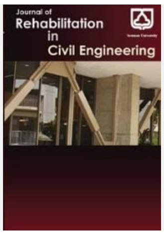

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Evaluating Aggregate Quality of Lorestan Province to Enhance the Mechanical Properties of Concrete Mix Designs

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ABSTRACT

This study investigates the influence of aggregate quality on the mechanical properties of concrete samples, utilizing a comprehensive analysis of aggregates sourced from 46 different batching plants across Lorestan Province. The quality assessment of these aggregates was conducted through several tests, including the sand equivalent test, sieve analysis, fineness modulus, and flakiness index. Following this initial evaluation, compressive strength tests were performed on a range of mix designs to identify the most suitable aggregate type for further experimentation. Subsequently, eigth optimized mix designs were developed, encompassing normal concrete, self-compacting concrete, and high-performance cementitious concrete reinforced with steel fibers. The mechanical properties of these selected mix designs were thoroughly evaluated, focusing on compressive strength, splitting tensile strength, and flexural strength. Results demonstrated that the high-performance cementitious concrete, particularly those incorporating steel fibers, exhibited superior mechanical properties compared to the other mix designs. This study underscores the critical role of aggregate quality in enhancing the mechanical performance of concrete, providing insights that can inform future concrete mix design practices. Also, the comparison between results shows that adding fibers can increase the flexural and splitting strength of specimens by up to 47% and 43%, respectively.

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1. Introduction

Concrete is one of the most widely used construction materials in the world, primarily due to its adaptability, strength, and durability [1–4]. However, the performance and longevity of concrete structures heavily depend on the quality of the constituent materials used in the concrete mix, particularly the aggregates [5]. Aggregates, which constitute a significant portion of concrete by volume, play a pivotal role in determining both the fresh and hardened properties of concrete. The selection and quality of aggregates are crucial, as they influence compressive strength, workability, durability, and overall performance of concrete [6–8] Consequently, an in-depth understanding of the mechanical properties of aggregates is essential for optimizing concrete mix designs that meet specific engineering requirements. The significance of aggregate quality can be classified into two categories: fresh properties and hardened properties of concrete. Fresh properties refer to the behavior of concrete during mixing, transportation, and placement, where factors such as workability, flow ability, and cohesiveness are critical. An aggregate's shape, texture, size, and grading directly affect the workability of the concrete mix [9]. For instance, angular aggregates may increase interlocking and friction, leading to reduced workability, whereas rounded aggregates can enhance the flow of the mix. Inadequate workability can lead to challenges during the placement and finishing phases, potentially compromising the integrity of the concrete structure [10,11]. Once the concrete has hardened, the quality of aggregates continues to play a decisive role. The mechanical properties of hardened concrete, including compressive strength, tensile strength, and flexural strength, are fundamentally influenced by the type and quality of aggregates used in the mix [12,13]. Poor-quality aggregates can lead to weak points within the concrete matrix, resulting in compromised structural performance and durability [14]. Factors such as the presence of deleterious materials, particle shape, and grading can significantly impact these properties [15–19]. For example, aggregates that contain high levels of clay or organic material can weaken the bond between the cement paste and aggregate particles, diminishing overall concrete strength. Therefore, it is imperative to establish robust aggregate quality assessment protocols that can inform mix design choices. For instance, aggregates with elevated amounts of clay or organic substances can compromise the adhesion between cement paste and aggregate particles, ultimately reducing the strength of the concrete. This highlights the importance of implementing comprehensive protocols for evaluating the quality of aggregates. Such protocols are essential for guiding decisions related to mix design, ensuring that the concrete produced meets the required performance standards. By prioritizing aggregate quality assessments, the construction industry can enhance the durability and longevity of concrete structures, which is critical for long-term safety and stability. Robust quality control measures will contribute significantly to achieving optimal concrete formulations. In light of the importance of aggregate quality, various testing methods have been developed to evaluate the suitability of aggregates for concrete production. Tests such as the sand equivalent test, sieve analysis, fineness modulus, and flakiness index provide critical data regarding the physical and mechanical properties of aggregates. The sand equivalent test assesses the relative proportion of fine dust or clay-like materials, which can adversely affect concrete's performance. Sieve analysis provides insights into particle size distribution, enabling the optimization of aggregate grading to enhance workability and strength. The fineness modulus offers a numerical value that helps evaluate the coarseness or fineness of the aggregate, while the flakiness index indicates the shape and angularity of the particles. Together, these tests can offer a comprehensive picture of the quality of aggregates, guiding engineers and producers in selecting the right materials for their specific applications. The primary objective of this study is to provide a thorough examination of the mechanical properties of various aggregates obtained from 46 batching plants across the Lorestan Province and to assess their influence on the mechanical properties of different concrete mix designs. The process began with a rigorous evaluation of aggregate quality through standard testing methods to identify the most suitable aggregates. After identifying the best aggregate type, we proceeded to design eight mix designs that included normal concrete, self-compacting concrete, and high-performance cementitious concrete enhanced with steel fibers [20–23]. In contemporary building practices, there is an increasing inclination to utilize high-performance concrete owing to its exceptional characteristics and advantages for sustainability [23]. Notably, steel fibers have demonstrated considerable improvements in both tensile and flexural strength of concrete, rendering them a desirable component in advanced cementitious formulations [24–27]. By focusing on the mechanical properties of these optimized mix designs, this study aims to elucidate the relationship between aggregate quality and the resultant concrete performance. Ultimately, the findings of this research are anticipated to contribute valuable insights into the critical role of aggregate quality in concrete production. By highlighting the significance of rigorous aggregate testing and its implications for concrete performance, this study seeks to inform best practices in concrete mix design, ensuring that construction projects achieve optimal strength, durability, and sustainability. The outcomes of this research will be particularly beneficial for engineers and construction professionals striving to improve concrete quality and enhance the longevity of infrastructure in an increasingly demanding built environment.

2. Research significant

The comprehensive analysis of aggregate resources in Lorestan province plays a crucial role in the concrete industry. Aggregates, comprising sand, gravel, and crushed stone, contribute significantly to the mechanical strength and durability of concrete, thus influencing the performance of structures. By systematically documenting the types, locations, and quantities of aggregate plants in Lorestan, this study provides valuable insights into the local supply chain of construction materials. Given the diverse geological features of Lorestan province, including both mountainous regions and riverbeds, understanding the characteristics of naturally occurring aggregates from these distinct sources is essential. The differentiation between mountain-type and river-type aggregates can have substantial implications on the properties of concrete mixes. This research not only identifies the existing aggregate plants but also addresses potential disparities regarding the quality and types of aggregates available. Furthermore, the selection of 46 aggregate plants across ten cities enables a nuanced exploration of regional variations and the availability of resources. This exploration is vital for construction professionals, engineers, and policymakers who are involved in large-scale infrastructure projects. By providing a solid foundation of knowledge regarding local aggregate supplies, the research contributes to informed decision-making in construction practices. Additionally, this work opens avenues for future studies on sustainable aggregate extraction practices and their environmental impact. Thus, this research is not just an inventory of resources but a pivotal step towards optimizing the use of local materials, enhancing concrete performance, and promoting sustainable development in the construction sector in Lorestan province.

