Emerging Technologies and Engineering Journal

Research Article

Compliance of Cement Concrete Produced Based on Previous Prepared Job-Mix Formula: Case Study

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Article Info

Article History
Received Jan 12, 2025
Revised Feb 23, 2025
Accepted Feb 25, 2025

Keywords

Portland cement concrete
Compressive strength
Ready-mixed concrete
Quality control
Conformity
Compliance

Abstract

The primary focus of construction is on concrete quality control to ensure compliance with manufacturing standards and fulfill its intended purpose. This study investigates the compliance of compressive strength requirements for Portland cement concrete used to manufacture precast New Jersey barriers, based on a previously prepared job-mix formula. The methodology involved selecting 90 cube specimens (150×150×150 mm) and testing them by applying compressive pressure after 28 days of curing. The evaluation methods followed the standards of the British and American Concrete Institute. The study found that the compressive strength of the new concrete mixture complied with the American statistical method, with a 3.4 MPa margin of safety and excellent concrete control. However, according to the British methodology, the initial production period did not meet compressive strength compliance due to only a marginal increase in strength compared to the required value. Nevertheless, the continuous production period satisfied the compliance requirements. The potential to utilize previously prepared job-mix formulas with comparable characteristics depends on the materials meeting the required property standards. There is a cost-benefit advantage due to reduced delays.

1. Introduction

Cement concrete plays an essential role in the construction of buildings, bridges, and cement concrete roads [1, 2]. Cement concrete appears to be a rock material with excellent compression resistance when it hardens. However, it can be shaped to match the required architectural form, making it more popular and attractive [3, 4]. There is a relationship between the compressive strength of concrete and the percentage of water in the mixture, which explains why pressure resistance increases when the water/cement ratio is lower [5, 6]. The lower water content in the concrete mix reduces the workability (mixing, transporting, compaction). However, the growing disparity between high resistance and low workability may solved by utilizing certain water-reducing additives (superplasticizers) [7].

For assessing the quality of concrete, the testing findings are subjected to statistical tests for evaluation [8]. One of the fundamental characteristics that indicate the quality of concrete is compressive strength, which alters from one specimen to another. The mixture's components and weight ratios, the amount of water/cement in the mix, changes in the materials' properties—aggregates being the most significant—the mixing plant's efficiency, the way the materials are stored and exposed to dust and sunlight, the mixing time, the mixer's efficiency, sampling, and compaction, curing, and the testing device's efficiency are some of the many factors that influence the sample results [9].

The main problem of the study is that some cement concrete plants have limited space and have limited aggregate stockpiles. The continuing production of cement concrete frequently results in the depletion of aggregates and cement. The situation necessitates the compensation and reprocessing of depleted materials, usually from different sources, which leads to periodic re-evaluation and redesign of the cement concrete job mix formula. This process takes a long time to test materials and prepare the job-mix formula, leading to delays in work and the cost of design.

The study aims to assess the feasibility of utilizing a previous job-mix formula for concrete mixtures with comparable quality in producing new mixtures to avoid delays and reduce design expenses. The experiments are done on test specimens to assess the outcomes represented by compressive strength conformity.

2. Study Description

A summary of the study assessing the concrete used in pouring a precast New Jersey barrier supplied by one of the ready-mixed concrete plants. According to contract requirements, the required cube compressive strength is 33 MPa for New Jersey. A previous mixing formula (350 kg cement, 790 kg fine aggregates, 1025 kg coarse aggregates, 140 liters of water, 8.75 liters of PC 175 additive) for precast piles with a cube characteristic compressive strength of 33 MPa designed in 2022 AD is adopted for the production of the concrete New Jersey. The same weight quantities of reference mixture ingredients were utilized in the new mixture to produce concrete New Jersey barrier with a change in the supplying source of cement and crushed coarse aggregate. Another type of additive, the superplasticizer PC 200 from DCP company, was used.

