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A Review and Assessment of the Influence of Cement Kiln Dust on Various Mechanical Properties of Concrete

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Abstract

The cement industry remains a crucial sector despite advancements in science and industry. However, cement production generates substantial byproducts, including Cement Kiln Dust (CKD), leading to environmental concerns. This study aims to evaluate the impact of CKD on the mechanical properties of concrete. The investigation includes slump, compressive strength, and flexural strength. The research fills existing knowledge gaps and provides insights into the benefits and limitations of incorporating CKD in concrete mixtures. The results indicate that increasing CKD content reduces slump and workability. Optimal CKD replacement percentages of 15% at seven days and 10% at 28 days yield satisfactory compressive strength.The flexural strength decreases by 5.3% with a 10% cement replacement. Empirical equations based on literature data demonstrate a correlation between CKD content and predicted strength values. These equations are a practical tool for estimating concrete properties with varying CKD percentages. This research contributes to sustainable construction practices by providing insights into CKD utilization and promoting environmentally friendly practices.

Keywords: Cement kiln dust (CKD), Concrete, Mechanical properties, Modeling, statistical analysis.

1. Introduction

Despite the rapid advancements in science and industry, making cement is still one of the most important sectors in many countries. In many different applications, cement is essential. It is primarily used as a binder in concrete for construction projects like dams, buildings, roads, etc. According to statistics from the global cement market, over the past thirteen years, the volume of cement produced worldwide has climbed from 3.31 to more than 4.4 billion metric tons per year (Fig. 1) [1-3].

Conversely, the environmental impact of producing a substantial quantity of cement can be negative due to the emission of byproducts like carbon dioxide and Cement Kiln Dust (CKD). Approximately 15–20% of the cement manufactured is estimated to be produced as CKD [4-7]. This implies that hundreds of millions of metric tons of CKD are generated each year globally in conjunction with cement production [1].

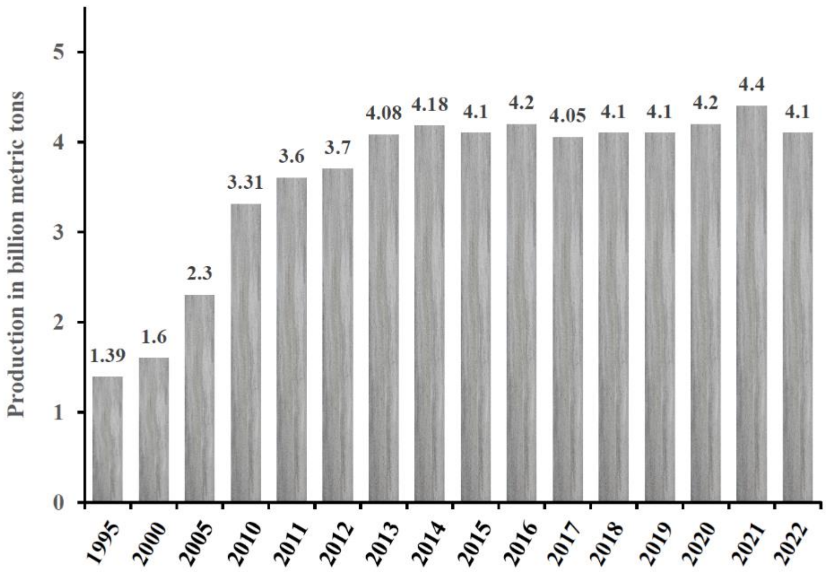

Figure 1. Cement Production Worldwide from 1995 to 2022 [2].

These numbers reflect the enormous amount of by-products the cement industry creates each year, including CKD, which is produced as dust or slurry [8,9]. CKD presents a major environmental risk, particularly in terms of health impacts. Its emission of byproducts like carbon dioxide and cement kiln dust raises serious concerns. Urgent action is needed to address CKD disposal and develop sustainable solutions for its management. By prioritizing CKD reuse and responsible practices, we can enhance construction industry efficiency and sustainability while mitigating environmental impact [10 -12]. However, CKD has a broad range of applications across various areas. When CKD was registered in the REACH (Registration, Evaluation, and Authorization of Chemicals) system in 2011, its classification as a waste product was changed to that of a product, permitting its use on the market [13]. CKD is a solid, fine-grained substance. It is an alkaline product with significant amounts of sodium and potassium chlorides, sulfates, and volatile metal compounds in its chemical composition [14,15]. Despite its negative chemical characteristics and presence in large quantities during cement production, its applicability in modern industry is growing. This is primarily because, with the right processing, it may be successfully applied in various fields. Water treatment, wastewater treatment, waste disposal, soil stabilization, cement replacement in manufacturing mortars and concretes, and asphalt pavements are the most typical uses of CKD [15].

Overall, while CKD presents challenges in terms of its environmental impact, there is ongoing research and development focused on finding sustainable and viable solutions to support the reuse of this waste material. This could improve the overall efficiency and sustainability of the built environment [13]. The composition of CKD is determined by the raw materials utilized for clinker production and the specific type and origins of carbon-based fuel employed for heating the materials within the rotary kiln [6]. Understanding the impact of CKD on concrete is essential for optimizing its utilization and addressing the environmental concerns associated with its disposal. Therefore, this study aims to evaluate the effect of CKD on the mechanical properties of concrete, such as compressive strength, flexural strength, and durability, which are critical factors in assessing the performance and quality of concrete. By examining the influence of CKD on these properties, this research aims to provide insights into the potential benefits and limitations of incorporating CKD in concrete mixtures.

Previous studies have shown conflicting results regarding the effect of CKD on concrete properties, highlighting the need for further investigation and a comprehensive understanding of the subject. The evaluation of the effect of CKD on the mechanical properties of concrete has practical implications for sustainable construction practices. The utilization of CKD in concrete mixtures not only has the potential to reduce waste generation but also offers opportunities for resource conservation and improved environmental performance. In conclusion, understanding the influence of CKD on the mechanical properties of concrete is essential for sustainable construction practices. This study aims to fill the existing knowledge gap by evaluating the effect of CKD on various mechanical properties of concrete, providing valuable insights for the industry and promoting environmentally friendly practices.