3. Aggregate selection procedure

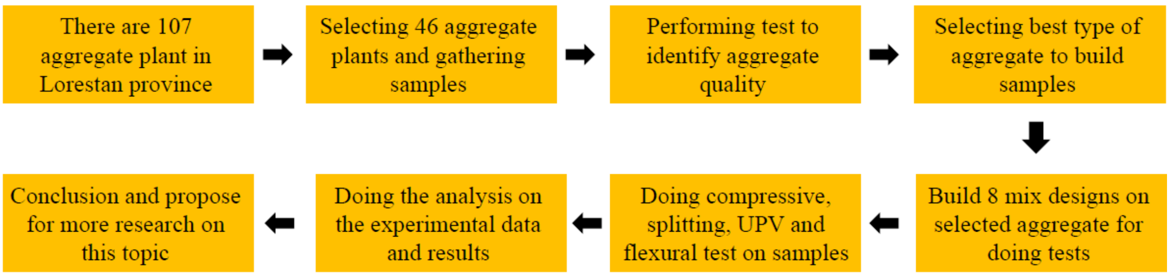
This research utilized a methodical strategy to identify appropriate aggregate materials for concrete manufacturing from an initial pool of 113 aggregate sources found in Lorestan province. To achieve a broad and varied selection of materials, 46 aggregate sources were chosen at random, as detailed in Table 1. This random selection process was designed to capture the diversity of resources available and facilitate a comprehensive analysis of the materials suitable for concrete production (refer to Table 1 for specifics). The goal was to ensure that a wide range of options was considered, reflecting the different characteristics and qualities of the aggregates in the region. By employing this systematic methodology, the study aimed to enhance the relevance and representativeness of the selected aggregates for subsequent evaluations and applications in concrete production contexts. This approach underlines the importance of careful resource selection in optimizing the performance and quality of concrete used in construction. From each of the selected aggregate resources, representative samples of both fine and coarse aggregates were collected. The samples were obtained in accordance with standard protocols to ensure consistency and reliability in the testing process. All samples were securely stored in moisture-proof containers to prevent contamination and degradation prior to testing. A series of laboratory tests were conducted on the collected aggregate samples to characterize their physical properties. These tests included Sand Equivalent test to evaluate the quality of fine aggregates, particularly their cleanliness and the presence of deleterious materials. The sand equivalent value was determined according to ASTM D2419 standards [28]. Also, a comprehensive sieve analysis was conducted to determine the particle size distribution of both fine and coarse aggregates. The aggregates were passed through a series of sieves, and the weight retained on each sieve was measured, allowing for the computation of the grading of the aggregates in accordance with ASTM C136 procedures [29]. Moreover, the fineness modulus of the fine aggregates was calculated as part of the sieve analysis process. This value provided insight into the average size of the particles and was instrumental in assessing the suitability of the fine aggregate for concrete production. Also, the flakiness index was determined to evaluate the shape of the coarse aggregates, contributing to the understanding of their impact on concrete workability and strength. The test followed the methodology as specified in BS 812-105.1 [30]. After the tests, the data were critically analyzed to assess the performance of each aggregate sample. Based on the results, eight superior aggregate types were identified and selected for further application.

Table 1. Selected aggregate resources across Lorestan province.

Number	Index	City	Type	Number	Plant's name	City	Type
1	01BM	Brojerd	Mountain	24	24KR	Khoramabad	River
2	02BR	Brojerd	River	25	25KR	Khoramabad	River
3	03AM	Aleshtar	Mountain	26	26KR	Khoramabad	River
4	04DM	Dorood	Mountain	27	27KR	Khoramabad	River
5	05DR	Dorood	River	28	28AzR	Azna	River
6	06AR	Aleshtar	River	29	29AzR	Azna	River
7	07AR	Aleshtar	River	30	30KM	Khoramabad	Mountain
8	08AM	Aleshtar	Mountain	31	31KM	Khoramabad	Mountain
9	09AM	Aleshtar	Mountain	32	32AlM	Aligodaz	Mountain
10	10DR	Dorood	River	33	33DR	Dorood	River
11	11DR	Dorood	River	34	34DM	Dorood	Mountain
12	12AM	Aleshtar	Mountain	35	35PM	Poldokhtar	Mountain
13	13AzR	Azna	River	36	36KR	Khoramabad	River
14	14AzM	Azna	Mountain	37	37KM	Khoramabad	Mountain
15	15AzM	Azna	Mountain	38	38KR	Khoramabad	River
16	16NM	Norabad	Mountain	39	39NR	Navkesh	River
17	17AlM	Aligodaz	Mountain	40	40CR	Chagalvandi	River
18	18DM	Dorood	Mountain	41	41AR	Aleshtar	River
19	19DR	Dorood	River	42	42AR	Aleshtar	River
20	20KR	Khoramabad	River	43	43PR	Poldokhtar	River
21	21KR	Khoramabad	River	44	44PR	Poldokhtar	River
22	22KM	Khoramabad	Mountain	45	45PM	Poldokhtar	Mountain
23	23KM	Khoramabad	Mountain	46	46KR	Khoramabad	River

a)

b)



c)

Fig. 1. a) steps to preparing aggregate; b) one the selected aggregate plants (Khoramabbad city); c) flowchart of steps.

Table 2. Test results of aggregate resources.

Index	Sand Equivalent	Fineness modulus	Flakiness index	Index	Sand Equivalent	Fineness modulus	Flakiness index
01BM	60	3.3	15	24KR	89	3.4	15
02BR	76	3.5	36	25KR	96	2.9	18
03AM	87	4.6	24	26KR	87	3.7	17
04DM	74	3.4	15	27KR	50	4.4	15
05DR	77	3	26	28AzR	92	4.5	17
06AR	84	3.5	18	29AzR	69	2.2	28
07AR	85	3.7	21	30KM	85	3.1	18
08AM	95	5	31	31KM	91	3.6	15
09AM	70	3.1	15	32AlM	92	3.9	25
10DR	73	3.7	52	33DR	70	3.8	20
11DR	81	3.1	18	34DM	85	4.4	14
12AM	83	4	28	35PM	68	3.6	36
13AzR	70	2.9	13	36KR	92	3.8	26
14AzM	80	3.5	18	37KM	85	4.3	27
15AzM	97	3.9	17	38KR	90	4.2	16
16NM	65	3.7	25	39NR	68	3.4	18
17AlM	87	5.1	17	40CR	76	3	19
18DM	80	4.2	22	41AR	80	3.5	24
19DR	73	3.9	17	42AR	79	3.1	30
20KR	88	3.3	24	43PR	85	2.3	19
21KR	89	3.4	23	44PR	95	2.9	17
22KM	75	3.2	19	45PM	71	4.1	20
23KM	83	3.5	24	46KR	95	3.3	28

The steps involved in preparing the aggregates for testing are illustrated in Fig. 1, which provides an overview of the processes, including the selection of aggregates from local plants. The results of the aggregate testing, including sand equivalent, fineness modulus, and flakiness index, are summarized in Table 2, which provides a comprehensive overview of the quality of the selected aggregates.

