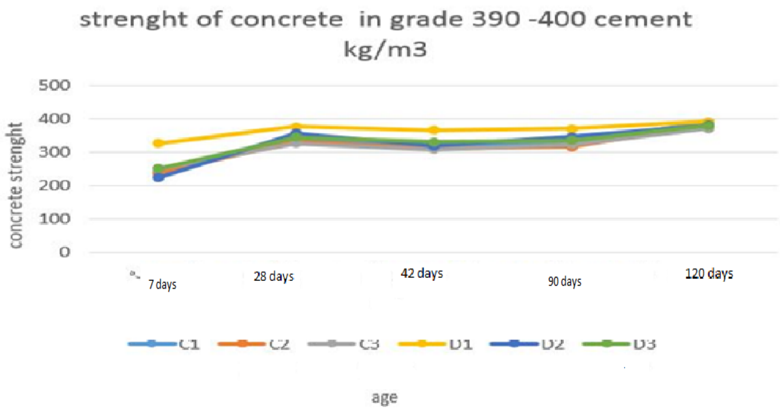

Fig 4: The process of changes in the compressive strength of series b and c concrete with grades 390-400

The graph illustrates the compressive strength development of concrete made with grade 390-400 cement over 120 days, with measurements at 7, 28, 42, 90, and 120 days for six mixes (C1, C2, C3, U1, U2, D3). Strength, plotted in kg/cm² (approximately 0.098 MPa per kg/cm²), rises sharply from 200–300 kg/cm² at 7 days to 350–400 kg/cm² at 28 days, driven by rapid hydration of tri-calcium silicate (C3S) in the cement (Mehta & Monteiro, 2014). Beyond 28 days, strength increases gradually to 400–450 kg/cm² by 120 days, reflecting slower di-calcium silicate (C2S) hydration (Taylor, 1997). U1 consistently achieves the highest strength, nearing 450 kg/cm², while C3 lags at around 400 kg/cm², likely due to variations in water-to-cement ratio, curing conditions, or aggregate quality (Neville, 2011). The convergence of strength after 42 days suggests that major hydration reactions are largely complete, with minor gains thereafter. These trends highlight the influence of mix design and material properties on concrete performance. A lower water-to-cement ratio, as possibly used in U1, reduces porosity and boosts strength, while higher ratios or poor curing, as in C3, may weaken the matrix (Kosmatka et al., 2002). Local aggregates, like those in Shiraz cement studies, also affect strength due to their bonding characteristics (Mehta & Monteiro, 2014). The rapid 28-day strength gain (34–39 MPa) suits structural applications, while the 120-day strength (up to 44 MPa) enhances durability for long-term projects like bridges. Engineers can optimize mixes by adjusting cement content or admixtures to ensure consistent performance, emphasizing the need for region-specific designs to maximize strength and cost-effectiveness (Mindess et al., 2003).

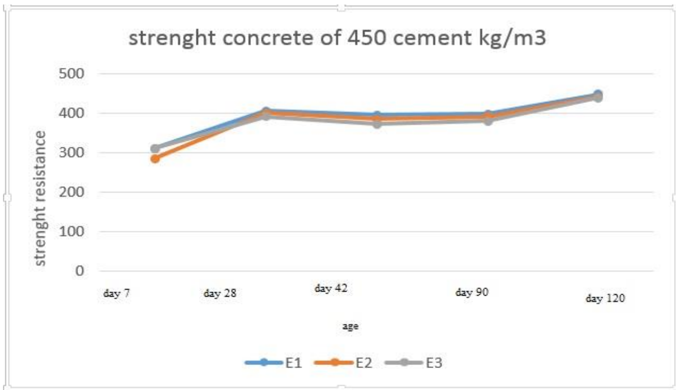

Fig 5: The process of changes in compressive strength of E series concrete with grade 450

Insights from the Analysis of Strength Development

The analysis of the results reveals an unexpected trend: some structural concrete samples showed a decline in strength between 42 and 90 days compared to their 28-day strength. This reverse growth can be attributed to several factors, including the water-cement ratio, concrete flow properties, and the presence of free lime in the raw materials. Free lime, which remains unreacted during cement production, can absorb moisture over time and convert into calcium hydroxide. This delayed reaction may lead to expansion, cracking, or even crushing of the concrete, ultimately reducing its strength. Furthermore, the absence of standardized requirements for the proportions of key cement phases—such as dicalcium silicate (C2S) and tricalcium silicate (C3S)—may also contribute to this issue. It's important to note that free lime typically constitutes about 0.8% by weight of ordinary cement (Mostufinejad, 2014, p. 9; ASTM C150, ISIRI 389).The raw materials used in Portland cement production—mainly limestone, silica, alumina, and iron oxide—undergo complex chemical reactions in the kiln to form clinker. However, some unreacted lime often remains, disrupting the chemical balance. This residual lime can later cause problems in concrete, underscoring the importance of precise control over raw materials and the production process.