The new mixing formula was 350 kg cement, 790 kg fine aggregates, 1025 kg coarse aggregates, 140 liters of water, and 8.75 liters of PC 200 additive. To confirm the necessary 33 MPa compressive strength, 12 concrete cubes measuring 150×150×150 mm in size were prepared as an experimental mixture combined using the new formula ratios. The cubes were tested at 7 and 28 days of age. The test results were 25, 27, 26.5, 29, 30, and 28.4, averaging 27.65 MPa for 7 days of age. The test results were 36, 37.3, 39, 39.5, 35, and 40, averaging 37.8 MPa for 28 days of age. After the required compressive strength of the experimental mixture had been obtained. The production of New Jersey barriers are begin. Twelve 150×150×150 mm cubes for each working day (50 m^3) were prepared; three were tested at seven and twenty-eight days of age, and six were reserve cubes (ignored if the required compressive strength is obtained). For the study, thirty working days with ninety test results (each three cubes representing a working day batch) at 28 days throughout six months were picked randomly. Raw materials were periodically checked to ensure the production process was controlled qualitatively. This study was carried out in Baghdad, the capital of Iraq. Figure 1 shows the New Jersey barrier and cement concrete plant.

(a) Cement concrete plant (b) New Jersey barriers

Figure 1. Cement Concrete plant and New Jersey barriers

3. Materials

The main components of the concrete mixture are sulfate-resistant Portland cement, crushed gravel, sand, and additives. The primary materials were periodically tested for cement four times, aggregates (coarse and fine) five times, and the additive and water used once during the six-month production period.

3.1. Portland Cement

The Lafarge factory in the Bazian city of Sulaymaniyah, Kurdistan, northern Iraq, provided the cement used in the previous reference mixture of unpacked sulfate-resistant cement (LB). In this study, the source that supplied the Portland cement has been altered. The Lafarge factory in Karbala, southern Iraq, provided the unpacked cement (sulfate-resistant) needed to manufacture the concrete New Jersey barrier (LK1, 2, 3, and 4). The physical and chemical test results for the reference and used Portland cement are displayed in Table 1.

Table 1. The physical and chemical test results of cement

Physical properties	**Test method**	**Results**					**Standard limit [10]**
		LK1	**LK2**	**LK3**	**LK4**	**LB**	
Fineness (m^2/kg)	ASTM C786 [11]	381	384	373	376	345	≥ 300
Initial setting time (min)	ASTM C191 [12]	125	120	135	130	141	≥ 45 minutes
Final setting time (h: mm)	ASTM C191 [12]	4:25	4:35	4:20	4:15	3:37	≤ 10 hours
Early compressive strength at 2 days (MPa)	ASTM C109 [13]	21.8	21.1	21.6	22.2	24.9	≥ 20 MPa
Standard compressive strength at 28 days (MPa)	ASTM C109 [13]	45.3	46	46.1	44.9	47.6	≥ 42.5 MPa
Chemical properties	ASTM C114 [14]						
Lime saturation factor		0.94	0.936	0.9	0.935	0.97	0.66-1.02
Sulphate Tri-Oxide (SO_3), %		2.27	2.25	2.21	2.29	2.38	≤ 2.5%
MgO, %		2.31	2.27	2.24	2.17	1.98	≤ 5%
Insoluble residue		0.92	0.85	1.05	0.85	0.56	≤ 1.5%
Tri Calcium Aluminates (C_3A)		2.59	2.87	2.8	2.62	2.36	≤ 3.5%
Loss of ignition (L.O.I)		3.74	3.79	3.7	3.77	3.66	≤ 4%

3.2. Aggregates

The quarries of Al-Sidor and Al-Naba'i are the two main sources of crushed gravel material for several projects in middle and southern Iraq. Natural sand is sourced from the Karbala quarries in southern Iraq for fine aggregates.