2. Literature review

To further explore the influence of CKD on concrete properties, the test data obtained in this study were compared with relevant literature data. Literature review papers on CKD conducted by other researchers were referenced to gather additional insights into the performance of CKD in concrete. The collected data from previous research for concrete compressive and flexural strength were summarized in **Table 1.**

2.1. Compressive Strength

Al-Harthy et al. [9] found that increasing CKD replacement for cement generally leads to a decline in compressive strength, as shown in Fig. 2. The control mixture, without CKD, consistently exhibits the highest strength values across all blends. Mixtures with higher water-to-binder (w/b) ratios of 0.70 show more significant reductions in compressive strength than those with lower ratios of 0.50. Although CKD has lower cementitious properties with less than 10% free lime content (as opposed to more than 60% in Portland cement), optimal replacements of 10% have minimal adverse effects on strength, particularly at low w/b ratios. At a w/b ratio of 0.50, a 5% reduction in 28-day compressive strength was observed, while at a higher w/b ratio of 0.60, the 28-day strength reductions became more pronounced, reaching 18% for 10% CKD replacement.

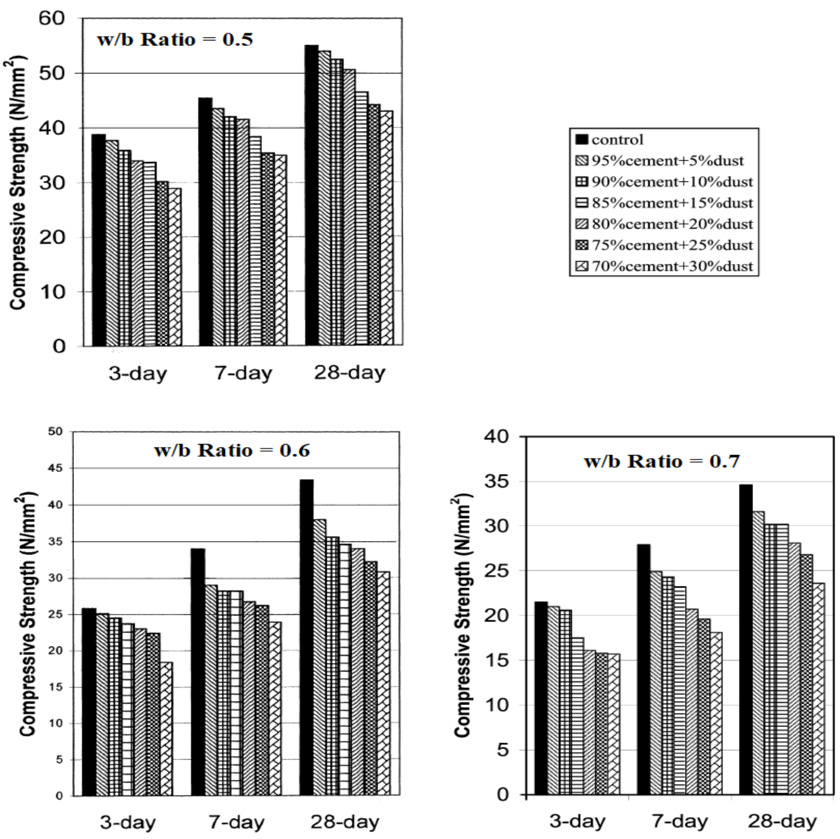

Figure 2. Effect of different w/b ratios on different concrete mix incorporation CKD [9].

The study conducted by Hassan et al. [16] examined the effect of CKD on the compressive strength of concrete by replacing OPC cement with varying percentages of CKD (5%, 10%, 15%, 20%, 25%, and 30% by weight). At the highest CKD replacement of 30%, the 28-day compressive strength decreased by 35%. The optimal CKD content was 10%, resulting in decreases of 4% for 7-day compressive strength and 9% for 28-day compressive strength.

Abdulabbas [17] studied the compressive strength of concrete by replacing cement with CKD at 10% and 20% in two groups using OPC and SRC cement types. At the highest CKD content of 20%, the SRC group experienced a 35% decrease in compressive strength, while the OPC group exhibited a 37% decrease.

Shoaib et al. [18] investigated the compressive strength of concrete by replacing Ordinary Portland Cement (OPC), Blast Furnace Slag Cement (BFSC), and Sulphate Resistance Cement (SRC) with CKD at ratios of 10, 20, 30, and 40% the data illustrated in Fig. 3. The control samples in each group were composed of 350kg of cement, and the w/b was consistently fixed at 0.5. The highest CKD replacement of 40% resulted in compressive strength at 28 days of age decreases of 44, 54, 46, 56, and 37% for OPC, BFSC, and SRC groups, respectively. The lowest CKD content of 10% exhibited a reduction of 15, 16, and 4% for the OPC, BFSC, and SRC groups, respectively.

