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RESEARCH ARTICLE

Design of Air-Entrained Concrete for Airport Pavements Through Local Aggregate Utilization: Performance Optimization and Economic Analysis

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ABSTRACT

Airport pavement construction in developing countries faces critical challenges balancing international performance standards with economic constraints, while limited research exists on optimizing air-entrained concrete mixes using locally sourced materials for cost-effective solutions. This study investigated the development of economical air-entrained concrete mix designs for airport pavements utilizing Pakistani aggregates and systematic cement content optimization. Comprehensive experimental evaluation included material characterization through petrographic analysis, alkali-aggregate reactivity assessment via accelerated mortar bar testing, and mechanical property development across cement contents from 360–450 kg/m³. Air entrainment was achieved through controlled admixture dosing while maintaining target slump of 50mm. Results demonstrated that locally sourced materials achieved flexural strength up to 9.2 MPa at 90 days, more than twice the minimum FAA requirements and significantly exceeding military specifications, while maintaining material costs between \$80.61 to \$88.94 per cubic meter. Accelerated testing confirmed non-reactive aggregates behaviour with 0.099% expansion. However, durability performance was inferred primarily alkali-aggregate reactivity assessment and was not directly validated through freeze-thaw or corrosion resistance testing. The research establishes that international airport pavement standards can be achieved in developing countries through strategic material selection and mix optimization, providing cost-effective infrastructure solutions while challenging assumptions about local material quality limitations in resource-constrained environment.

Keywords: Airport pavement, Air-entrained concrete, Flexural strength, Cost optimization, Alkali-aggregate reactivity, Pakistani aggregates

1. Introduction

Airport pavements represent critical infrastructure components that require substantial capital investments for construction, rehabilitation and long-term maintenance [1]. Modern aviation has experienced unprecedented growth in aircraft frequencies and loading capacities, which have increased the structural demands imposed on runway surfaces [2].

Larger commercial aircraft, including Airbus A-380 and Boeing 747 variants, generate concentrated wheel loads that exceed historical pavement design parameters, thereby necessitating enhanced structural capacity and durability of pavement systems [3]. In response to these escalating demands, contemporary airport construction prioritizes rigid pavement systems constructed with Portland cement concrete, owing to their superior load distribution mechanisms,

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higher structural stiffness, and extended service life compared to flexible asphalt pavements [4].

The structural effectiveness of rigid airport pavements lies in their load transfer mechanism. Unlike flexible systems, rigid pavements distribute aircraft loads through slab action, whereby the concrete surface layer behaves as a beam and transfers loading through flexural resistance to the underlying foundation materials [5]. Consequently, the structural design of airport concrete pavements depends primarily on flexural strength rather than compressive strength, as failure mechanisms typically involve bottom-up cracking under repetitive loading conditions [6]. Reflecting this performance requirement, the Federal Aviation Administration specifies a minimum flexural strength of 4.1 MPa for airport concrete pavements, while military airfield specifications recommend values exceeding 4.5 MPa to accommodate heavier aircraft operations [7].

While structural capacity is fundamental, long-term durability under environmental exposure is equally critical to pavement performance. Air entrainment has become essential for airport concrete pavements subjected to freezing and thawing cycles, as entrained air voids provide internal space to accommodate ice formation and prevent frost-related deterioration [8, 9]. Research has demonstrated that properly designed air-entrained concrete maintains superior durability characteristics while preserving flexural strength properties necessary for structural performance [8, 9]. The optimal air content typically ranges from 3% to 6% for airport applications, depending on aggregate characteristics and exposure conditions [10].

In addition to air entrainment, advancements in chemical admixtures, particularly superplasticizers, have revolutionized concrete mix design by enabling water content reduction while maintaining workability requirements [11]. High-range water-reducing admixtures allow for decreased water-cement ratios, which directly correlate with improved strength and durability characteristics in hardened concrete [3]. Recent investigations into the combined use of air-entraining agents and superplasticizers for airport pavement concrete report enhanced freeze-thaw resistance while maintaining adequate mechanical properties [12].

Beyond admixtures, material selection and aggregate quality significantly influence concrete pavement performance and longevity [13]. Potential durability risks, including alkali-silica reaction and alkali-carbonate reaction require careful material selection characterization and testing [14]. Furthermore, proper aggregate gradation and blending optimize particle packing efficiency, reduce cement

requirements, and improve overall concrete performance characteristics [15]. While advanced materials such as ultra-high-performance concrete (UHPC) formulations have demonstrated compressive strengths exceeding 140 MPa and flexural strengths approaching 25 MPa, their application in airport pavements remains limited by economic considerations particularly in developing regions [4].

Despite extensive research in innovative concrete technology for airport pavement design, significant gaps remain in optimizing mix designs for developing countries where cost constraints and limited access to specialized materials present unique challenges. Limited research has addressed the economic optimization of air-entrained concrete mixes using locally available aggregates from developing regions. Moreover, comprehensive cost-benefit analyses comparing varying cement dosages and admixture combinations for airport pavement applications remain insufficient in the existing literature.

This study addresses these research gaps by developing cost-effective air-entrained concrete mix designs tailored specifically for airport pavement construction using locally sourced materials from Pakistan. The research systematically examines mechanical performance, alkali-aggregate reactivity, and economic feasibility to support sustainable airport infrastructure development in developing countries.

2. Materials and methods

2.1. Cement

Type IV Portland cement conforming to ASTM C150 [16] was selected for this investigation due to its low heat of hydration characteristics and reduced tricalcium aluminate (C_3A) content. The cement was procured from a local Pakistani manufacturing facility and stored in moisture-controlled conditions to prevent hydration prior to testing. Chemical analysis was conducted to verify compliance with ASTM specifications, with particular attention to the total equivalent alkalies ($Na_2O + 0.658K_2O$) content which was maintained below 0.6%. The chemical composition and physical properties were determined and are presented in Table 1 and Table 2.

2.2. Fine aggregate

Lawrencepur sand sourced from the Indus River was used as fine aggregate throughout this study. Petrographic examination was performed according to ASTM C295 [17] to determine mineralogical composition and assess potential alkali-aggregate reactivity, with microscopic analysis conducted

Table 1. Chemical composition of Type-IV cement.

Constituent	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Insoluble Residue	Loss on Ignition
Content (%)	22.09	4.96	4.68	61.76	2.30	1.68	0.76	0.03	0.53	1.72

Table 2. Physical properties of Type-IV cement.