Crushed gravel from Al-Naba'i quarries was used in a gradient (5–19) mm for the reference mixture (NQ). In this study, the source for supplying crushed gravel has been altered. Crushed gravel gradation (5-19) from Al-Sidor quarries mm (SQ1, 2, 3, 4, and 5) have been used for manufacturing the New Jersey barrier. The fine aggregate was prepared from the same source as the previous one (reference), the Karbala quarry (KQ1, 2, 3, 4, and 5 for new fine aggregates and KR for reference). Tables 2 and 3 show the physical properties of aggregates.

Table 2. Physical properties of fine aggregates

Test required	**Test method**	**Results**						**Standard limits [15]**
		KQ1	**KQ2**	**KQ3**	**KQ4**	**KQ5**	**KR**	
Gradation\ Sieve size (mm)								
9.5	AASHTO T 27 [16]	100	100	100	100	100	100	100
4.75		95	96	95	96	95	99.3	95-100
1.18		61	63	58	63	61	70.6	45-80
0.3		12	13	15	16	15	26.1	10-30
0.15		3	4	3	4	4	4.2	2-10
Materials finer than 75 µm	AASHTO T11 [17]	2.14	1.92	2.19	1.86	2.48	0.9	≤ 3%
Sulphate expressed as SO_3	BS 1744-1:2012 [18]	0.226	0.37	0.297	0.4	0.305	0.131	≤ 0.5%
Soundness (5 cycles) in Na_2SO_4	AASHTO T104 [19]	4.2	5	5.7	4.8	4.5	1.98	≤ 10%
Fineness modulus	ASTM C125 [20]	3.13	3.02	3.18	2.99	3.07	2.56	-
Bulk specific gravity (S.S.D)	AASHTO T84 [21]	-	-	-	-	-	2.65	-
Water absorption	AASHTO T84 [21]	-	-	-	-	-	1.44	-

Table 3. Physical properties of coarse aggregates

Test required	**Test method**	**Results**						**Standard limits [15]**
		SQ1	**SQ2**	**SQ3**	**SQ4**	**SQ5**	**NQ**	
Gradation\ Sieve size (mm)								
37.5	AASHTO T 27 [16]	100	100	100	100	100	100	100
19		95	96	96	95	95	95.8	95-100
9.5		28	22	26	25	29	25.4	20-55
4.75		2	0	3	1	1	0.8	0-10
Friable particles, %	AASHTO T 112 [22]	0.79	0.54	0.49	0.69	0.58	Nil	≤ 2%
Materials finer than 75 µm	AASHTO T 11 [17]	0.38	0.35	0.36	0.44	0.38	0.04	≤ 1%
Flakiness index, %	ASTM D 4791 [23]	6.2	4.1	3.1	4.7	4.5	8.6	≤ 25%
Elongation index, %	ASTM D 4791 [23]	4.3	3.5	2.2	2.9	3.3	3	≤ 15%
Sulphate expressed as SO3	BS 1744-1:2012 [18]	0.176	0.129	0.112	0.146	0.122	0.092	≤ 0.25%
Los Angeles abrasion, %	AASHTO T96 [24]	23	19	20	22	21	26.4	≤ 35%
Soundness (5 cycles) in Na_2SO_4	AASHTO T104 [21]	1	1.8	1	1.1	1.9	3.14	≤ 12%
Bulk specific gravity (S.S.D)	AASHTO T85 [25]	-	-	-	-	-	2.66	-
Water absorption	AASHTO T85 [25]	-	-	-	-	-	0.52	-

3.3. Water

Freshwater (tap water) has been used in cement concrete manufacturing (N for new mix, R for reference mix). Table 4 shows the water test results.

Table 4. Water test results

Test required	Test results		Limits of standard [26]
	N	R	
SO_4 content, mg\liter	116	281	≤ 2000
Chloride content, mg\liter	11	205	≤ 1000
PH	7.3	-	6-8.5
Inorganic impurities, mg\liter	195	2117	≤ 3000
Bicarbonate	38	-	≤ 1000

3.4. Additives

Additives are common materials incorporated in concrete mixes, which are commonly superplasticizers and permeability-reducing. The reference concrete mixture used the Hyperplast PC 175 superplasticizer additive from DCP Company (Don Construction Products) with 2.50 liters per 100 kg of cementitious materials in the mix. The manufacturer recommends it for use in pile concrete work.