4. Concrete mix design

The selected aggregate samples were subsequently utilized to develop eight different concrete mix designs. The concrete types included normal concrete, self-compacting concrete (SCC) and high-performance concrete (HPC). As can be shown in Table 3, each mix design was carefully formulated to optimize the use of the selected aggregates while adhering to established standards for concrete performance. The proportions of cement, water, and any supplementary materials were calculated for each concrete type to achieve target workability, strength, and durability characteristics. Table 3, shows the characteristics of selected mix designs. The used cement in this research was produced by the Dorod factory, specifically Type II, which is a common type of cement widely used in construction projects. The physical properties of the cement were evaluated and found to have a specific gravity of 3.1 g/cm^3, which is within the acceptable range specified by the American Concrete Institute (ACI) Standard 318-14. Additionally, the specific surface area of the cement was measured to be 3000 cm^2/g, which is consistent with the values reported in the ASTM C150 standard [31]. The chemical composition and physical properties of the utilized cement are presented in Table 4 and Table 5 respectively. Table 4 provides a detailed breakdown of the cement's chemical composition, including the percentages of calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and others. Table 5 presents the physical properties of the cement, including its specific gravity, specific surface area, and other relevant characteristics. Moreover, the properties of the steel fiber used are shown in Table 6.

Table 3. Concrete mix compositions.

Number	Index	W/C	Cement (kg)	Corse aggregate (kg)		Fine aggregate (kg)		Silica fume	Nano silica (lit)	Powder (kg)	Steel Fiber (%)
				≤9.5mm	≥9.5mm	≤6mm	≥6mm				
1	NCA	0.54	370	330	560	410	330	40	--	--	--
2	NCB	0.54	370	186	704	316	424	40	--	--	--
3	NCC	0.54	370	259	631	467	273	40	2.67	--	--
4	NCD	0.54	370	195	695	451	289	40	2.67	--	--
5	SCC	0.55	370	195	555	451	269	40	--	78	--
6	HP0.5	0.37	390	195	555	451	269	40	---	78	0.5
7	HP1	0.37	390	195	555	451	269	40	---	78	1
8	HP1.5	0.37	390	195	555	451	269	40	---	78	1.5

Table 4. Cement's chemical composition of Dorod factory.

L.O.I	Cao.f	SO_3	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2
1.05	0.75	2.1	1.75	63.2	4.4	5.1	21.5

Table 5. Cement's physical properties of Dorod factory.

Final time setting (min)	Initial time setting (min)	Longitude Expansion (%)	Blaine (cm^2/gr)
215	130	0.03	3000

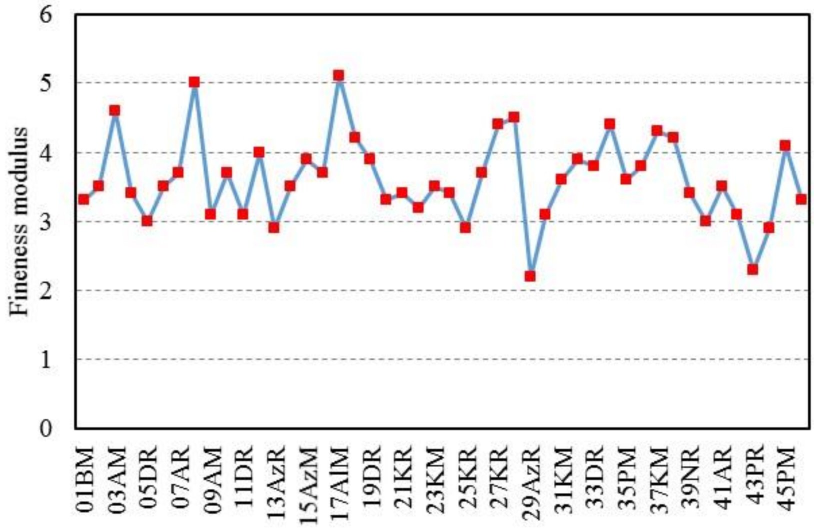
Table 6. Steel fiber properties.

Length (mm)	Diameter (mm)	Yielding stress (MPa)	Density
50	0.8	110	7850

5. Results and discussion

5.1. Aggregate test results

The aggregate testing program assessed several essential parameters that play a significant role in the quality and performance of construction materials. The tests performed included the Sand Equivalent test, fineness modulus, and flakiness index. The outcomes of these tests are illustrated in Fig. 2, which provides a visual summary of the ranges and averages for each of the forty-six chosen aggregates.



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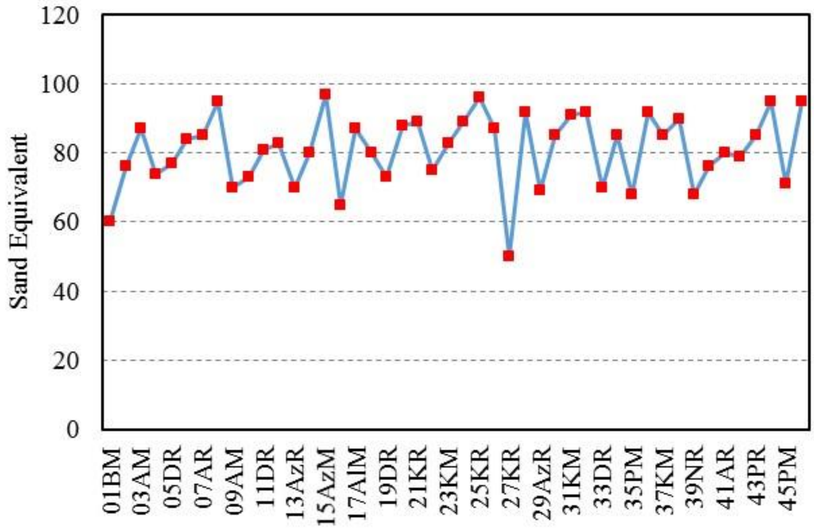