Property	Value	Age/Duration
Fineness (cm ² /g)	3055	–
Standard consistency (%)	24.4	–
Initial setting time (min)	140	–
Final setting time (min)	190	–
Autoclave expansion (%)	0.0215	–
Heat of hydration (kJ/kg)	215	7 days
Heat of hydration (kJ/kg)	260	28 days
Compressive strength (MPa)	16.7	3 days
Compressive strength (MPa)	23.6	7 days
Compressive strength (MPa)	31.8	28 days

under plane-polarized light conditions with 10x scale bar length as shown in Fig. 1. Sand equivalence testing was conducted following ASTM D2419 [18] procedures using standard measuring cylinders and clay reading measurements. Sieve analysis was performed according to ASTM C117 [19] with washing procedures to determine particle size distribution and fineness modulus. The testing procedures and results are documented in Table 3 and Table 4.

2.3. Water

Potable water meeting drinking water standards was utilized for both concrete mixing and curing

operations. Water quality analysis was performed according to BS 3148:1980 [20] specifications to evaluate total alkalinity, chloride content, sulfate content, total dissolved solids, and organic matter content. The test procedures and acceptance criteria are summarized in Table 5.

2.4. Coarse aggregates

Three gradations of crushed stone aggregate were obtained from Sargodha quarry sources (Mountain #116 and #127), comprising size fractions of 5–10mm, 10–20mm, and 20–38mm as shown in Fig. 2. Aggregate blending was performed using proportions of 15% (5–10mm), 50% (10–20mm), and 35% (20–38mm) to optimize particle packing density. Sieve analysis was conducted according to ASTM C33 [21] for each size fraction and the combined gradation, with procedures detailed in Table 6. The combined gradation curve was plotted to verify compliance with specification limits as shown in Fig. 3.

Physical property testing was conducted following standard ASTM procedures. Specific gravity and water absorption were determined according to ASTM C127 [22] using the saturated surface-dry method. Flat and elongated particle analysis was conducted

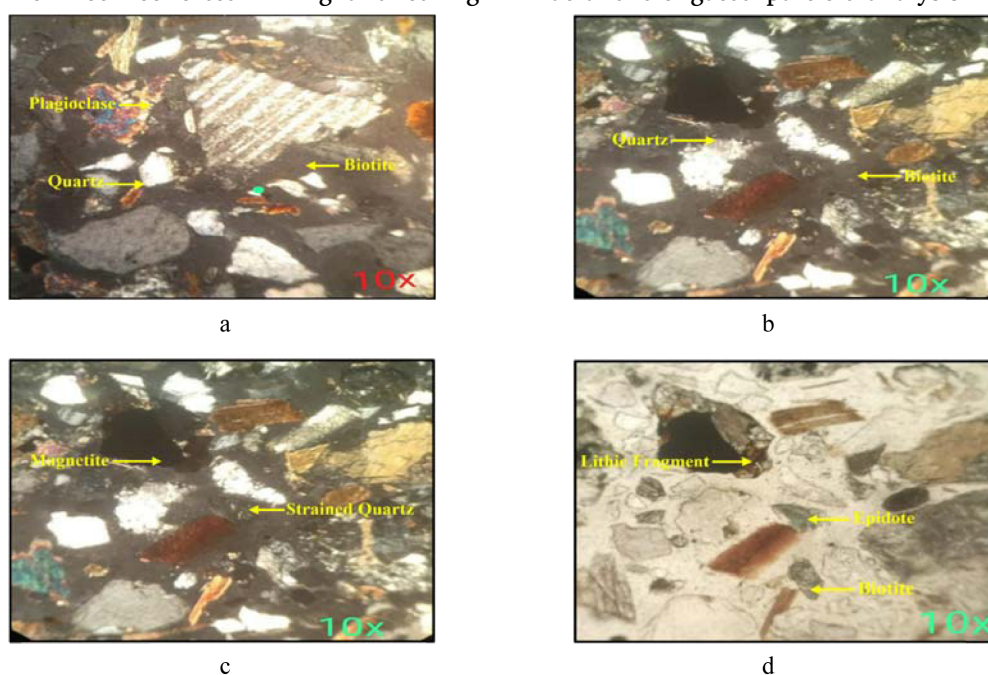


Fig. 1. Petrography test for fine grains in Lawrencepur Sand; (a) Plagioclase and Quartz with Biotite grains, (b) Quartz with Biotite grains, (c) Magnetite grains with strained Quartz, (d) Lithic fragment, Epidote and Biotite grains.

Table 3. Sand equivalence test (ASTM D2419).

Measuring Glass Cylinder Number	Clay Reading H1 cm	Sand Reading H2 cm	ES=H2/H1 *100		Average
			Individual		
1	5.9	4.6	78	78	78%
2	6.2	4.8	77.4	78	
3	6.1	4.7	77	77	

Table 4. Fine aggregates sieve analysis test (ASTM C117).

Initial Wt. of Dry Sample (g)		1450.5	Wt. of Dry Sample after Washing (g)		1412.4
ASTM Sieve	Size (mm)	Cumulative Wt. of Retained (g)	Percent of Retain (%)	Percent of Passing (%)	Specification
3/8 in	9.5	Nil	Nil	100.0	100
#4	4.75	22.8	1.6	98.4	95~100
#8	2.36	80	5.5	94.5	80~100
#16	1.18	282.9	19.5	80.5	50~85
#30	0.60	705.8	48.7	51.3	25~60
#50	0.30	1091.2	75.2	24.8	05~30
#100	0.15	1380	95.1	4.9	00~10
#200	0.075	1412.4	97.4	2.6	00~03
Fineness Modulus				2.456	2.3~3.1
Percentage of Material Passing #200 Sieve $C = [(A-B)/A] \times 100$					
A	Original Dry Wt. of Sample (g)				692.5
B	Dry Wt. of Sample after Washing (g)				674.5
C	% of Material Finer than #200 Sieve by Washing				2.6

Table 5. Water test for concrete mixing (BS 3148:1980).

Parameter	Value Found	BS 3148
Total alkalinity as CaCO ₃	469.8 ppm	≤ 1000 ppm
Chloride	29.7 ppm	≤ 500 ppm
Sulphate	17.2 ppm	≤ 1000 ppm
Total dissolved solids	846.3 ppm	≤ 2000 ppm
Organic matter	97.9 ppm	–

according to ASTM D4791 [23] using proportional calipers. Los Angeles abrasion testing was performed according to ASTM C131 [24] using the standard grading and 500 revolutions. Test results are summarized in Table 7.

2.5. Alkali-aggregate reactivity testing

2.5.1. Accelerated mortar bar test

Accelerated mortar bar testing was conducted according to ASTM C1260 [25] to evaluate potential alkali-silica reaction. Standard mortar bars (25×25×285 mm) were prepared using 1:2.25 cement-to-aggregate ratio with 0.47 water-cement ratio. Specimens were stored at 80°C in 1N NaOH solution with length measurements recorded at 1, 7, 14, and 28 days using a length comparator. Expansion calculations were performed using the standard formula for percentage length change.