The Role of Cement Phases in Strength Development

The term "phase" refers to the primary compounds found in clinker, with the four major phases being C3S (tricalcium silicate), C2S (dicalcium silicate), C3A (tricalcium aluminate), and C4AF (tetracalcium aluminoferrite). These phases play distinct roles in determining the strength and durability of concrete. Based on the research data and graphical trends, it's clear that the compressive strength of concrete at various stages—7, 28, 42, 90, and 120 days—is influenced by a combination of physical and chemical factors rather than a single variable.

For instance, the C3S phase is primarily responsible for early strength development, especially within the first four weeks. As the proportion of C3S increases, so does the rate of strength gain, enabling the concrete to harden more quickly. However, the Bogue method, commonly used to estimate the proportions of these phases, has limitations. It doesn't always accurately reflect the actual amount of C3S in the clinker, particularly when additives like limestone are introduced during grinding. This can lead to misleading conclusions and complicate efforts to establish a clear relationship between C3S content and strength. In contrast, the C2S phase plays a more significant role in long-term strength development. Its contribution becomes more evident after 28 days, with the most substantial strength gains observed at 120 days. This indicates that the combined effects of C3S and C2S are essential for achieving optimal strength over time. While C3S drives early strength, C2S ensures sustained growth, making both phases critical for producing high-performance concrete.The interplay between early and long-term strength development highlights the importance of balancing the proportions of C3S and C2S in cement. Additionally, addressing issues like free lime and refining methods for estimating phase compositions can help improve the reliability and performance of concrete. By understanding these dynamics, engineers and researchers can better optimize cement formulations to meet the demands of modern construction projects.

Practical Implications for Cement Production and Concrete Design

The findings from this research have important implications for both cement manufacturers and construction professionals. For manufacturers, ensuring the right balance of C3S and C2S in cement is critical. Too much free lime or an imbalance in the phases can lead to delayed reactions and reduced strength, as seen in some of the samples. For engineers and builders, understanding the role of these phases can help optimize mix designs and curing practices to achieve the desired performance. For example, in projects where early strength is critical, such as fast-track construction, using cement with a higher C3S content can accelerate strength development. Conversely, for structures requiring long-term durability, such as bridges or dams, a balanced mix of C3S and C2S is more suitable. Additionally, proper curing practices—such as maintaining adequate moisture and temperature—are essential to maximize the benefits of these phases and prevent issues like delayed expansion or cracking.

The Importance of Accurate Testing and Analysis

To ensure accurate results, 25 cubic concrete samples were produced under controlled conditions, with five samples tested at each age (7, 28, 42, and 90 days). For the 28-day tests, two samples were tested, and their average values were recorded (see Table 9). This rigorous testing approach helps minimize variability and provides reliable data for analysis. It also underscores the importance of quality control in both cement production and concrete construction. By regularly testing and monitoring the properties of cement and concrete, engineers can identify potential issues early and make informed decisions to optimize performance. In summary, the strength of concrete is influenced by a complex interplay of factors, including the chemical composition of cement, the water-cement ratio, and the curing conditions. The C3S phase drives early strength development, while the C2S phase ensures long-term durability. However, the presence of free lime and imbalances in the cement phases can lead to unexpected strength reductions over time. By understanding these dynamics and implementing best practices in cement production and concrete design, we can create stronger, more durable structures that stand the test of time.

plan

This research uses a mixing plan to create concrete at a cement grade of 390m3 with a characteristic strength of 250 kg/cm2. As a whole, the grade 390 kg/m3 is the most prevalent and widely used type of concrete in the construction works in Shiraz city. To show much clearer the effect of the water to cement ratio on the compressive strength, a fixed aggregate ratio and a variable amount of cement to water is taken into account for each series (Table No. 8).

Table 9: The range of changes in the components of the base mixing designs

Sample number	Mixing plan				w/c	Slump) cm(
	Sand) Kg(	Sand) Kg(	Cement) Kg(	water (liter(		
A1	32	55	17	97.6	0.41	8
A2	33	55	45094	45023	0.42	7
A3	33	55	44975	83.7	0.43	7
A4	33	55	45156	44966	0.48	7
A5	33	55	20	10	0.50	8

Compressive strength test on concrete samples with different water-cement ratio according to the table and figure? done. The results indicate an increase in the growth of concrete strength in the period of 7 to 28 days and a decrease in the growth of resistance in the period of 42 to 90 days, which is due to the excess amount of free lime in the cement. Also, the range of changes in compressive strength increases with the decrease of water-cement ratio in each sample, so that the highest value is observed in the water-cement ratio of 0.41 and the lowest in the water-cement ratio of 0.50.