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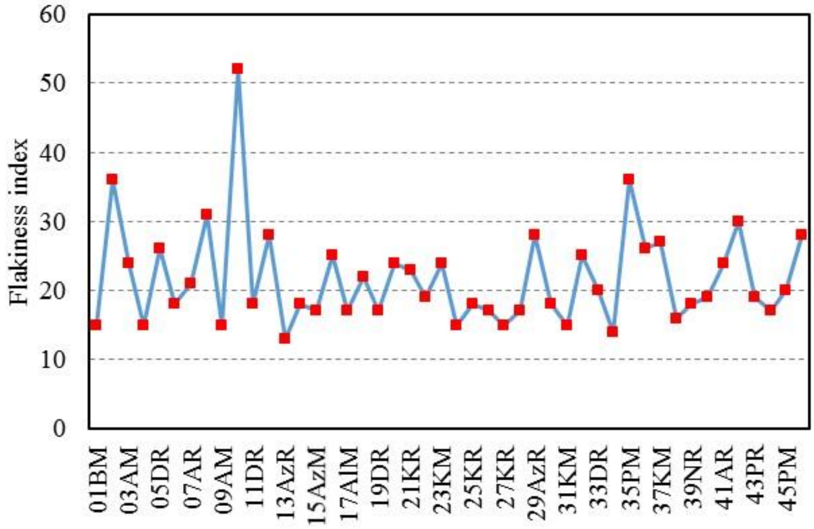

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Fig. 2. a) Fineness modulus; b) sand Equivalent; c) flakiness index.

The fineness modulus (FM) serves as an indicator of an aggregate's coarseness or fineness and is crucial for estimating the necessary cement content in concrete (refer to Fig. 2a). As per industry guidelines, the acceptable fineness mfgodulus values for sand fall between 2.3 and 3.7. Values exceeding 3.1 may suggest a potential increase in cement usage, leading to higher costs. Our analysis revealed that the fineness modulus of the examined aggregates varied from 2.1 to 5.1, with an average value of 3.6. This average lies within the acceptable range as per the guidelines, suggesting that the aggregates are generally appropriate for concrete applications. However, the presence of aggregates with FM values above 3.7 suggests a need for careful consideration during mix design to mitigate the risk of excessive cement consumption. The Sand Equivalent test evaluates the cleanliness of fine aggregates, which is essential for ensuring the durability and longevity of concrete structures. The results of the Sand Equivalent test, displayed in Fig. 2b, indicate that the values for all aggregate samples ranged from 50% to 97%. Reference standards suggest that a Sand Equivalent value of less than 75% is acceptable for concrete use. Notably, thirteen of the forty-six aggregates reviewed fell below this threshold, thereby satisfying the recommendation codes. The overall average Sand Equivalent for the selected aggregates was approximately 80%, which reflects a predominantly satisfactory level of cleanliness. This suggests that the aggregates possess adequate quality, enhancing the anticipated performance of concrete mixes made with them. The flakiness index assesses the shape and size distribution of coarse aggregates, where a higher index indicates more elongated and flat particles that can adversely affect the packing density and strength of concrete. The results, as shown in Fig. 2c, ranged from 13 to 52, with an average flakiness index of 21.8. According to recommended guidelines, an acceptable flakiness index should be less than 30. The results indicate that while the average flakiness index of 21.8 is acceptable, some aggregates display values that exceed this recommendation. This implies a need for caution, as using aggregates with a high flakiness index can lead to reduced workability and increased air voids within concrete mixes, ultimately impacting structural integrity.

5.2. Compressive strength

The compressive strength of concrete is a critical parameter that directly influences its structural performance and longevity. In this part, a series of eight concrete mix designs were evaluated for their compressive strength at four key curing ages: 3, 7, 28, and 90 days. The mixes included standard normal concrete formulations (NCA, NCB, NCC, NCD), self-compacting concrete (SCC), and high-performance concrete with varying percentages of steel fiber (HP0.5, HP1, HP1.5). The results of the compressive strength tests are summarized in Fig. 3. Analysis of the compressive strength data reveals a clear trend and the strength of all mix designs increased with curing age, reaching a maximum at 90 days. Specifically, the average compressive strength at this age was recorded at 59.23 MPa, with the lowest value from the NCA group at 52.33 MPa and the highest noted in the HP1 group at 68.19 MPa. The incremental increases across the different curing times demonstrate the effects of hydration and material properties on the overall strength development of the concrete. Focusing first on the normal concrete groups, it is evident that NCA, NCB, NCC, and NCD demonstrate progressive strength development. At 3 days, the compressive strengths ranged from 16.67 MPa for NCA to 20.33 MPa for NCD. By contrast, at 90 days, NCA exhibited a compressive strength of 52.33 MPa, while NCD reached 56.33 MPa. Notably, NCB and NCC showed a similar upward trend with strengths of 53.67 MPa and 54.67 MPa at the same age, respectively. This comparative analysis highlights that while all normal concrete mixes perform adequately, the variations in proportions or aggregates used within NCB and NCC offer slightly enhanced performance over NCA and NCD. The self-compacting concrete showed commendable performance as well, achieving a compressive strength of 59.41 MPa at 90 days. This indicates that the incorporation of self-compacting properties enhances the density and uniformity of the mix, thereby fostering an environment for improved hydration and strength development. The results underscore the advantages of SCC in terms of ease of application and performance, suggesting it is a suitable option for structures requiring high durability. The high-performance concrete (HPC) variants exhibited remarkable strengths, particularly with the increasing percentage of steel fibers. For instance, the HP1 mix delivered a striking compressive strength of 68.19 MPa at 90 days, showcasing the positive impact of incorporating steel fibers. The incremental changes from HP0.5 to HP1.5, with compressive strengths of 64.10 MPa and 65.17 MPa, respectively, support the notion that certain fiber contents significantly enhance tensile strength and crack resistance in concrete. HP1 demonstrated the most optimal performance, suggesting a critical balance between fiber content and overall structural integrity. Furthermore, the compressive strength data illustrates that the enhancement in strength provided by high-performance concrete mixes can be attributed to enhanced bond characteristics and reduced porosity, leading to lower permeability of the material. This is crucial in applications that demand high durability and resistance to environmental factors [32,33].