2.5.2. Petrographic analysis of coarse aggregates

Petrographic analysis was conducted according to ASTM C295 [17] using thin section preparation

and polarized light microscopy. Modal analysis was performed to determine mineral composition percentages using point counting techniques. Sample preparation involved standard thin section preparation with 30-micron thickness, and examination was conducted using polarized light microscopy at 100x and 400x magnifications under both plane-polarized and cross-polarized light conditions.

2.6. Chemical admixtures

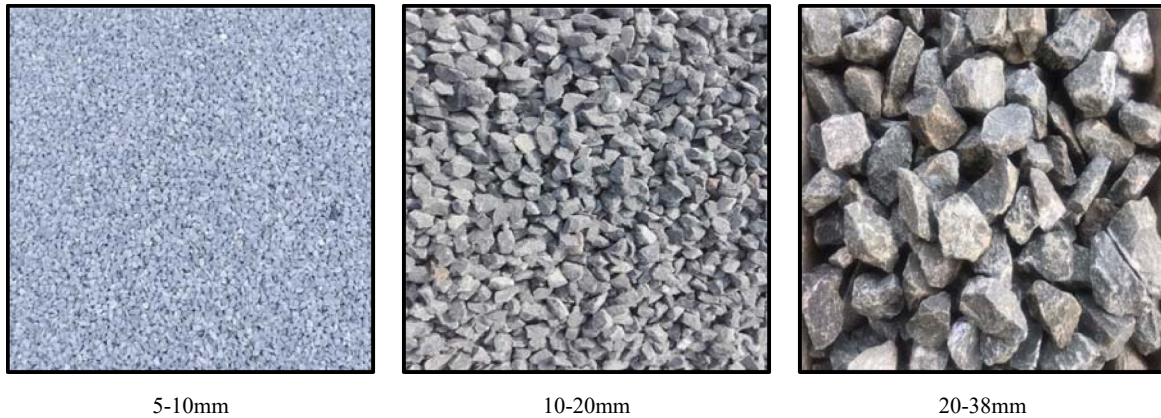
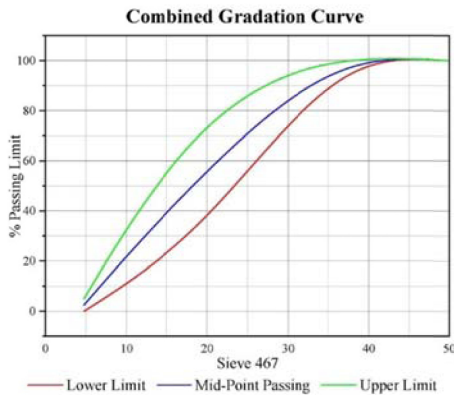
High-range water-reducing admixture (Sikament HRM) conforming to ASTM C494 [26] Type G specifications was incorporated. This dual-action superplasticizer was selected for water reduction capabilities of 12-25% and set retardation properties suitable for hot climate conditions. Dosage rates were established through trial mixing to achieve target slump values. Air-entraining admixture (Sika-Aer) complying with ASTM C260 [27] was added to achieve target air content of 3-6%. Dosage rates of 0.03-0.15% by cement mass were evaluated through systematic testing. Regular air content measurements were performed using the pressure method to ensure consistent entrainment levels.

2.7. Concrete mix design

Mix designs were developed using the absolute volume method for cement contents ranging from 360 to 450 kg/m³. Water-cement ratios were maintained

Table 6. Sieve analysis test for coarse aggregates (ASTM C33).

Blending of Aggregates									
Sr. #	Size of Aggregates (mm)		Sieve Analysis (mm)						
			50	38	25	19	12.50	9.50	4.75
1)	05~10mm		100	100	100	100	100	100	27.8
2)	10~20mm		100	100	100	100	48	25.2	1.3
3)	20~38mm		100	100	58.7	3	0.6	–	–
Combined Gradation									
1)	05~10mm	15%	15	15	15	15	15	15	4.2
2)	10~20mm	50%	50	50	50	50	24	12.6	0.7
3)	20~38mm	35%	35	35	20.5	1.05	0.21	0	0
Total	100 %		100	100	85.5	66.1	39.2	27.6	4.8
Mid-Point			100	97.5	–	52.5	–	20	2.5
Specification Limits			100	95~100	–	35~70	–	10~30	0~5

**Fig. 2.** Various sized coarse aggregates studied.**Fig. 3.** Coarse aggregates combined gradation curve.

through superplasticizer optimization. Target slump was established at 50mm in accordance with ACI 211.1-9.1 [28] recommendations for pavement applications, which specify 25-70mm range for slabs and pavements.

For each cement content, fine aggregate content was calculated to fill remaining volume after coarse aggregate, cement, water, and air. Superplasticizer dosage was adjusted to maintain 50mm slump while

air-entraining admixture was dosed to achieve 3-6% air content. Water content was adjusted based on admixture interactions to maintain workability requirements. The complete mix proportions for 1m³ concrete including material costs are presented in Table 8.

The economic assessment of 1 m³ of concrete was performed based on prevailing local market rates for the year 2026. All costs were initially calculated in Pakistani Rupees (PKR) and subsequently converted into US Dollars (USD) using an exchange rate of 1 USD = 280 PKR. The unit prices of constituent materials and associated production costs were obtained from local suppliers and market surveys. Table 9 summarizes the local market rates (2026) of the materials considered in the cost analysis.

2.8. Specimen preparation and curing

Test specimens were prepared for flexural strength testing using 500mm × 150mm × 150mm beam specimens, while compressive and split tensile strength evaluations utilized ø150mm × 300mm cylindrical specimens. For each mix proportion and testing age,

Table 7. Physical characteristics of coarse aggregates used in this research.

Properties	Size	Standards	Results	Specification Limits
Specific Gravity	5–10 mm	ASTM C127	2.92	–
	10–20 mm		2.93	
	20–38 mm		2.92	
Water Absorption	5–10 mm	ASTM C127	0.51	Max. 2
	10–20 mm		0.38	
	20–38 mm		0.21	
Flat & Elongated Particles	5–10 mm	ASTM D4791	≤5	Max. 10
	10–20 mm		≤5	
	20–38 mm		≤5	
Los Angeles Test	Blended Aggregates	ASTM C131	18.6	Max. 30

Table 8. Mix design proportions for 1m³ concrete with price.