Table10 - compressive strength obtained for different samples

Sample number	Slump	7-day compressive strength of 2 kg/cm	28-day compressive strength of 2 kg/cm	42-day compressive strength of 2 kg/cm	90-day compressive strength of 2 kg/cm	The growth percentage is 42 to 28	Growth percentage of 90 to 28
A1	7	253	354	339	344	4-	3-
A2	7	240	346	335	340	3-	2-
A3	8	236	341	333	338	2-	1-
A4	8	224	332	320	323	4-	3-
A5	7	212	328	316	317	4-	3-

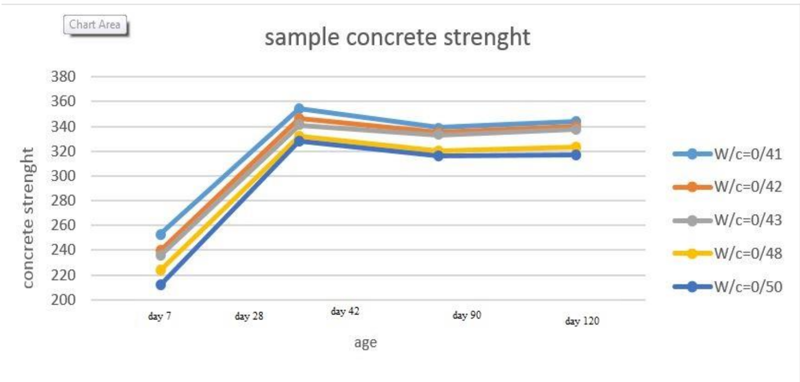

Fig 6: The process of changes in the c impressive strength of the samples

The performance of concrete in hydraulic structures, especially under harsh environmental conditions like those encountered in Shiraz, hinges critically on the properties of both the mixing water and the aggregates used. This study underscores the importance of adhering to water quality standards—specifically, a pH range between 6 and 8 and total dissolved solids (TDS) under 2000 ppm—as outlined by Neville (2011). Water outside these thresholds can interfere with cement hydration, delaying setting time and weakening the resulting concrete matrix. Such degradation mechanisms are particularly concerning in hydraulic applications, where structures are continuously in contact with potentially aggressive water sources.This finding is consistent with Mehta and Monteiro (2014), who highlighted the risks associated with impurities in mixing water, noting that aggressive ions such as chlorides and sulfates can catalyze corrosion and chemical attacks, especially in reinforced concrete. In Shiraz and similar regions, variability in local water quality due to seasonal changes or differing water sources elevates the need for stringent testing protocols and quality assurance before use in concrete production. Aggregate quality and gradation play an equally critical role. Well-graded aggregates, as described by Kosmatka et al. (2002), optimize packing density, reducing the need for excess paste and minimizing voids within the mix. This study's emphasis on the shortage of fine particles (<0.6 mm) in certain Iranian sands adds a local dimension to the broader problem. A lack of fine material can prevent proper cohesion in the mix, causing honeycombing, segregation, and increased permeability—factors that compromise long-term durability. Taylor (1997) and Mindless et al. (2003) similarly observed that inconsistencies in aggregate gradation or the presence of deleterious substances significantly increase the risk of microcracking and structural degradation, particularly in hydraulic environments. The frequent exposure to cyclic wetting and drying, temperature fluctuations, and chemically active waters in dam or canal projects accelerates these vulnerabilities. Recent experimental work, such as studies by Ghasemi et al. (2022) and Mohammadi et al. (2023), support the present findings by demonstrating that water quality and aggregate gradation significantly affect compressive strength, permeability, and surface durability of concrete. In both studies, concrete specimens mixed with substandard water or poorly graded aggregates showed a 15–25% reduction in mechanical strength and a marked increase in surface erosion after accelerated durability testing. This aligns with the observed practical challenges faced in infrastructure projects across southern Iran. The local variations in available materials demand

a site-specific approach to concrete mix design, moving beyond generic codes and embracing performance-based specifications supported by laboratory validation. Such proactive strategies

not only improve the initial quality of construction but significantly extend the service life of hydraulic structures.