The Hyperplast PC 200 superplasticizer additive from DCP with 2.50 liters per 100 kg of cementitious materials in the mix was used for the concrete mixture of the precast New Jersey barrier. The manufacturer recommends it for use in self-compacting concrete works. It was selected because of the need for a fair face of New Jersey barriers.

4. Methods

For this work, 90 cube specimens size 150×150×150 mm were molded following BS EN 12390-2:2009 [27], curred inside a water bath at room temperature, and tested in 7 and 28 days for compressive strength according to BS EN 12390-3:2009 [28] as shown in Figure 2.

Figure 2. Test method of specimens

Two approaches have been used to assess the concrete production control level by compressive strength at 28 days age: statistical analysis by ACI method [29] and conformity by BS EN 206-1:2000 [30].

4.1. Statistical method according to the American Concrete Institute (ACI) [29]

Analyzing the results to ascertain the concrete's homogeneity, quality, and compliance with standards is the objective of statistical quality control. The data set can be arranged as a normal frequency distribution, with the mean and standard deviation determining its characteristics. The components of the concrete mixture are chosen to ensure the average target compressive strength is equal to the sum of the characteristic compressive strength plus a safety margin, as shown in Equation 1.

$$f_m = f_{cu} + M \tag{1}$$

where: fm = Target compressive strength (average compressive strength for tested specimens), fcu = Characteristics compressive strength (structural design compressive strength), and M= Safety margin.

It is perfectly acceptable if the concrete resistance results correspond to the normal frequency distribution curve. The mean and standard deviation are the two statistical parameters that provide a mathematical definition of the normal distribution [29]. In the case of a confidence level of 95%, the margin of safety is equal to the standard deviation (S) multiplied by the coefficient of probability equal to 1.64, as shown in Figure 3 [31]. Upon substitution into Equation 1, it becomes the form presented in Equation 2.

$$f_m = f_{cu} + 1.64s \tag{2}$$

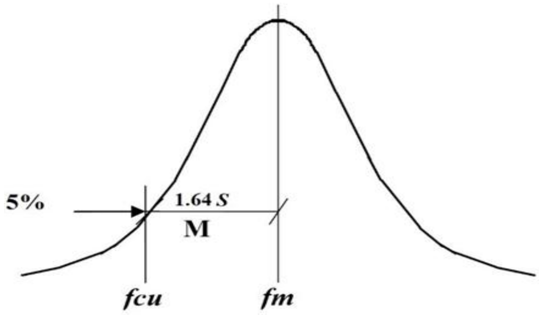

Figure 3. The normal frequency distribution curve of compressive strength [31]

In the lack of statistically valid sample sizes, several other derivative statistics are frequently employed for dispersion estimation or comparing various data sets. The strength level's magnitude has less impact on the coefficient of variance. Consequently, comparing the degree of control throughout a wide range of compressive strengths is more helpful than the standard deviation. The coefficient of variation is often employed when evaluating the variance of test results with mean compressive strengths more than roughly 7 MPa difference [29]. Equation 3 shows the coefficient of variation.

$$V = \frac{S}{f_m} \tag{3}$$

where: V = coefficient of variation, S = Standard deviation, and fm = Average compressive strength for tested specimens.

It is possible to reformulate Equation 2 after substituting the standard deviation in terms of the coefficient of variation, as in Equation 4.

$$f_{cu} = f_m(1 - 1.64\,V) \tag{4}$$

where: fcu= Characteristics compressive strength for assessment that should be not less than the distinctive compressive strength value utilized for the structural design, fm = Average compressive strength for tested specimens, and V = coefficient of variation.