Cement (Kg/m ³)	Sand (Kg/m ³)	Aggregate (Kg/m ³)	Water (Kg/m ³)	Sikament HRM (Kg/m ³)	Sika-AER (Kg/m ³)	Material Cost per m ³
360	784	1197	125	4.71	0.252	\$80.61
365	773	1197	127	4.77	0.256	\$81.05
370	763	1197	130	4.84	0.259	\$81.53
375	753	1197	132	4.91	0.263	\$82.01
380	742	1197	134	4.97	0.266	\$82.45
385	732	1197	137	5.04	0.270	\$82.93
390	721	1197	139	5.10	0.273	\$83.37
395	711	1197	142	5.17	0.277	\$83.85
400	701	1197	144	5.23	0.280	\$84.30
405	690	1197	146	5.30	0.284	\$84.76
410	680	1197	149	5.36	0.287	\$85.23
415	670	1197	151	5.43	0.291	\$85.70
420	659	1197	154	5.49	0.294	\$86.15
425	649	1197	156	5.56	0.298	\$86.62
430	639	1197	158	5.62	0.301	\$87.08
435	628	1197	161	5.69	0.305	\$87.54
440	618	1197	163	5.76	0.308	\$88.01
445	607	1197	166	5.82	0.312	\$88.47
450	597	1197	168	5.89	0.315	\$88.94

Table 9. Local market rates of construction materials (2026).

Material	Unit Rate	Source Basis
Cement	27 PKR/Kg	Local Market Rate
Lawrencepur Sand	6710 PKR/m ³	Supplier Rate
Sargodha Aggregates	6640 PKR/m ³	Supplier Rate
Sika HRM	450 PKR/L	Supplier Rate
Sika-AER	400 PKR/L	Supplier Rate
Water	3 PKR/L	–
Batching Plant Mix	2000 PKR/m ³	Local Market Rate

a minimum of three specimens ($n = 3$) were prepared and tested in accordance with standard practice, and the reported results represent the average values. All specimens were cast in steel moulds and compacted using mechanical vibration with steel rods to ensure proper consolidation without segregation. Initial curing was performed under controlled laboratory conditions with plastic covering for 24 hours to prevent moisture loss during the critical early hydration period. After demoulding, specimens were transferred to water curing tanks maintained at constant temperature until testing ages of 3, 7, 28, and 90 days to evaluate strength development characteristics

over time. Representative photographs of mechanical testing setups are provided in Fig. 4.

2.9. Mechanical testing procedure

Flexural strength tests were conducted according to ASTM C78 [29] using third-point loading on simply supported beam specimens. Loading rate was maintained at 1.0 MPa/min until failure, with maximum load recorded and flexural strength calculated using standard beam theory. Compressive strength tests were performed on cylindrical specimens with loading rate of 0.25 MPa/s, with end preparation including sulphur capping to ensure uniform load distribution throughout the cross-sectional area. Split tensile strength tests were conducted according to ASTM C496 [30] using diametral loading on cylindrical specimens, where loading strips were placed along the specimen length and load applied at constant rate until splitting failure occurred along the loaded diameter. For each mechanical test, three replicate specimens were evaluated and the reported strength values correspond to the mean results.

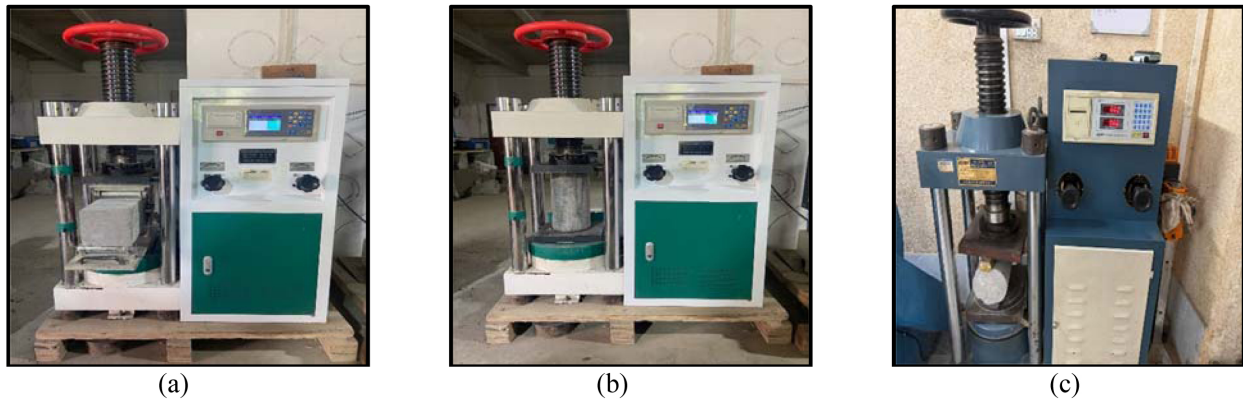


Fig. 4. Testing setup; (a) Flexural strength test (b) Compressive strength test (c) Split tensile strength test.

3. Results and analysis

3.1. Material characterization results

3.1.1. Cement properties

The chemical composition and physical properties of the Type IV cement used in this study are presented in Table 1. The cement exhibited silica content of 22.09% and calcium oxide content of 61.76%, conforming to ASTM C150 requirements for Type IV cement. The total equivalent alkalies content was 0.53%, well below the 0.6% specification limit for low-alkali cement. Physical testing revealed a fineness of 3055 cm²/g, standard consistency of 24.4%, and setting times of 140 and 190 minutes for initial and final set, respectively. Compressive strength development showed values of 2416 psi at 3 days, increasing to 4609 psi at 28 days, which satisfied the minimum requirements for Type IV cement applications.

3.1.2. Fine aggregate characterization

Petrographic examination of Lawrencepur sand revealed a predominantly quartz composition (57%) with subordinate feldspar (14%), amphibole (8%), rock fragments (6%), and biotite (6%), as illustrated in the photomicrographs presented in Fig. 1. The mineral grains exhibited predominantly sub-rounded morphology, indicating moderate transport distance and suitable surface characteristics for cement paste bonding [4]. Sand equivalence testing according to ASTM D2419 indicated an average value of 78%, demonstrating low clay content and minimal plastic fines that could adversely affect concrete workability or strength development. Sieve analysis, confirmed a fineness modulus of 2.456, falling within the acceptable range of 2.3–3.1 for concrete applications. The gradation curve indicated good particle distribution with 2.6% material passing the #200 sieve, meeting ASTM C33 specifications for concrete aggregates.