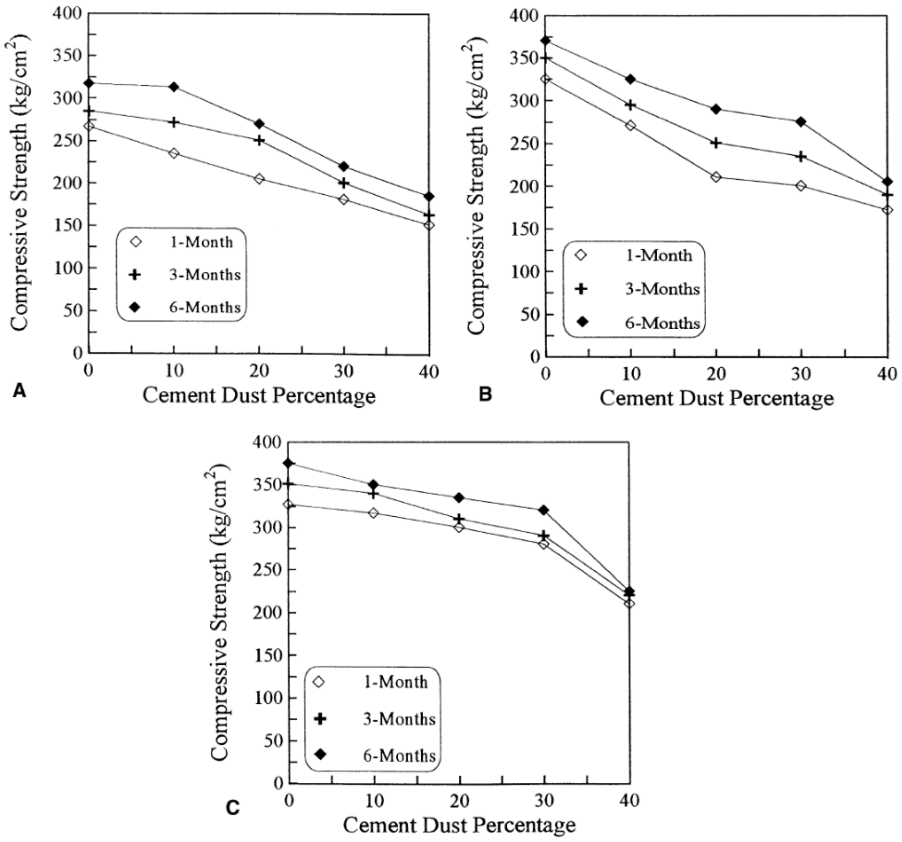

Figure 3. Effect of CKD on compressive strength of concrete for different types of cement: A. CKD with OPC. B. CKD with BFSC. C. CKD with SRC [18].

Maslehuddin et al. [19], as shown in Fig. 4, examined the compressive strength of concrete by replacing type I and type V cement with CKD at ratios of 5, 10, and 15. The 5% replacement ratio for type I cement showed no decrease in compressive strength, but in 10% of replacement, the strength decreased by 14%. For type V cement, the optimum replacement was 10%, resulting in only a 1% drop in compressive strength.

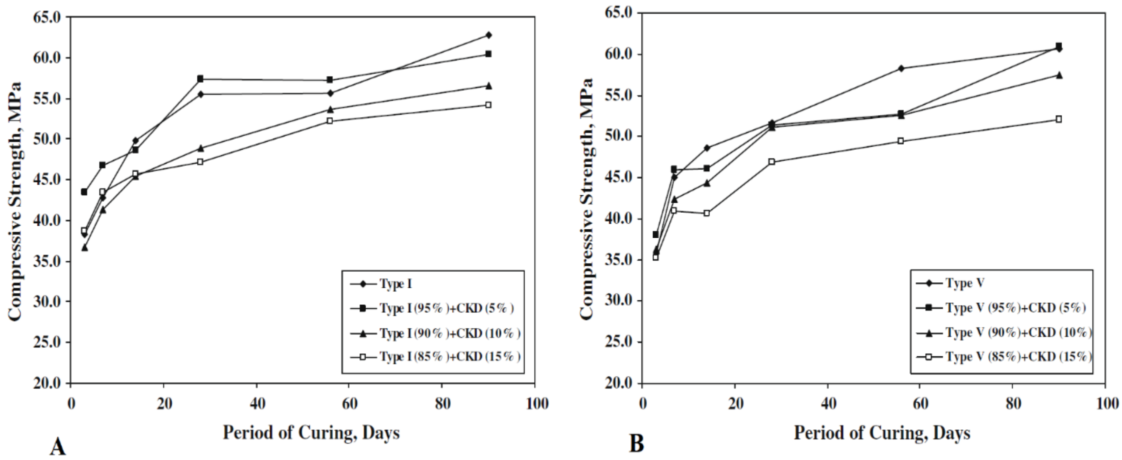

Figure 4. Effect of CKD on two different types of cement: A. Type I of cement. B. Type V of cement [19].

Ravindrarajah [20] investigated the effect of CKD on the compressive strength of concrete. Concrete mixtures were prepared with different ratios of CKD replacement (15%, 25%, 35%, and 45%) for ordinary Portland cement (OPC) at various curing ages (3, 7, 14, 28, 56, and 90 days). Two groups of concrete batches with different mix proportions were used: 1:2:4 (310 kg OPC, w/b ratio of 0.65) and 1:1.5:3 (390 kg OPC, w/b ratio of 0.5). The results showed that the compressive strength decreased with increasing CKD replacement. At the highest replacement ratio of 45%, the 28-day compressive strength decreased by 45% in the 1:2:4 mixes and 37% in the 1:1.5:3 mixes. The optimal amount of CKD replacement for all batches was 15% of the cement weight, and the strength was reduced by 7 and 21% for 1:2:4 and 1:1.5:3 mixes, respectively.

Hilal and Medulla [21] investigated the compressive strength of concrete by replacing OPC cement with CKD at ratios of 0%, 10%, 30%, and 50%. The highest CKD replacement of 50% led to a 28-day compressive strength decrease of 37%. The optimal CKD content was 10%, resulting in a decrease of 20% in compressive strength.

Udoeyo and Hyee [22] studied the compressive strength of concrete with different levels of CKD replacement (20%, 40%, 60%, and 80% of cement weight) at curing ages of 1, 3, 7, and 28 days. The w/b ratio was fixed at 0.65 for all batches. At the highest replacement ratio of 80%, the 28-day compressive strength decreased by 85%. At the lowest replacement ratio of 20%, the compressive strength decreased by 8% at 7 days and 8% at 28 days compared to the control group.