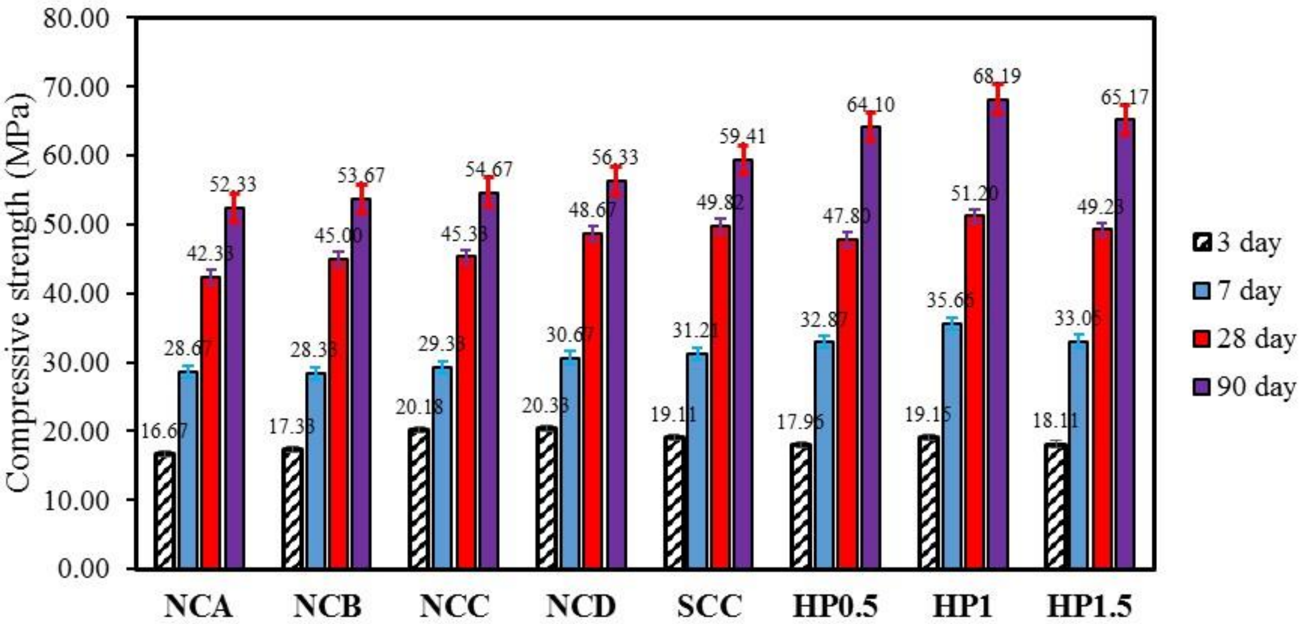


Fig. 3. Compressive strength of all groups.

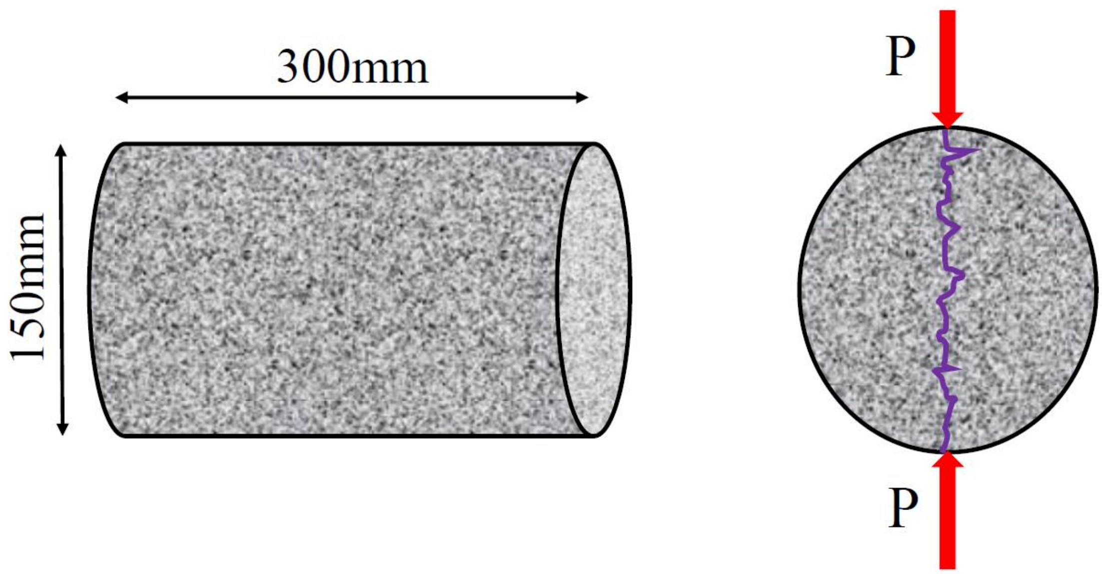


Fig. 4. Splitting tensile strength test setup.