3.1.3. Water quality test

Water quality analysis performed according to BS 3148:1980 standards confirmed the suitability of the potable water used for concrete mixing and curing operations. As shown in Table 5, total alkalinity measured 469.8 ppm, chloride content was 29.7 ppm, and sulphate content was 17.2 ppm, all values falling well within acceptable limits for concrete production. Total dissolved solids content of 846.3 ppm remained substantially below the 2000 ppm maximum allowable limit, ensuring no adverse effects on cement hydration or concrete durability.

3.1.4. Coarse aggregate properties

The physical characteristics of the blended coarse aggregates from Sargodha quarries are summarized in Table 7. Specific gravity values ranged from 2.92 to 2.93 for all size fractions, indicating consistent mineralogy and density characteristics suitable for structural concrete applications. Water absorption values were consistently low, ranging from 0.21% for the 20–38mm fraction to 0.51% for the 5–10mm fraction, all well below the 2% maximum specification limit. Flat and elongated particle content remained below 5% for all size fractions, ensuring good workability and strength characteristics. The Los Angeles abrasion test result of 18.6% for the blended aggregates demonstrated excellent toughness and resistance to mechanical degradation, comfortably meeting the 30% specification limit for structural applications.

The combined gradation curve presented in Fig. 3 shows that the blended aggregate proportions produced a well-graded material that fell within ASTM C33 specification limits. The aggregate blending strategy successfully achieved optimal particle packing with the mid-point curve closely following the specification band, which contributed to reduced cement paste requirements and improved concrete economy.

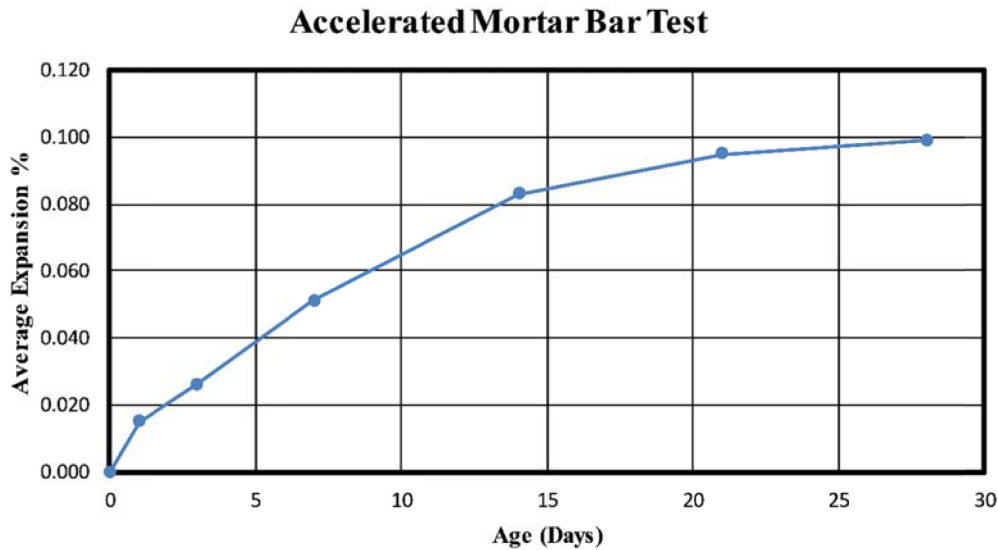


Fig. 5. Accelerated mortar bar test.

3.2. Alkali-aggregate reactivity assessment

3.2.1. Accelerated mortar bar test

The accelerated mortar bar test results are presented in Fig. 5, showing the expansion characteristics of mortar bars prepared with Sargodha aggregates over the 28-day test period. The average expansion at 28 days was 0.099%, falling well within the safe limits established by ASTM C1260 for non-reactive aggregate classification. The expansion curve demonstrated low initial expansion in the first 14 days, followed by minimal additional expansion through 28 days, indicating stable behaviour and low potential for deleterious alkali-silica reaction. These results confirmed that the selected aggregates posed no risk for long-term expansion or deterioration in concrete applications.

3.2.2. Petrographic analysis results

Petrographic examination (scale bar length 10x) of the coarse aggregates revealed the mineral composition presented in Fig. 6 through representative photomicrographs. The modal analysis indicated plagioclase content of 39.4%, followed by chlorite (23%), calcite (21.9%), magnetite/limonite (7.6%), amphibole (2.2%), and quartz (2.1%). The remaining constituents included K-feldspar (1.6%), hydromica/illite (0.9%), epidote (0.9%), and sphene/leucoxene (0.4%). The low quartz content and absence of strained quartz or other potentially reactive silica phases confirmed the non-deleterious nature of these aggregates. The analysis demonstrated that both fine and coarse aggregates could be safely used with ordinary Portland cement and high-alkali cement without risk of alkali-silica or alkali-carbonate reactions.

3.3. Mechanical properties development

Each data point presented in Figs. 7 to 12 represents the average of three specimens ($n = 3$), and corresponding standard deviation values are included in Figs. 8 and 10 and Fig. 12 to indicate experimental variability, which remained within acceptable limits for structural concrete testing.

3.3.1. Flexural strength performance

Flexural strength test results for the various mix designs are presented in Fig. 7, while Fig. 8 shows the corresponding error bars ($\pm$ standard deviation). The strength development at 3, 7, 28, and 90 days for cement contents ranging from 360 to 450 kg/m³. The maximum flexural strength achieved was 8.0 MPa at 28 days and 9.2 MPa at 90 days for the 450 kg/m³ cement content mix, representing significant improvements over the minimum 4.1 MPa requirement specified by FAA guidelines [31] and the 4.5 MPa requirement specified by military standards [32]. The strength development pattern showed consistent improvement with increased cement content, with flexural strength increases averaging 1.04 times from 28 to 90 days across all mix designs.

Analysis of the flexural-to-compressive strength relationship revealed that flexural strength represented 11–23% of compressive strength at 3 days, 14–24% at 7 days, 13–18% at 28 days, and 13–16% at 90 days. These ratios fell within the typical range of 10–15% reported in literature for well-designed concrete mixes, with the higher ratios at early ages reflecting the different hydration kinetics affecting tensile versus compressive strength development.