2.2. Flexural Strength

In their study, Gamil et al. [12] evaluated the flexural strength properties of concrete after 28 days, substituting OPC with CKD in various ratios up to 100% with 10% increments. Normal and heat-treated CKD were investigated, and the results showed adverse effects on flexural strengths at the 28-day mark. Notably, at 50% and 100% CKD replacements, the 28-day flexural strength experienced significant reductions of 56% and 83%, respectively. The optimal cement replacement with normal CKD was 10%, resulting in a 9% reduction in flexural strength compared to the control mix.

Hilal and Medulla [21] found that the flexural strength of concrete generally increased with age for all mixtures. However, including CKD in the mix decreased flexural strength, with a more significant reduction as the CKD percentage increased. For instance, at 28 days, the flexural strength decreased from 4.3 MPa in the reference concrete mix to 3.0 (30%), 2.5 (42%), and 2.4 MPa (44%) for mixtures with 10%, 30%, and 50% CKD replacement, respectively. The decline in strength can be attributed to cement clinker substitution and higher chloride content in cement kiln dust, leading to pore system opening and reduced strength.

Al-Harthy et al. [9] examined the flexural strength of concrete with varying CKD replacement ratios. The results demonstrated in Fig. 5 a decrease in flexural strength with increasing CKD replacement for w/b ratio 0.7 and 0.6 batches. Still, in w/b ratio 0.5 up to 15% replacement, the strength was increased, and by adding more CKD from 15 to 30%, the strength was decreased. At the highest CKD replacement ratio of 30%, the 28-day flexural strength decreased by 29% for a w/b ratio of 0.7, 19% for a w/b ratio of 0.6, and 23% for a w/b ratio of 0.5. The optimal CKD replacement ratios for flexural strength were 15% for a w/b ratio of 0.5 and 0.7 and 10% for a w/b ratio of 0.5.

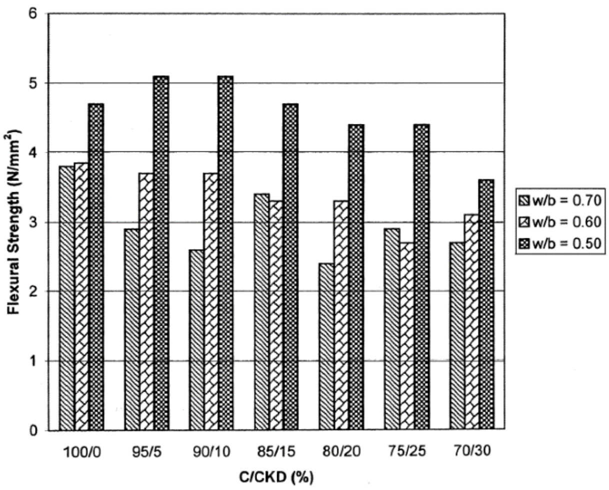

Figure 5. Effect of CKD on flexural strength of concrete [9].

Ravindrarajah [20] observed decreased flexural strength with increased CKD replacement. At the highest CKD replacement ratio of 45%, the 28-day flexural strength decreased by 47% in the 1:2:4 mixes and 29% in the 1:1.5:3 mixes. This decrease in flexural strength highlights the impact of CKD on the ability of the concrete to withstand bending forces, which is crucial for structural applications.

Table 1. The collected data from the literature.

References	Sample name	W/B Ratio	CKD (%) Replacement	Compressive Strength 7 days (MPa)	Compressive Strength 28 days (MPa)	Flexural Strength (MPa)
Ravindrarajah [20]	A	0.65	0	18.9	27.8	3.75
	B		15	17.9	26.1	2.95
	C		25	16.3	22	3
	D		35	14.1	18.4	2.45
	E		45	11.2	15.3	2
	F	0.5	0	31.4	46.2	4.6
	G		15	28.3	36.1	4.4
	H		25	26.6	31.7	4.05
	I		35	21.7	29.6	3.6
	J		45	19.9	25.32	3.3
Shoaib et al. [18]	1	0.5	0	-	26.39	-
	2		10	-	22.96	-
	3		20	-	19.91	-
	4		30	-	17.66	-
	5		40	-	14.72	-
Udoeyo and Hyee [22]	1	Not indicate	0	15.44	18.39	5.53
	2		20	12.01	15.01	4.62
	3		40	9.99	10.29	2.58
	4		60	4.46	5.18	-
	5		80	3.22	2.70	-
Al-Harthy et al. [9]	1	0.7	0	28	34.60	3.8
	2		5	25	31.70	2.9
	3		10	24.4	30.2	2.6
	4		15	23.3	30.2	3.40
	5		20	20.8	28.1	2.4
	6		25	19.7	26.9	2.9
	7		30	18.1	23.8	2.7
	8	0.6	0	34	43.5	3.85
	9		5	29	38	3.7
	10		10	28.2	35.7	3.7
	11		15	28.2	34.8	3.30
	12		20	26.8	34.1	3.3
	13		25	26.3	32.3	2.7
	14		30	24	30.9	3.1
	15	0.5	0	45.5	55.1	-
	16		5	43.5	53.1	-
	17		10	42	52.1	-
	18		15	41.6	49.1	-
	19		20	38.2	45.5	-
	20		25	35.5	41.12	-
	21		30	35	40.1	-
Maslehuddin et al. [19]	A	Not indicate	0	42.7	55.5	-
	B		5	46.7	56.1	-