4.2. Compliance Method According to BS EN 206-1:2000 [30]

This methodology is utilized in the context of individual or family concrete production. BS EN 206-1 categorizes conformance for strength into initial and continuous production periods. During the initial manufacturing phase, there is inadequate data to adopt a statistical method for conformance, necessitating the application of set margin criteria. A minimum of 35 test results must be collected throughout the initial production. A continuous period requires at least 35 test results throughout at least three months and no more than twelve months. Two criteria should be satisfied for the mean compressive strength of group overlapping or no overlapping in test results. Table 5 shows the conformity of compressive strength criteria according to BS EN 206-1:2000 [30].

Table 5. Conformity criteria for compressive strength [30]

Production period	Number of specimens in the tested group	Criteria 1 The mean of the tested group f_{cm}	Criteria 2 Individual test result f_{ci}
Initial	3	$\geq f_{ck} + 4$	$\geq f_{ck} - 4$
Continuous	15	$\geq f_{ck} + 1.48\,S$	$\geq f_{ck} - 4$

Notes: fck = Characteristics compressive strength. S = Standard deviation of the population (at least 35 consecutive test results)

5. Results and Discussion

5.1. Statistical Method Results

Following the compilation of results from 90 specimens as illustrated in Table 6. It was statistically analyzed by SPSS software, and it was found that the data followed a normal distribution, as shown in Figure 4.

The mean compressive strength is 36.77 MPa, the maximum is 40.8 MPa, and the minimum is 32.4MPa. The difference between the value of the mean compressive strength and the minimum and maximum value is less than 7 MPa. Therefore, Equation No. 2 is relied on in the evaluation.

Utilizing a standard deviation of 2.08 and a mean compressive strength (fm) of 36.77 MPa in Equation 2 results in the characteristic compressive strength (fcu) of 33.35 MPa, above the minimum required compressive strength of 33 MPa. This data confirms compliance with the quality standards for compressive strength. The margin of safety resulted is 3.4 MPa (1.64×2.08). The standard deviation is 2.08 < 2.8, indicating excellent concrete control for overall- variation, the general construction testing operation class [29].

A normal distribution curve with a 5% percentile offers a compressive strength of 33.1 MPa, which indicates higher than 33 MPa. This result means less than 5% of the 90 outcomes fall below the required compressive strength value of 33 MPa.

Table 6. Compressive strength test results

No	f_{ci}	No	f_{ci}	No	f_{ci}	No	f_{ci}	No	f_{ci}	No	f_{ci}
1	38.9	16	38.6	31	39.5	46	38.7	61	35.1	76	36.3
2	35.8	17	39.8	32	34.2	47	40.2	62	38.1	77	36.2
3	36.7	18	37.4	33	39.7	48	39.8	63	36.5	78	37.4
4	36.7	19	37.4	34	32.6	49	36.4	64	34.1	79	36.9
5	35.2	20	35.2	35	35	50	32.5	65	39.4	80	34.2
6	34.2	21	35.5	36	33.7	51	36.6	66	38.7	81	39.6
7	38.2	22	34.7	37	37.3	52	38.5	67	37.2	82	34.9
8	36.4	23	34.8	38	35.2	53	38.4	68	38.4	83	36.6
9	33.3	24	37.3	39	33.8	54	37.5	69	38.8	84	33.7
10	33.6	25	40.3	40	35.6	55	35.7	70	40.8	85	36.9
11	37.8	26	39.3	41	40.5	56	35.3	71	38.3	86	37.9
12	33.1	27	38.2	42	36.1	57	39.6	72	32.4	87	36.5
13	38.6	28	34.6	43	35.9	58	37.7	73	38.5	88	36.8
14	39.2	29	37.6	44	34.5	59	37.6	74	37.5	89	32.7
15	37.1	30	37.2	45	36.8	60	35.4	75	37.5	90	38.9

Note: fci = Compressive strength of individual specimens (MPa)