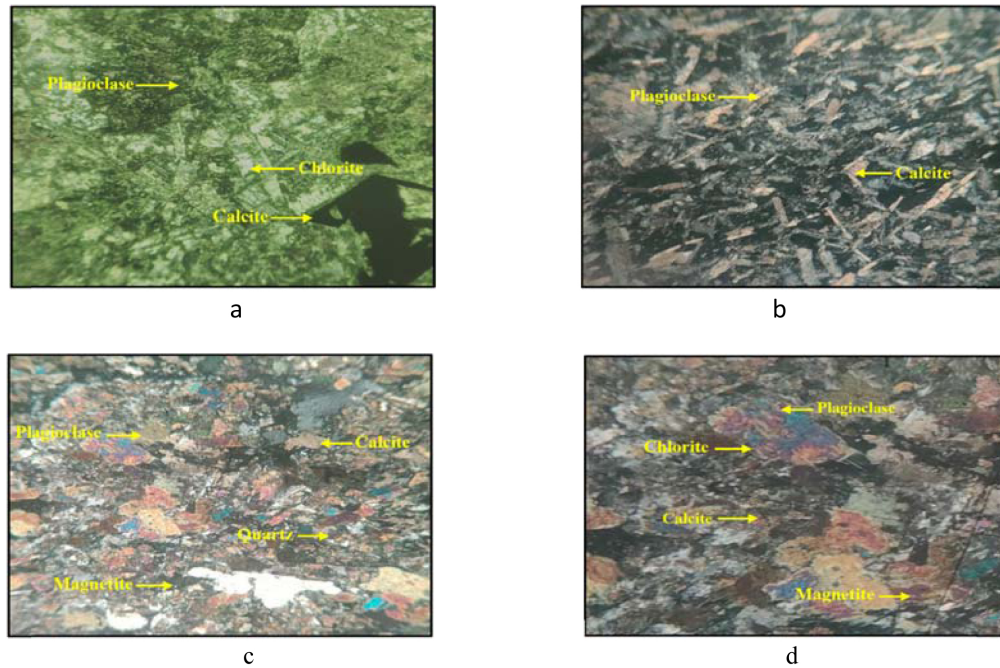


Fig. 6. Petrography test for Sargodha coarse aggregates; (a) Plagioclase with Chlorite and Calcite grains, (b) Plagioclase with Calcite grains, (c) Plagioclase with Chlorite, Calcite, Magnetite and some Quartz grains, (d) Plagioclase with Chlorite, Calcite, and Magnetite grains.

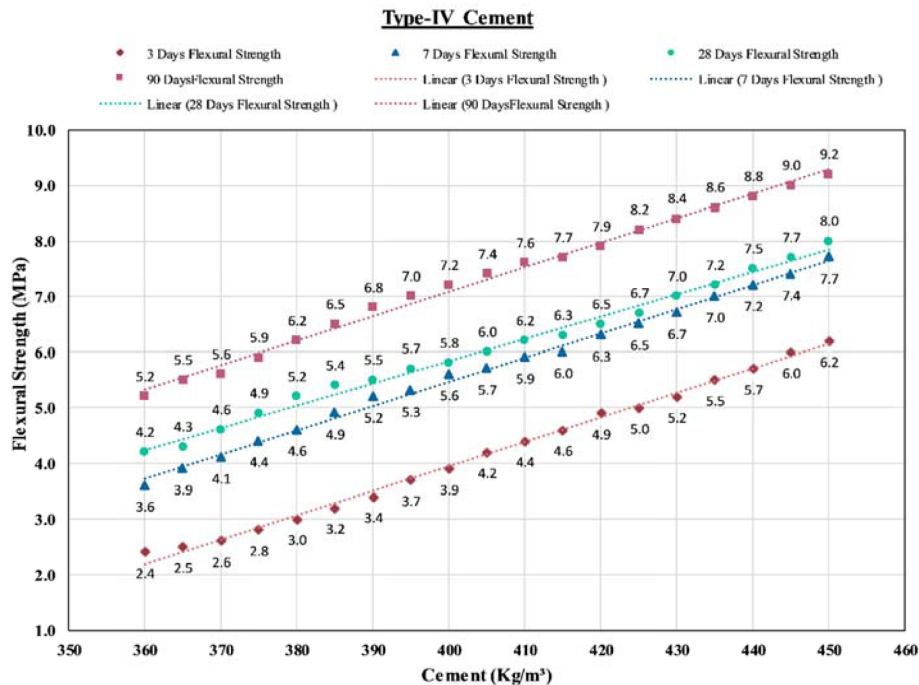


Fig. 7. Flexural strength test results (3, 7, 28 and 90 days).

3.3.2. Compressive strength development

Compressive strength test results for the various mix designs are presented in Fig. 9, while Fig. 10 shows the corresponding error bars ($\pm$ standard deviation).

The minimum compressive strength achieved was 33.4 MPa at 28 days for the 360 kg/m³ cement content, increasing to 45.2 MPa for the 450 kg/m³ mix. At 90 days, compressive strengths ranged from approximately 40 MPa to 57.0 MPa for the same

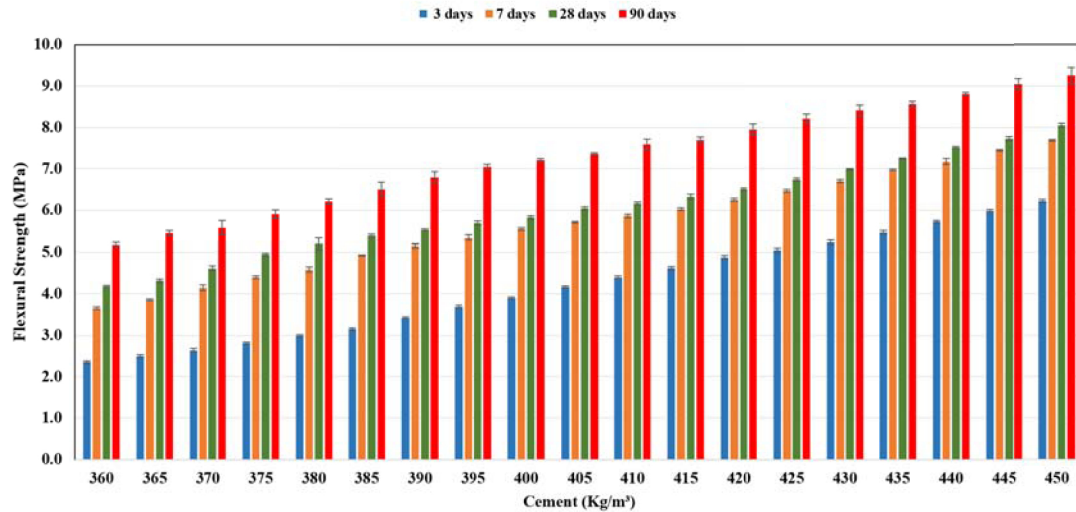


Fig. 8. Flexural strength test results (3, 7, 28 and 90 days) with error bars $\pm$ SD ($n = 3$).