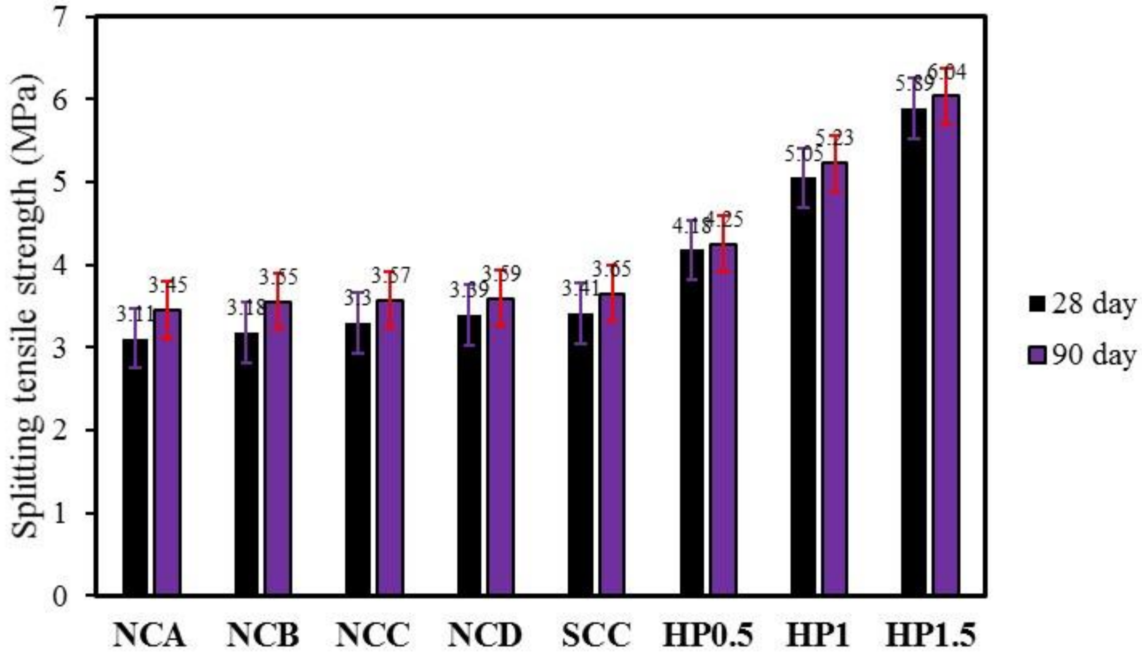


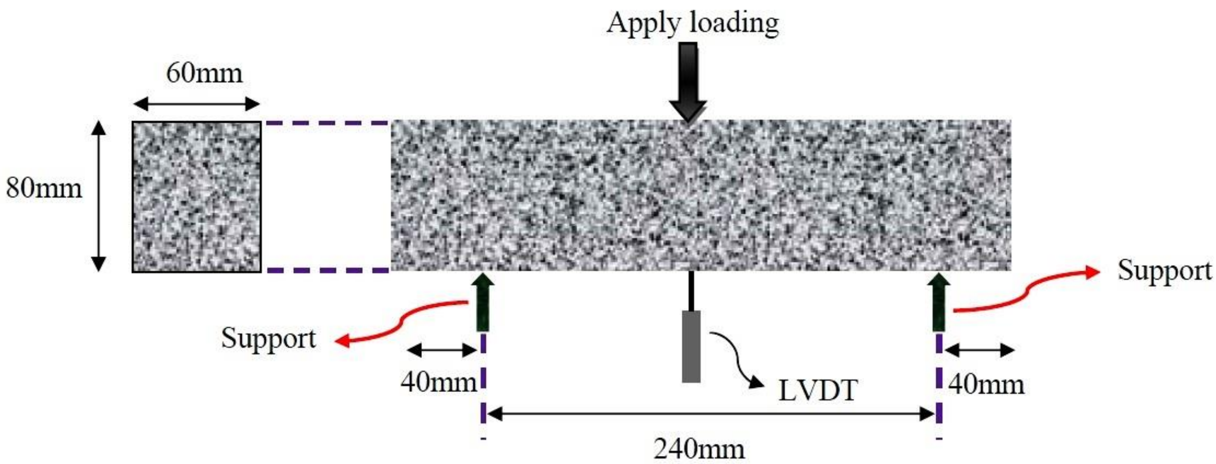
Fig. 5. Splitting tensile strength of all specimens.

5.3. Tensile strength

The aim of this study was to assess the splitting tensile strength of eight different concrete mix designs, including normal concrete, self-compacting concrete, and high-performance concrete with varying percentages of steel fiber. The splitting tensile strength tests were conducted in accordance with ASTM C 496 (see Fig. 4) at the ages of 28 days and 90 days to provide a comprehensive view of the performance of each mix design over time [34]. The results are summarized in Fig. 5. The average splitting tensile strength at 28 days for normal concrete and self-compacting concrete (SCC) ranged from 3.11 MPa to 3.41 MPa, highlighting a relatively consistent performance across these mix designs. At 90 days, the average values exhibited slight improvements, with strengths ranging from 3.45 MPa for NCA to 3.65 MPa for SCC. These values correspond with the expected behavior of normal and self-compacting concrete, where strength gains are typically lower compared to high-performance mixes. Conversely, the high-performance concrete mixes demonstrated significantly higher splitting tensile strengths. At 28 days, the strength for HP0.5 was recorded at 4.18 MPa, while HP1 and HP1.5 reached 5.05 MPa and 5.89 MPa, respectively. By 90 days, these values increased to 4.25 MPa for HP0.5, 5.23 MPa for HP1, and 6.04 MPa for HP1.5. Notably, the inclusion of steel fibers directly correlated with enhanced tensile strength, with HP1.5 showcasing the highest performance, validating the hypothesis that steel fibers contribute positively to the mechanical properties of concrete. A further comparison highlights that the average splitting tensile strength of mixes incorporating steel fibers was 5.04 MPa at 28 days and 5.17 MPa at 90 days. In contrast, the average for mixes without steel fibers was significantly lower at 3.28 MPa and 3.56 MPa for the same ages. The presence of steel fibers not only augmented tensile strength but also improved the overall durability and crack resistance of the specimens, which is particularly beneficial in applications subject to dynamic loading conditions. Statistical analysis indicates that the difference in splitting tensile strength between the ordinary concrete mixes and the high-performance concrete mixes is substantial. With a minimum recorded strength of 4.16 MPa for the 90-day-old high-performance mixes compared to a maximum of 3.65 MPa for the self-compacting mix, it is evident that the addition of steel fibers dramatically enhances performance. The disparity in strength between the fiber-reinforced and non-fiber-reinforced mixes reinforces the principle that fibers can effectively bridge cracks and improve stress distribution under loading conditions. The splitting tensile strength results demonstrate that the addition of steel fibers significantly enhances the splitting tensile strength of concrete. The high-performance concrete mixtures consistently outperformed the normal and self-compacting concrete mixes, particularly at the 90-day mark, where the effects of maturation and the incorporation of fibers provided marked improvements in mechanical properties. As such, the findings emphasize the importance of mix design in optimizing concrete performance, steering future applications towards the use of engineered fibers to meet increased structural demands. Further research may explore the long-term performance and additional benefits of varying fiber types and configurations to fully realize the potential of fiber-reinforced concrete in construction applications [35]. The incremental tensile strength improvement in high-performance concrete (HPC) mixes containing steel fibers indeed highlights an enhanced stress distribution mechanism. Steel fibers bridge micro-cracks and help to redistribute stresses across the concrete matrix, reducing the likelihood of failure. This leads to improved energy absorption and tougher structural responses under loads. However, a deeper exploration of the microstructural interactions between the fibers and the cement matrix is crucial. Understanding the bond mechanisms at the interface, and how fibers influence the hydration process, pore structure, and overall microstructure, can provide insights into optimizing fiber content and distribution. Investigating these interactions can further enhance the durability and performance of HPC materials with steel fibers, leading to better design and application in structural engineering.

5.4. Flexural strength

The flexural strength test results of the eight different concrete mix designs are pivotal in understanding the structural performance of various types of concrete. The flexural test setup according to ASTM C78 [36] is shown in Fig. 6. The flexural strengths of these mixes were assessed at 28 and 90 days of curing, as shown in Fig. 7. The results indicate a clear differentiation in flexural strength across the varying mix designs. The normal concrete mixes exhibited lower flexural strengths, with values ranging from 4.01 MPa for NCB specimen at 28 days to 4.58 MPa for NCD specimen at 90 days. Conversely, the self-compacting concrete mix of SCC performed slightly better, recording flexural strengths of 4.51 MPa at 28 days and 4.71 MPa at 90 days. However, the most notable performance improvement is observed in the high-performance concrete mixes, which displayed a significant increase in flexural strength due to the inclusion of steel fibers. At 28 days, the HP0.5, HP1, and HP1.5 mixes were presented flexural strengths of 5.12 MPa, 5.91 MPa, and 7.41 MPa, respectively, with corresponding 90-day strengths of 5.43 MPa, 6.29 MPa, and 7.75 MPa. The increase in flexural strength from 28 to 90 days across all mixes demonstrates ongoing hydration and strengthening processes. The HP1.5 mix was achieved the highest flexural strength at both testing intervals, highlighting the effectiveness of incorporating a higher percentage of steel fibers.The comparison between steel-fiber reinforced concrete and conventional mixes illustrates the substantial impact of fibers on flexural performance. The average flexural strength for the conventional concrete mixes without fiber was 4.23 MPa at 28 days and 4.45 MPa at 90 days. In contrast, the average flexural strength for the fiber-reinforced mixes was considerably higher, at 6.15 MPa and 6.49 MPa for the respective ages. This is approximately a 45% increase in flexural strength attributable to steel fiber incorporation, confirming the hypothesis that steel fibers effectively enhance the mechanical properties of concrete. Further, analyzing the relative performance of the mixed designs reveals that the introduction of steel fibers not only augmented the flexural strength but also contributed to improved ductility and energy absorption capacity of the concrete, especially under loading conditions where cracks might initiate. This characteristic is particularly advantageous in structures subjected to dynamic or impact loads. Moreover, in terms of the ageing effects observed in the flexural strength results, a consistent trend of increased strength between the 28-day and 90-day tests was noted across all mixes. This suggests that longer curing periods facilitate increased hydration and bond development within the cement matrix, thus enhancing overall structural integrity. However, the growth rate of strength varied among the mixes; notably, the high-performance mixes exhibited a more significant leap in strength than the normal and self-compacting concrete.