	C		10	41.4	48.7	-
	D		15	43.6	47.3	-
	E		0	45	51.5	-
	F		5	46	51.3	-
	G		10	42.2	51	-
	H		15	41	44.3	-
Hilal and Medulla [21]	A	0.4	0	24	-	-
	B		10	21	-	-
	C		30	20	-	-
	E		50	15	-	-
Hassan et al. [16]	1	Not indicate	0	43.5	59.5	-
	2		5	41.8	56.5	-
	3		10	40.3	54.2	-
	4		15	37	47	-
	5		20	31.5	46.5	-
	6		25	33.5	50	-
	7		30	22.7	38.2	-
Najim et al. [33]	SCC	0.3 With SP	0	-	52	-
	S10		10	-	48	-
	S20		20	-	42.4	-
	S30		30	-	36.8	-
Gamil et al. [12]	Control	0.45	0	35.01	46.01	5.6
	M2		10	26.91	39.31	5.1
	M3		20	24.3	31.91	4.21
	M4		30	21.02	24.89	3.95
	M5		40	18.3	20.02	3.01
	M6		50	14.78	17.05	2.46
	M7		60	11.81	15.71	2.27
	M8		70	10.01	12.28	2.01
	M9		80	8.82	10.26	1.74
	M10		90	6.98	10.1	1.01
	M11		100	4.72	8.43	0.97
Abd El-Mohsen [34]	NVC	0.45	0	24.1	29.5	-
	SCC-10		10	23.4	27.5	-
	SCC-20		20	22.5	24.6	-
	SCC-30		30	18	21.14	-
	SCC-40		40	16.5	17.15	-
Hussein and Amed [35]	MT	0.5	0	-	51	-
	MCKD1	0.505	1	-	50.5	-
	MCKD2	0.51	2	-	50	-
	MCKD3	0.515	3	-	49	-
	MCKD4	0.521	4	-	48.8	-
	MCKD5	0.526	5	-	47.8	-
	MCKD10	0.556	10	-	45.2	-
Barnat-Hunek et al. [15]	C0	0.4	0	-	53.6	7.12
	C5		5	-	52.9	6.24
	C10		10	-	50.1	5.98
	C20		20	-	41.3	5.74
Bagheri et al. [36]	Control	0.37	0	-	49	-
	C5		5	-	51	-
	C10		10	-	48	-
	C15		15	-	45.5	-
	C20		20	-	39	-
	C30		30	-	32	-
	C40		40	-	26.5	-

	Control	0.4	0	-	46	-
	C5		5	-	44.5	-
	C10		10	-	35	-
	C15		15	-	32.7	-
	C20		20	-	30	-
	C30		30	-	27	-
	C40		40	-	24	-
Alharthi et al. [37]	Control	0.48	0	-	28.72	-
	2%		2	-	28.45	-
	5%		5	-	27.8	-
	8%		8	-	27	-
	10%		10	-	26.5	-
	15%		15	-	24.2	-
	20%		20	-	21.67	-

3. Materials and Methods

3.1. Materials

3.1.1. Cement Kiln Dust (CKD)

The Cement Kiln Dust (CKD) used in this study was obtained from Ramadi Cement Factory. CKD is a byproduct generated during the cement manufacturing process. It is a fine powder collected from the cement kiln's exhaust gases. Table 2 provides the chemical composition of the CKD generated at the Ramadi cement factory. The table presents the major chemical constituents and their respective percentages in CKD.

Table 2. Chemical Composition of CKD from Ramadi Cement Factory.

Chemical Component	Percentage by Weight
Calcium Oxide (CaO)	56.62 %
Silica (SiO_2)	9.61 %
Aluminum Oxide (Al_2O_3)	2.71 %
Iron Oxide (Fe_2O_3)	3.45 %
Magnesium Oxide (MgO)	2.00 %
Sulfur Trioxide (SO_3)	4.22 %
Potassium Oxide (K_2O)	0.96 %
Sodium Oxide (Na_2O)	0.19 %
Loss of ignition	19.34 %

3.1.2. Cement

This study prepared all the concrete mixes using cement type (CEM-1, 42.5 R) sourced from Tasluja, Al-Sulaymaniyah, Iraq. The selected cement adheres to the chemical and physical property specifications outlined in Table 3 and meets the requirements set by ASTM-C150 [23].

Table 3. Chemical and physical properties of cement from Tasluja cement factory [Author].

Chemical Test		
Chemical Component	**Percentage by Weight**	**ASTM C150**
Calcium Oxide (CaO)	63.55	--
Silica (SiO_2)	19.12	--
Aluminum Oxide (Al_2O_3)	4.65	≤ 6
Iron Oxide (Fe_2O_3)	3.22	≤ 6
Magnesium Oxide (MgO)	1.87	≤ 6
Sulfur Trioxide (SO_3)	2.48	≤ 3
Loss of ignition	3.48	--
Lime Saturation Factor	1.01	0.66 – 1.02
Insoluble residue (I.R)	0.71	≤ 0.75
C_3S	70.12	-
C_2S	- 0.09	-
C_3A	6.88	-
C_4AF	9.79	-
Physical property		
Color	Grey	-
Compressive strength fc' at 3 days	26.5	≥ 12 MPa
Compressive strength fc' at 7 days	46.8	≥ 19 MPa
Initial setting time - I.S.T	149	≥ 45 minutes
Final setting time – F.S.T	187	≤ 375 minutes
Fineness, specific surface	336	≥ 260 m^2/kg
Autoclave expansion	0.0	0.8%, max.

3.1.3. Aggregate

Coarse aggregates with a maximum size of 12.5 mm were used in the concrete mixtures. They met the requirements of ASTM C33 [24] C136 [25], as shown in Fig. 6, which specifies the grading and quality of coarse aggregates for use in concrete. The coarse aggregates were selected based on availability and suitability for the intended application.

Fine aggregates with a fineness modulus of 2.55. They met the requirements of ASTM C33 [24] and C136 [25], as shown in Fig. 6, which provides a standard test method for sieve analysis of fine and coarse aggregates. The fineness modulus measures the fineness of the fine aggregate particles and is calculated based on the sieve analysis results.

Before use, the aggregates underwent thorough washing to remove any harmful materials, such as clay, dust, or organic impurities, as per ASTM C33 [24]. They were then dried following ASTM C127 [26] and ASTM C128 [27] to achieve a constant weight and ensure consistent moisture content.

The physical properties of the aggregates were determined following ASTM standards. The specific gravity of the coarse and fine aggregates was determined using ASTM C127 [26] and ASTM C128 [27], respectively. These tests provide guidelines for measuring the specific gravity of aggregates and calculating their absorption capacity and the physical characteristics of the aggregates summarized in Table 4.