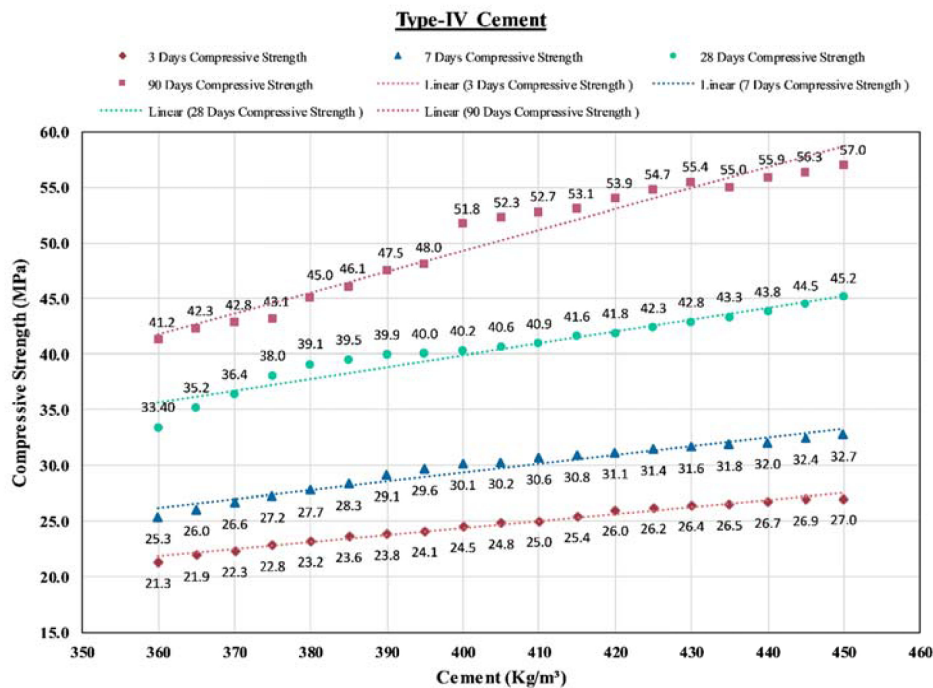


Fig. 9. Compressive strength test results (3, 7, 28 and 90 days).

cement content range. These values exceeded the requirements specified in military guidelines UFC 3-250-01 [32] for heavy-duty pavement applications. The strength gain from 28 to 90 days showed an average increase factor of 1.02, indicating continued hydration and strength development beyond the standard 28-day testing age, which was beneficial for long-term pavement performance.

3.3.3. Split tensile strength characteristics

Split tensile strength test results for the various mix designs are displayed in Fig. 11, while Fig. 12 shows the corresponding error bars ($\pm$ standard deviation).

The minimum split tensile strength of 2.70 MPa was achieved with 360 kg/m³ cement content at 28 days, while the maximum value of 3.90 MPa was obtained with 450 kg/m³ cement content. At 90 days, the maximum split tensile strength reached 5.9 MPa, demonstrating substantial improvement in tensile characteristics with extended curing. The split tensile strength represented approximately 6-8% of compressive strength at 3 days, 9-11% at 7 days, 7-9% at 28 days, and 9-10% at 90 days, which aligned well with established relationships between these properties in high-quality concrete.

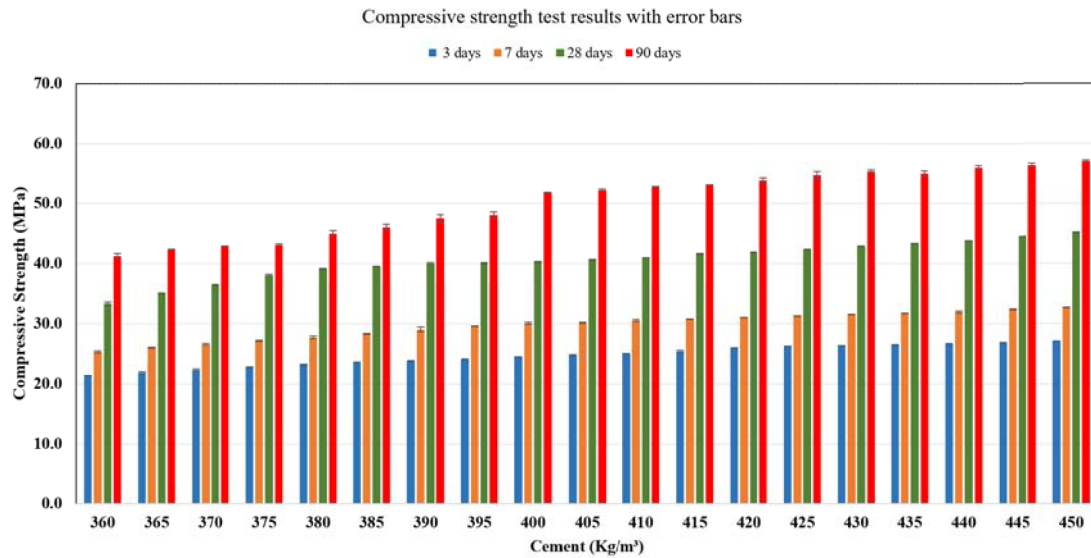


Fig. 10. Compressive strength test results (3, 7, 28 and 90 days) with error bars $\pm$ SD ($n = 3$).

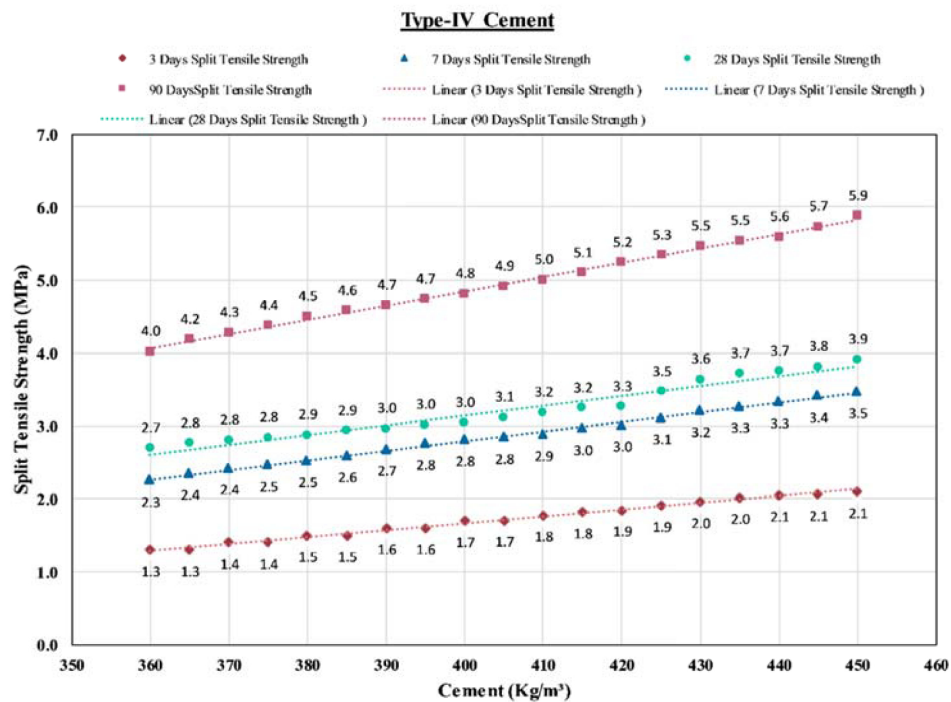


Fig. 11. Split tensile strength test results (3, 7, 28 and 90 days).