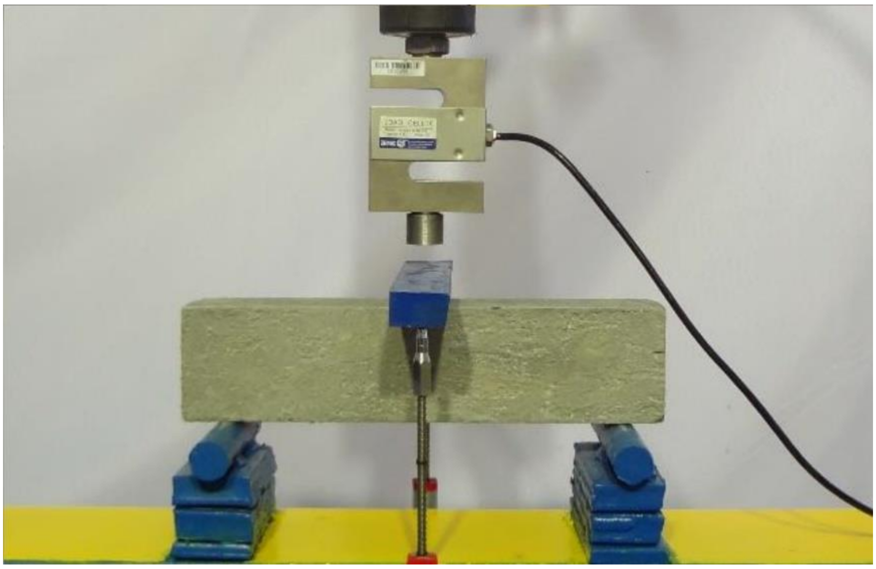


Fig. 6. Flexural strength test setup.

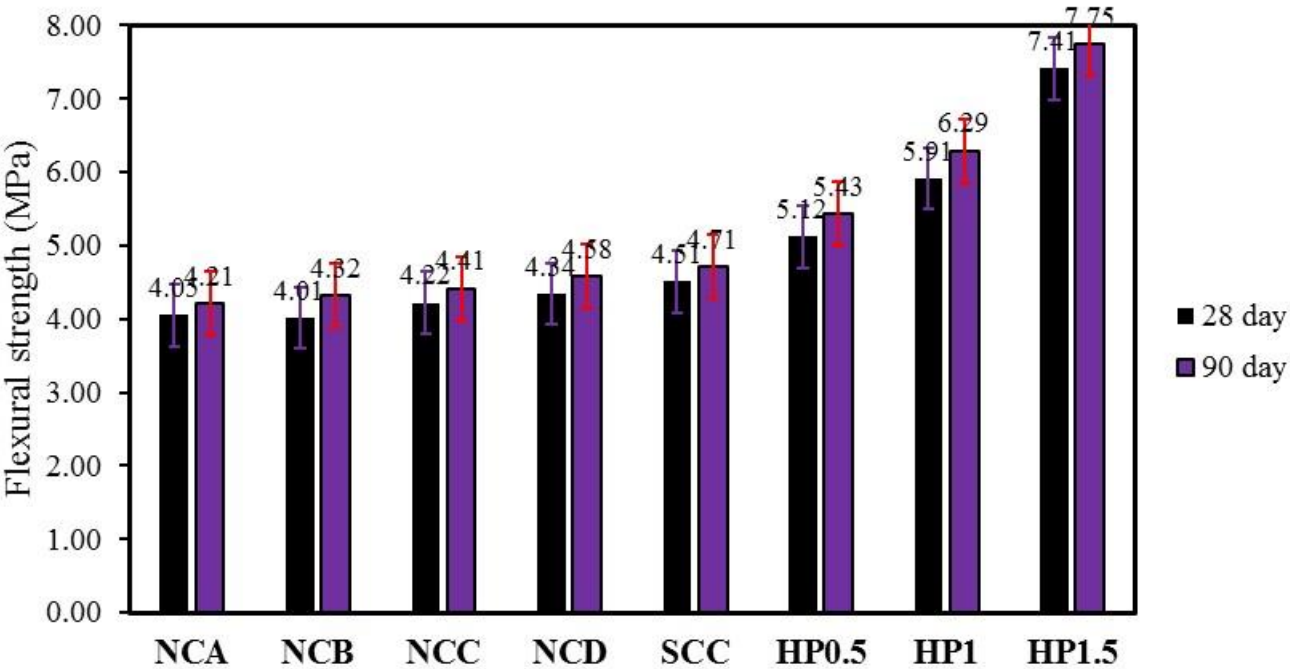


Fig. 7. Flexural strength test results for all groups.

This could be attributed to the optimized material properties and the role of steel fibers in reducing micro-crack propagation throughout the concrete. The flexural results suggest that the use of steel fibers in concrete mix design can lead to substantial improvements in flexural strength and overall performance, warranting further exploration and potential applications in structural elements. Additionally, the conducted flexural strength tests reveal distinct advantages of high-performance and self-compacting concrete mixes over conventional options, particularly when enhanced with steel fibers [37–39].