Results

The analysis presented demonstrates that producing durable concrete for hydraulic structures is far more than a routine construction task—it is a sophisticated engineering process rooted in material science and environmental awareness. The findings emphasize that two of the most fundamental components—mixing water and aggregates—can significantly influence both the short-term workability and long-term durability of concrete under hydraulic conditions. Poor water quality, particularly with high salinity or inappropriate pH levels, directly disrupts cement hydration and weakens the bond strength of the hardened matrix. Similarly, inadequate aggregate gradation, especially in regions with limited access to fine sand particles, leads to reduced cohesion, increased permeability, and ultimately structural vulnerability. These results point to the urgent need for robust local standards and thorough pre-construction testing in variable environments like Shiraz. From a broader perspective, this study offers a deep understanding that aligns with recent research in concrete technology. It reinforces the principle that durability begins at the material selection stage, not during or after construction. Engineers and project managers must internalize this concept: durable infrastructure is born from informed choices, not assumptions. By systematically evaluating water chemistry and aggregate gradation, and adapting to local material availability, practitioners can create concrete mixes that don't merely meet minimum standards but excel under demanding conditions. This approach ensures that hydraulic structures will not just survive but perform reliably across decades, withstanding the environmental pressures that inevitably accompany water-based infrastructure.

References

Arafa, M., Shihada, S. M., & Karmout, M. (2010). Mechanical properties of ultra high-performance concrete produced in the Gaza Strip. *Asian Journal of Materials Science, 2,* 1–12.

ASTM International. (1959). *Determine the compressive strength of cylindrical concrete samples (ASTM C39).* American Society for Testing and Materials.

ASTM International. (1959). *Methods of treating concrete samples (ASTM C31).* American Society for Testing and Materials.

ASTM International. (1959). *Test methods for chemical analysis of hydraulic cement (ASTM C114).* American Society for Testing and Materials.

ASTM International. (1959). *The effect of water-reducing additives and concrete setting control.* American Society for Testing and Materials.

ASTM International. (1962). *Chemical admixtures for concrete.* American Society for Testing and Materials.

ASTM International. (2020). *Standard test methods for chemical analysis of hydraulic cement (ASTM C114).* ASTM International.

Family, H., & Shah Nazari, M. R. (2020). *Getting to know concrete.* Tehran: Ain al-Qadah, Iran University of Science and Technology. [In Persian]

Farooq, F., Akbar, A., Khushnood, R. A., Muhammad, W. L. B., Rehman, S. K. U., & Javed, M. F. (2020). Experimental investigation of hybrid carbon nanotubes and graphite nanoplatelets on rheology, shrinkage, mechanical, and microstructure of SCCM. *Materials, 13*(1), 230. https://doi.org/10.3390/ma13010230

Han, Q., Gui, C., Xu, J., & Lacidogna, G. (2019). A generalized method to predict the compressive strength of high-performance concrete by improved random forest algorithm. *Construction and Building Materials, 226,* 734–742. https://doi.org/10.1016/j.conbuildmat.2019.07.315

Hewlett, P. C., & Liska, M. (2019). *Lea's chemistry of cement and concrete* (5th ed.). Butterworth-Heinemann.

Keshavarz, Z., & Torkian, H. (2018). Application of ANN and ANFIS models in determining compressive strength of concrete. *Journal of Soft Computing in Civil Engineering, 2*(1), 62–70. http://www.jsoftcivil.com/ [In Persian]

Kosmatka, S. H., Kerkhoff, B., & Panarese, W. C. (2002). *Design and control of concrete mixtures* (14th ed.). Portland Cement Association.

Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, properties, and materials* (4th ed.). McGraw-Hill Education.

Mehta, P. K., & Monteiro, P. J. M. (2017). *Concrete: Microstructure, properties, and materials* (4th ed.). McGraw-Hill Education.

Mindess, S., Young, J. F., & Darwin, D. (2003). *Concrete* (2nd ed.). Prentice Hall.

Neville, A. M. (2011). *Properties of concrete* (5th ed.). Pearson Education.

Ramazanianpour, A. A. (2015). *Cement and concrete science.* Tehran: Amirkabir University Press. [In Persian]

Ramazanianpour, A. A. (2017). *Special concretes for special conditions.* Tehran: Amirkabir University of Technology. [In Persian]

Ramazanianpour, A. A., & Arabi, N. (2018). *Concrete technology.* Tehran: Mogarande Danesh. [In Persian]

Taylor, H. F. W. (1997). *Cement chemistry* (2nd ed.). Thomas Telford Publishing.

Tedin, M., Mohajeri, P., & Shabanian, M. R. (2014). The relationship between the strength of concrete and different cements in Iran. *Proceedings of the First National Conference of Concrete Industry*, Kerman, International Center for Advanced Science and Technology and Environmental Sciences. [In Persian]

Yeh, I. C. (1998). Modeling of strength of high-performance concrete using artificial neural networks. *Cement and Concrete Research, 28*(12), 1797–1808.

Zia, P., Leming, M. L., & Ahmad, S. H. (1991). *High performance concrete: A state-of-the-art report (SHRP-C/FR-91-103).* North Carolina State University.