3.4. Economic analysis

The cost analysis summarized in Table 8 evaluates the economic feasibility of the developed concrete mixtures using current local market prices (2026). This assessment accounts for both material expenses, batching and transportation, offering a practical estimate of the overall cost for field scale production.

The material cost per cubic meter ranged from \$80.61 for the 360 kg/m³ cement content mix to \$88.94 for the 450 kg/m³ mix, representing an approximate 9.4 % increase in cost relative to the baseline mix (360 kg/m³). However, this increase in cost corresponds to comparatively smaller gains in mechanical performance, particularly beyond 420 kg/m³ cement content.

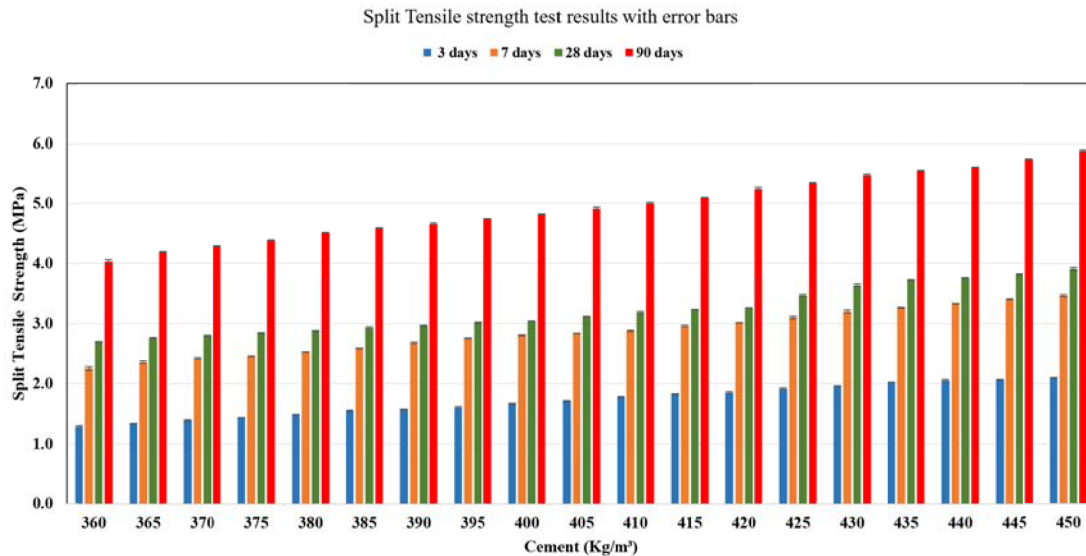


Fig. 12. Split Tensile strength test results (3, 7, 28 and 90 days) with error bars $\pm$ SD ($n = 3$).

The analysis indicates that mixtures within the 400–420 kg/m³ range provide an optimal balance between mechanical performance and economic efficiency. These mix designs achieved flexural strengths exceeding 7.0 MPa at 28 days while maintaining material costs below \$86.25 per cubic meter, making them attractive options for airport pavement projects requiring both structural performance and economic viability.

3.5. Performance optimization discussion

The optimization of air-entrained concrete mixtures for airport pavements was carried out by analysing the relationship between cement content, mechanical performance, and material cost.

The findings show that increasing the cement content leads to improvements in flexural, compressive, and tensile strengths; however, beyond approximately 420 kg/m³, the rate of improvement decreases, indicating diminishing returns in strength relative to cost. This identifies an optimal cement content in the range of 400–420 kg/m³, where adequate structural performance is achieved without excessive material cost.

The dosage of air-entraining admixtures was regulated to maintain an air content between 3–6%, which enhanced workability and potential durability benefits without significantly compromising strength. Furthermore, the use of optimized aggregate gradation improved particle packing efficiency, thereby reducing paste demand and contributing to overall mix efficiency.

It should be noted that, although alkali–aggregate reactivity tests confirmed the aggregates to be non-reactive, durability was not directly assessed through freeze–thaw resistance, or corrosion tests, representing a limitation of this study.

4. Conclusions

This study developed cost-effective air-entrained concrete mixes for airport pavements using locally sourced materials in Pakistan. The conclusions are limited to mechanical performance, alkali–aggregate reactivity, and economic evaluation.

Key findings are as follows:

- Aggregate blending at a 15:50:35 ratio (5–10 mm: 10–20 mm: 20–38 mm) improved packing efficiency and reduced cement demand while maintaining mechanical performance.
- Flexural strength exhibited a nonlinear response to cement content with marginal gains beyond 420 kg/m³, identifying an optimal dosage for cost-effective pavement design.
- Flexural strength increased with cement content; however, marginal gains beyond 420 kg/m³ indicate diminishing returns in relation to cost.
- The optimal cement content range was identified as 400–420 kg/m³ based on performance–cost efficiency.
- Split tensile/compressive strength ratios stabilized at 9–10% at 90 days, supporting indirect tensile estimation for quality control.

- Air-entrainment integration with superplasticizers maintained 3–6% air content without degrading mechanical properties.
- Petrographic and accelerated mortar-bar testing confirmed non-reactive aggregate behavior; however, these results do not fully represent overall durability performance.
- The maximum cost increase (approximately 9.4%) was observed for the 450 kg/m³ relative to the baseline mix (360 kg/m³).
- Finally, 90-day strength results provided more reliable performance indicators than conventional 28-day criteria for airport pavements.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article

Author's contribution

Author #1 Wentao & Li: Conceptualization, investigation, methodology, data analysis, writing original draft

Author #2 Rizwan & Qadir: Investigation, methodology, validation, experiment and result analysis.

Author #3 Arslan & Mushtaq: Mentoring, results analysis, editing of manuscript.

Author #4 Hilal & Khan: Editing of manuscript.

Author #5 Kamran & Gillani: Mentoring

All authors have read and agreed to the published version of the manuscript.

Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article.

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