5.5. Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) tests are used to assess the quality and integrity of concrete structures. This non-destructive method measures the speed of ultrasonic waves passing through the concrete, providing insights into its density and homogeneity. Faster velocities typically indicate better quality, while slower velocities may suggest issues such as cracks or voids within the material [40–42]. The assessment of the UPV test is a vital tool for evaluating the quality and integrity of concrete. The UPV values corresponding to different mix designs conducted at 90 days are presented in Fig. 8, encompassing eight distinct concrete formulations. The results, illustrated in Fig. 8, demonstrate significant variability across the different mix diagrams, affirming the influence of mix composition on concrete's structural properties. The Ultrasonic Pulse Velocity values recorded across the eight mixes indicate a spectrum from the minimum of 5840 m/s (for NCB specimen) to the maximum of 7410 m/s (for HP1 specimen). Such a range in UPV values suggests profound differences in terms of density, void content, and overall microstructural quality of the concrete specimens [43,44]. These findings align with previous literature, which indicates that UPV correlates positively with concrete strength and durability, enabling effective non-destructive evaluation. Also, NCB specimen exhibited the lowest UPV value among all tested samples, which could be indicative of a poor microstructure or a higher volume of voids. This finding underscores the importance of careful mix design in achieving optimal performance characteristics. Conversely, the specimen from the HP1 group, which recorded the highest UPV, showcases the enhanced performance associated with high-performance concrete. The incorporation of optimal proportions of material and additives in HP1 not only contributes to enhanced density but also improves the bonding between the aggregates and the cement matrix, thus facilitating better ultrasonic wave propagation. Moreover, SCC group are particularly noteworthy, achieving a UPV of 7050 m/s, which is indicative of a well-compacted mix due to its self-compacting nature. This supports existing research that highlights the effectiveness of SCC in ensuring uniform density and minimized voids without extensive mechanical compaction.The performance of high-performance concrete mix designs is commendable, with UPV values consistently higher than normal and self-compacting concrete. This is especially clear in the HP1 and HP0.5 mixes, which not only provide a superior UPV but also suggest improved compressive strength qualities attributed to the strategic use of steel fibers. The fibers can improve the concrete's toughness and load-bearing capacities, with the HP1 mix offering a remarkable UPV of 7410 m/s. It reflects the potential gains in structural integrity that can be obtained through high-performance designs. In terms of apparent relationships, as the percentage of steel fiber in the high-performance concrete increases, the corresponding UPV values do not appear to decrease, as one might expect when considering the potential for increased brittleness. Instead, it suggests that well-designed high-performance mixes can retain their integrity and quality even with the addition of fiber reinforcement. This area represents a promising avenue for future research, particularly in optimizing the quantity and types of fibers utilized in high-performance concrete. Furthermore, the UPV results indicate a general trend of increasing velocity with higher-quality mixes, supporting the notion that the compressive strength of concrete can be effectively inferred through UPV assessments. Ultimatums, UPV testing serves as a useful non-destructive technique to predict concrete durability and performance, reinforcing the suitability of the selected mix designs for structural applications.

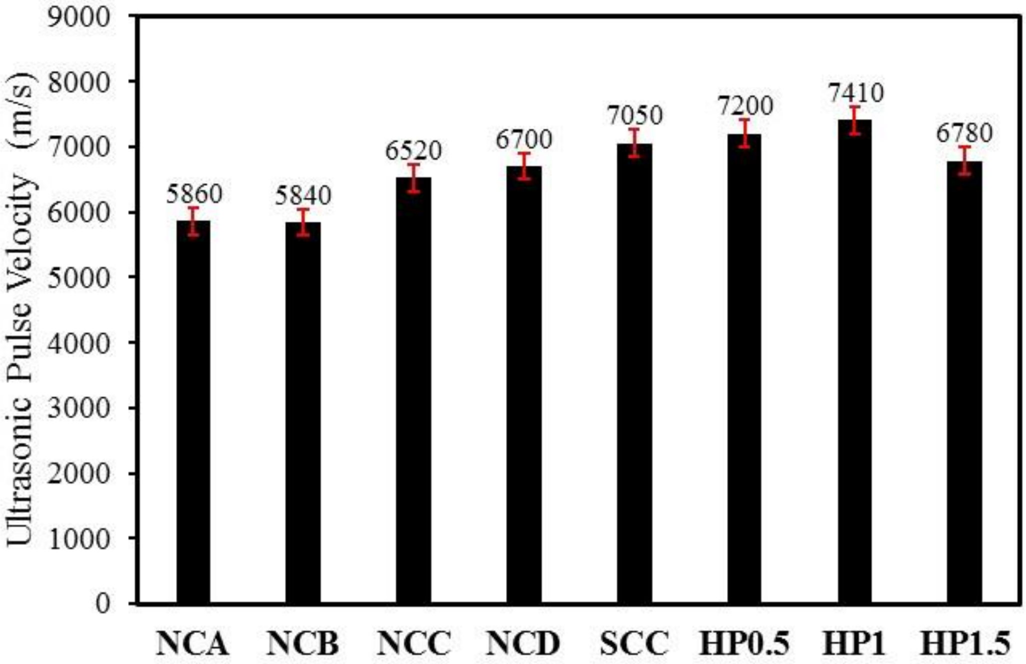


Fig. 8. Ultrasonic pulse velocity results.

6. Conclusion

In conclusion, this research has elucidated the significant effects of various concrete mix designs on the fundamental mechanical properties of concrete, including compressive strength, splitting tensile strength, flexural strength, and ultrasonic pulse velocity. By meticulously examining eight distinct mix designs, and four based on normal concrete (NCA, NCB, NCC, NCD), one self-compacting concrete, and three high-performance concrete designs (HP0.5, HP1, HP1.5). Some of the other conclusions can be as follows:

1- The aggregate testing program assesses essential quality metrics for construction materials, including fineness modulus, sand equivalent, and flakiness index. Of the 46 aggregates tested, the majority conform to industry standards, confirming their suitability for concrete and durability enhancement. However, some aggregates exceed acceptable limits, indicating a need for careful mix design to optimize cement efficiency.

2- The results from the compressive strength tests revealed that conventional concrete mixes exhibited a steady rise in strength. In contrast, self-compacting and high-performance mixes showed much greater strength, with the HP1 mix reaching an impressive maximum of 68.19 MPa.

3- As can be seen from the experimental results, this study demonstrated that the incorporation of steel fibers significantly enhances the splitting tensile strength of concrete. At 90 days, the highest strength recorded was 6.04 MPa for the HP1.5 mix, compared to an average of 3.56 MPa for normal mixes, highlighting the superior performance of high-performance concrete designs.

4- In accord with the result, this study demonstrates that high-performance concrete with varying steel fiber content significantly enhances flexural strength, achieving a peak value of 7.75 MPa at 90 days for the HP1.5 mix. In contrast, normal concrete mixes yielded lower strengths, emphasizing the benefits of incorporating steel fibers in concrete design for improved structural performance.

5- In summary, the results from the Ultrasonic Pulse Velocity test demonstrated that the high-performance concrete reinforced with steel fibers (HP1) reached the maximum velocity of 7410 m/s, indicating exceptional material integrity. On the other hand, the NCB mix recorded the minimum velocity at 5840 m/s, which emphasizes how mix design affects the overall quality of concrete. These outcomes highlight the critical role of choosing suitable combinations to improve structural performance.

6- Future research could explore the long-term effects of different aggregate types on concrete durability under varying environmental conditions. Additionally, comparative studies between the performance of locally sourced aggregates and alternatives could provide insights into optimization. Investigating innovative mix designs that incorporate sustainable materials may also contribute to enhancing concrete properties in Lorestan province.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Ahmad Moradpour: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – original draft.

Hamidreza Babaali: Methodology; Project administration; Resources; Supervision; Validation; Writing – review & editing.

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