Table 4. Physical Characteristics of the Fine and Coarse Aggregates.

Aggregate type	Coarse Agg.	Fine Agg.
Specific gravity	2.65	2.7
Unit weight (Kg/m³)	1514	1680
Water absorption %	1.45	1.42
Fineness modulus (F.M)	--	2.55

The particle size distribution of the fine aggregates was determined using the sieve analysis method outlined in ASTM C136 [25]. This standard test method allows for determining aggregates' gradation and particle size distribution, which is crucial for assessing their suitability in concrete mixtures. It is important to note that the properties of aggregates, such as particle size distribution, specific gravity, and water absorption, can significantly influence the workability, strength, and durability of concrete. Therefore, understanding the characteristics of the aggregates used is essential for evaluating the specific effect of CKD on the mechanical properties of concrete.

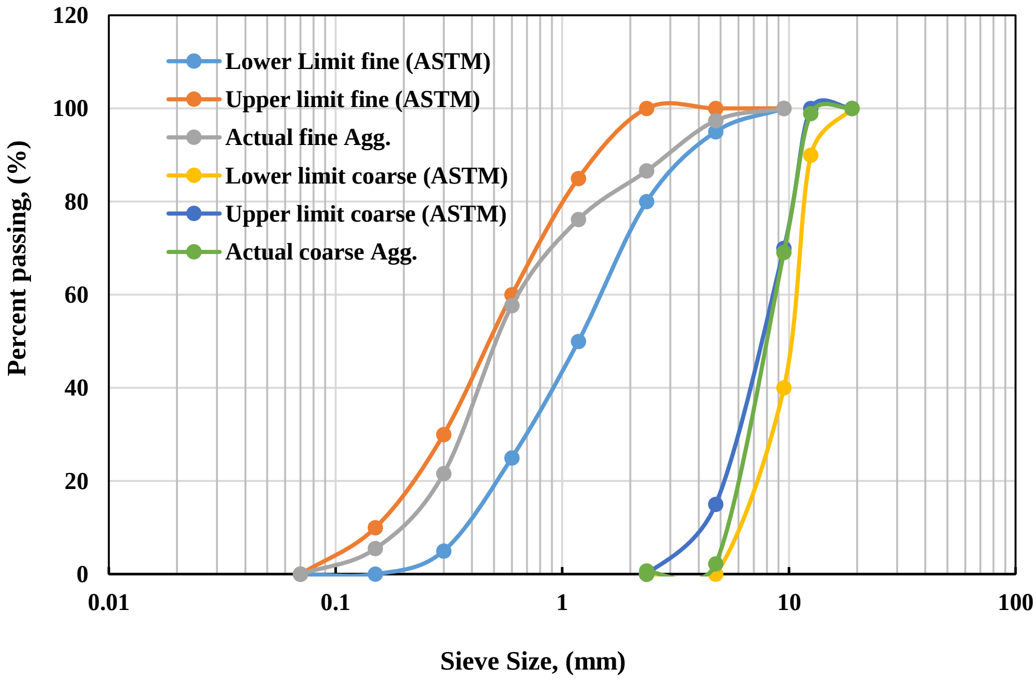

Figure 6. Sieve Analysis of Fine and Coarse Aggregate According to ASTM C33 [24].

3.2. Methods

3.2.1. Concrete Mix Proportions

The concrete mix proportions were determined following the guidelines provided by the ACI 211.1-91 [28] standard, which offers recommendations for selecting concrete mixtures based on desired performance criteria. The mix design aimed to achieve a maximum slump of 100 mm, indicating the desired consistency and workability of the concrete. The proportions of cement, fine aggregate, coarse aggregate, and water were carefully selected to meet the requirements of the ACI 211.1-91 [28] standard and achieve the desired properties of the concrete. The specific mix proportions used in the study are detailed in Table 5. The selected mix proportions were based on a comprehensive evaluation of desired strength, workability, and durability, as the ACI 211.1-91 [28] standard specified. Adhering to these guidelines ensures the consistency and reliability of the concrete mixtures used in the experimental investigation.

Table 5. Mix Design According to ACI 211.1.91 [28].

Sample name	W/B ratio	Cement (Kg/m³)	CKD (Kg/m³)	Water (Kg/m³)	Air (%)	Gravel (Kg/m³)	Sand (Kg/m³)	Total (Kg/m³)
Control	0.42	514.3	0.00	216	2.5	870.5	709.2	2310.0
R-5%	0.42	488.6	25.7	216	2.5	870.5	709.2	2310.0
R-10%	0.42	462.9	51.4	216	2.5	870.5	709.2	2310.0
R-15%	0.42	437.1	77.1	216	2.5	870.5	709.2	2310.0
R-20%	0.42	411.4	102.9	216	2.5	870.5	709.2	2310.0
R-30%	0.42	360.0	154.3	216	2.5	870.5	790.2	2310.0

3.2.2. Mixing Procedure and Casting Specimens

The concrete mixtures were prepared using a rotating drum mixer, as shown in Fig. 7a. The aggregates used in the mixtures were prepared in a saturated surface dry (SSD) condition by soaking them in water until fully saturated and draining excess surface water. Before the mixing process, the water content of the aggregates was determined by weighing representative samples and drying them in an oven to obtain the moisture content. The moisture content of the aggregates was then multiplied by the total mass of aggregates used in the mix, and the resulting value was added to the initially calculated water content for the mix to determine the final water content. The SSD aggregates, cement, and other dry ingredients were mixed to ensure uniform distribution.

Following ASTM C143 [29], the water content, considering the moisture contributed by the aggregates, was gradually incorporated into the mixture while it was being mixed. This process continued until a homogeneous blend with the intended consistency and workability was achieved.

The confirmation of the desired consistency and workability was obtained through the performance of the slump test, as illustrated in Fig. 7b.