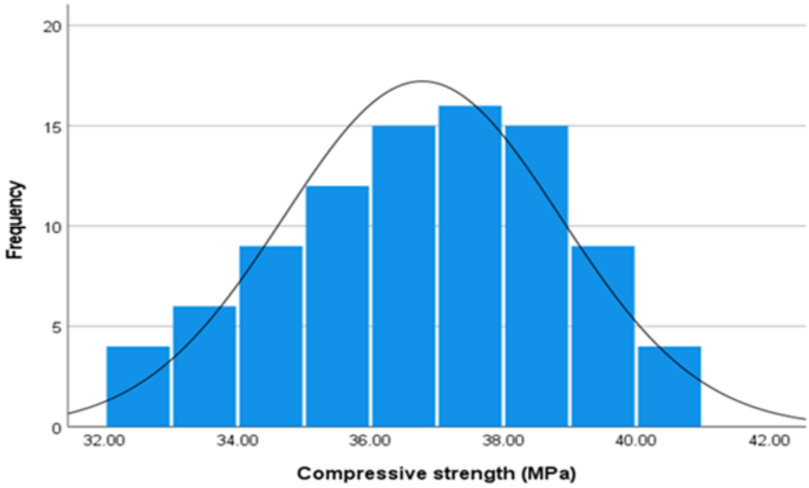

Figure 4. Frequency distribution histogram

Compressive strength variation results from two main sources: test method variation and properties variation, which include properties of materials, proportion of components, type of delivery, and climatic conditions. In this study, the strength variance within the thirty working days was explored due to the partial difference between the materials and the environmental circumstances of the production that lasted 6 months, from the beginning of May to October 2024 AD. The compressive strength listed in Table 6 is for thirty working days, where every three consecutive values represent the compressive strength of three cubes for a batch of a working day. Strength variance between working day batches was verified by examining a one-way analysis of variance test (ANOVA) using SPSS software. The null hypothesis was imposed that there is no statistically significant difference between the daily work batches, and to achieve it, the significant value must be greater than 5% (95% confidence level). The result of the ANOVA test in Table 7 shows that the sig-value of 0.114 is greater than 0.05, indicating acceptance of the null hypothesis, which has no variation in strength between the working day batch. This is an indicator of full oversight during production in the plant during this work period by maintaining the temperature of the mixture below 35 ° C and ensuring the accuracy of the material balances.

Table 7. ANOVA test results

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	159.226	29	5.491	1.447	0.114
Within Groups	227.720	60	3.795		
Total	386.946	89			

5.2. Compliance Method According to BS EN 206-1:2000 Results

Table 8 presents the initial production of the first 36 test results. The conformance depicted is derived from the average of three test results in the group and characteristics of compressive strength (fck) of 33 MPa. The results do not meet the requirements of criterion 1, as the compressive strengths (fcm) of 35.4, 36, 34.8, 36, 35.6, 36.5, and 33.8 are all below 37 MPa (limit of initial period criterion 1 that result from 33+4). However, all individual compressive strengths (fci) are above 29 MPa (result from 33-4), indicating compliance with initial period criterion 2.

Table 8. Conformity of initial production

No	f_{ci}	f_{cm}	No	f_{ci}	f_{cm}	No	f_{ci}	f_{cm}	No	f_{ci}	f_{cm}
1	38.9		10	33.6		19	37.4		28	34.6	
2	35.8		11	37.8		20	35.2		29	37.6	
3	36.7	37.1	12	33.1	34.8	21	35.5	36	30	37.2	36.5
4	36.7		13	38.6		22	34.7		31	39.5	
5	35.2		14	39.2		23	34.8		32	34.2	
6	34.2	35.4	15	37.1	38.3	24	37.3	35.6	33	39.7	37.8
7	38.2		16	38.6		25	40.3		34	32.6	
8	36.4		17	39.8		26	39.3		35	35	
9	33.3	36	18	37.4	38.6	27	38.2	39.3	36	33.7	33.8

Note: fci = Compressive strength of individual specimens (MPa), fcm= average of group compressive strength (MPa)

Following 36 test results assigned during initial production, 54 have been classified as continuous production. The conformity exhibited in Table 9 is generated from 15 test results within the group and 33 MPa characteristics of compressive strength (fck) and a standard deviation of 2.03. Indicators of compliance for criterion 1 are present, as all mean compressive strength values (fcm) exceed 36 MPa (limit of continuous criterion 1 that result from 33+1.48×2.03) and all individual compressive strength values (fci) transcend 29 MPa (result from 33-4), thus satisfying conformance for continuous criterion 2 limit.