For the compressive strength test, cylindrical specimens measuring 100 mm x 200 mm (diameter x height) were cast, as shown in Fig. 8. A total of 4 batches were prepared, with each batch incorporating a different percentage of CKD as a partial replacement of cement. The fresh concrete mixtures were carefully poured into the cylindrical molds, ensuring proper compaction to minimize voids and achieve uniform density. Subsequently, the molds were covered and stored in a curing chamber, maintained at the specified conditions, for the designated curing period.

For the flexural strength test, beam specimens with dimensions of 100 mm x 100 mm x 500 mm (width x height x length) were cast, as shown in Fig. 9. Similarly, the 7 trial batches were used to prepare the fresh concrete mixtures. The mixtures were poured into rectangular molds, ensuring adequate compaction and eliminating trapped air. The molds were also covered and placed in the curing chamber for the specified curing period.

The trial batches were designed to explore the effect of different CKD percentages on the mechanical properties of fresh concrete. Each trial batch represented a different CKD content, as shown in Table 4, allowing for a comparative analysis of the concrete's performance under varying proportions of CKD.

Figure 7. (a) Rotary Mixer Drum. (b) Slump Test According to ASTM C143 [29].

2

Figure 8. Casting Concrete Using a Cylinder for the Compression Strength Test.

Figure 9. Casting Concrete by Using a Beam Size 100 X 100 X 500 mm to Find the Modulus of Rupture.

3.2.3. Testing of the Specimens

At the end of the designated curing period, the concrete specimens were subjected to various mechanical tests to evaluate their properties. The following tests were conducted following the corresponding ASTM standards:

Compressive Strength Test: Cylindrical specimens measuring 100 mm x 200 mm (diameter x height) were prepared for compressive strength testing, following the ASTM C39 standard (Fig. 10a). To ensure proper alignment and load transfer, the specimen ends were capped with sulfur-sand compound as per the ASTM C617 standard. The compound was applied to the specimens' flat, smooth, and perpendicular ends. The capped specimens were placed in a compression testing machine, where a gradually increasing axial load was applied until failure. The maximum load at failure was recorded, and the compressive strength was computed based on the specimens' cross-sectional area.

Flexural Strength Test (Rupture Test): Beam specimens with 100 mm x 100 mm x 500 mm (width x height x length) were employed for the flexural strength test. The test was conducted following the ASTM C78 [32] standard. A load was applied at the midpoint of the beam until it fractured, as shown in Fig. 10b. The maximum load at failure was recorded, and the flexural strength was determined based on the dimensions of the specimens.

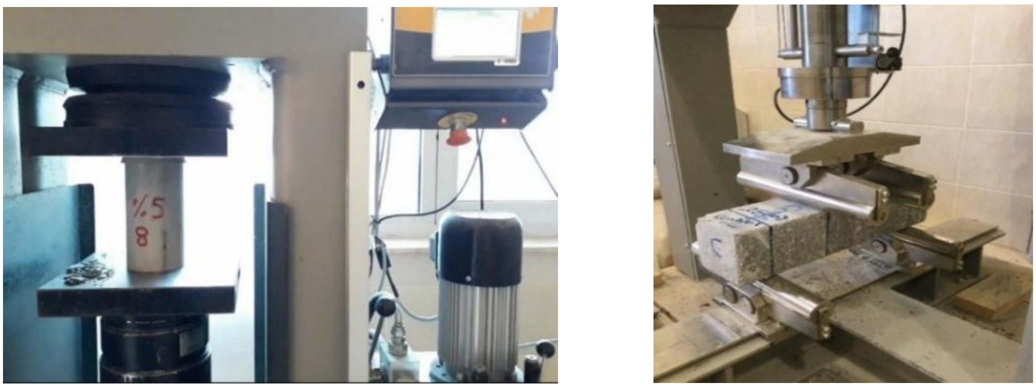

Figure 10. (a) Compressive Test Machine. (b) Flexural Strength Machine Test.

4. Results and Discussion

4.1. Experimental Result and Discussions

The experimental data collected in the laboratory investigates the effects of replacing cement with CKD on various concrete properties. These properties include slump measurements for workability during casting, compressive strength evaluations at 7, 28, and 56 days, and flexural strength assessments at 28 days. The outcomes are summarized in Table 6, with dedicated discussions provided for each property to highlight how CKD replacement influences them individually. This systematic approach offers insights into the material's performance across different curing periods and provides a comprehensive understanding of CKD's impact on concrete characteristics.

Table 6. The test Data Obtained from the Laboratory.

Sample name	W/B Raito	CKD Content (%)	Slump (mm)	Compressive strength (MPa)			Flexural strength test (MPa)
				7 days	28 Days	56 Days	28 days
Control	0.42	0	110	36.79	49.65	58.34	5.07
R – 5%		5	97	39.95	48.08	57.98	4.99
R – 10%		10	83	35.96	46.18	54.34	4.8
R – 15%		15	65	35.08	44.94	54.25	4.35
R – 20%		20	54	34.88	38.3	44.85	4.2
R – 30%		30	43	23.61	33.02	41.78	4.21

4.1.1. Slump

The slump test measures the consistency and workability of fresh concrete, providing insights into its ability to flow and be easily compacted. Fig. 11 and Table 6 data compare the slump values for different CKD replacement percentages.

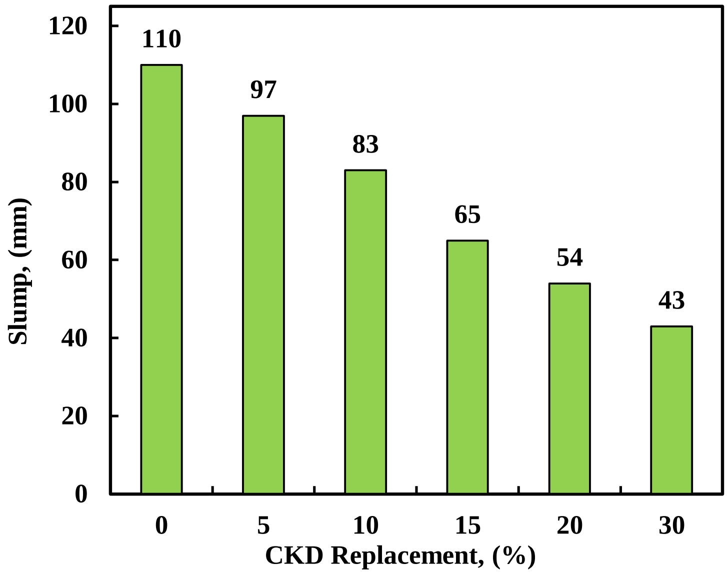

Figure 11. Effect of CKD on the Slump of the Concrete.