Compressive strength satisfies criteria 1 and 2 in Table 5 for the BS EN 206-1:2000 continuous production period because of its high value of compressive strength that has been gathered in the group and low standard deviation due to a large number of specimens in the groups (15 specimens).

The BS EN 206-1:2000 initial period of compressive strength compliance is often more restricted than the BS continuous period and the statistical approach at the lower standard deviation. The BS initial period requires the minimum average compressive strength of the three cube specimens to be equal to or greater than the characteristic compressive strength plus four (safety margin) and individual compressive strength not less than the characteristic compressive strength minus four according to criteria 1 in Table 5, implying that any variation in one of the three specimens requires to compensate by the other two, which results in a significant standard deviation. BS-continuous period and statistical procedures depend totally on standard deviation. For BS-continuous period production, the minimal standard deviation of 2.7 is required for the safety margin to have a minimum of 4. In the statistical method, the minimum standard deviation of 2.44 for the safety margin is a minimum of 4.

Table 9. Conformity of continuous production

No	f_{ci}	f_{cm}	No	f_{ci}	f_{cm}	No	f_{ci}	f_{cm}
1	37.3		19	35.7		37	38.5	
2	35.2		20	35.3		38	37.5	
3	33.8		21	39.6		39	37.5	
4	35.6		22	37.7		40	36.3	
5	40.5		23	37.6		41	36.2	
6	36.1		24	35.4		42	37.4	
7	35.9		25	35.1		43	36.9	
8	34.5		26	38.1		44	34.2	
9	36.8		27	36.5		45	39.6	37.3
10	38.7		28	34.1		46	34.9	
11	40.2		29	39.4		47	36.6	
12	39.8		30	38.7	37.2	48	33.7	
13	36.4		31	37.2		49	36.9	
14	32.5		32	38.4		50	37.9	
15	36.6	36.7	33	38.8		51	36.5	
16	38.5		34	40.8		52	36.8	
17	38.4		35	38.3		53	32.7	
18	37.5		36	32.4		54	38.9	

Note: fci = Compressive strength of individual specimens (MPa), fcm= average of group compressive strength (MPa)

5.3. Cost-Benefit Analysis

The main target of this work is to save design costs and reduce the delay incurred by waiting for the 28-day cube testing. The cost of mixture design for 2024 AD is roughly \$2300 for one mixture design. The materials changed four times; hence, a redesign was necessary four times. The entire cost is 4 × 2300

= $9200. Another expense resulting from the delay is renting the New Jersey molds, which is $1 per mold per day. The total number of rental molds was 50; hence, the cost of delay is 50 × 28 × 4 = $5600. The total benefit was 5600+9200=14800 $ per 6 months.

6. Conclusion

By focusing on the materials utilized, the tests performed on them, the study methods and results, the conclusions can be drawn as follows:

The compressive strength results were altered insignificantly by the tiny variances in the physical raw materials' characteristics that fell within the limits of the standard. It indicates the potential to utilize previously prepared job-mix formula with comparable characteristics or prepare and adopt it at the beginning of the work, with no need for updating when altering raw materials, reliant on the materials that possess properties within the requirement standards. Because of the decrease in delays, there is economic viability. Despite the presence of compressive strength outliers below the required limit, their effect dissipated by the large number of test results that have been simulated of the study population's 90 specimens that gave lowering standard deviation (reduced data dispersion from the arithmetic mean), it resulted in the compliance of compressive strength by the statistical method. Because of the lower or marginally higher compressive strength gathered in the initial period study groups (3 specimens), the initial production criteria did not correspond with the BS EN 206-1:2000.

Declaration of Competing Interest: The author declare that he has no known competing interests.

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