Starting with the control sample, which has 0% CKD replacement, a slump value of 110 mm was obtained. As the CKD replacement percentage increased, a slight decrease in slump values can be observed. The 5% CKD replacement showed a slump value of 97 mm, indicating slightly lower workability than the control sample by 11.8 %. Similarly, the 10% CKD replacement sample exhibited a slump reduction of 24.5%, with a slump value of 83 mm. This reduction indicates a further decrease in workability.

As the CKD content percentage increased to 15%, 20%, and 30%, more significant reductions in slump values were observed. The 15% CKD replacement sample experienced a slump reduction of 40.9%, resulting in a slump value of 65 mm. The 20% CKD replacement sample exhibited a slump reduction of 50.9%, with a slump value of 54 mm. Finally, the 30% CKD replacement sample showed a slump reduction of 60.9%, resulting in a slump value of 43 mm. This significantly lower value indicates a stiffer and less workable consistency than the control sample. This slump reduction is attributed to the cement kiln dust particles being irregular and smaller than the OPC, as confirmed by SEM analysis (Fig. 12). The unique shape and texture of CKD particles disrupt the particle packing in the mix, impeding smooth flow and causing decreased workability, which aligns with the slump measurements.

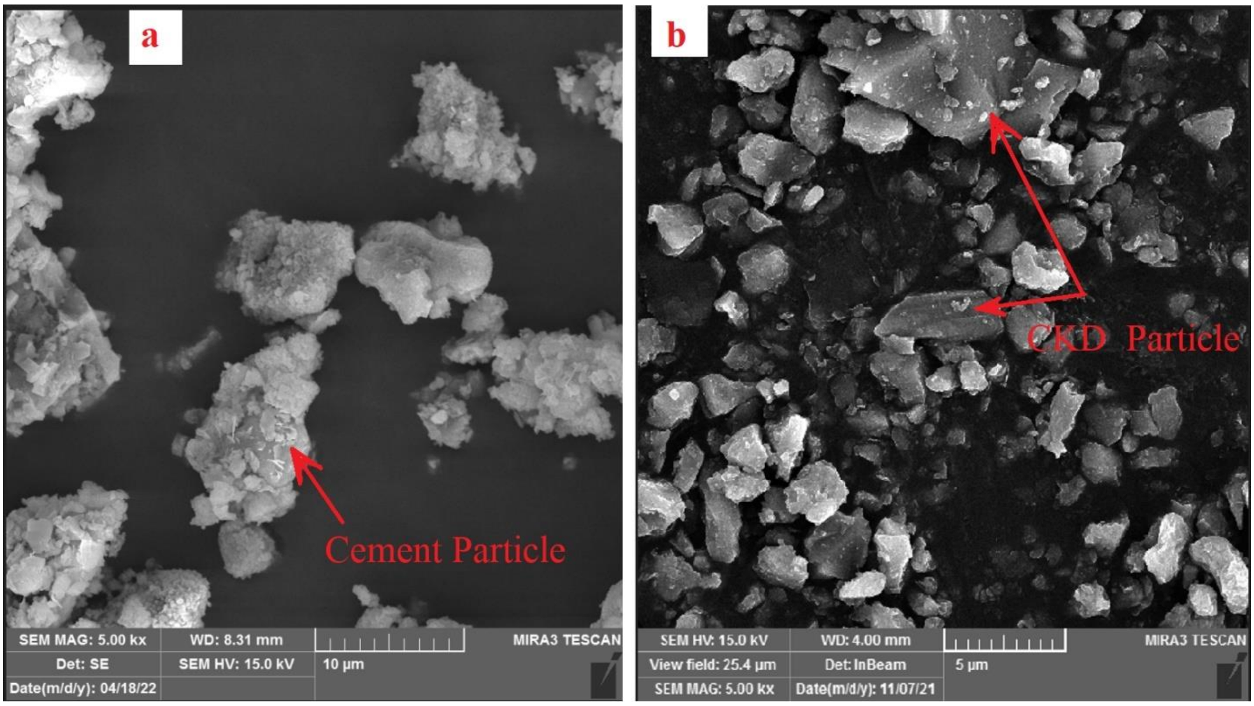

Figure 12. SEM of (a) Cement (OPC) and (b) CKD [Author].

4.1.2. Compression Strength

The provided data in Table 6 and Fig. 13 illustrates how the compressive strength of concrete is influenced by varying CKD content percentages at different curing ages (7 days, 28 days, and 56 days). These results enable a comparison of the extent to which different CKD replacement levels contribute to strength reduction.

At 7 days, the control sample achieved a compressive strength of 36.79 MPa. Among the CKD replacement samples, the 5% CKD replacement exhibited a slightly higher compressive strength (39.95 MPa) than the control, resulting in an increase of 8.6% in strength. However, as the CKD replacement ratio increased to 10, 15, 20, and 30%, the compressive strength reductions compared to the control were 2.3, 4.6, 5.2, and 35%, respectively.

At 28 days, different trends were observed. The 5% CKD replacement showed a lower compressive strength than the control, with a reduction of only 3.2%. However, the 10, 15, 20, and 30% CKD replacement exhibited higher reductions in compressive strength compared to the control: 7.0, 9.5, 22.9, and 33.5%, respectively. At 56 days, the compressive strength reductions became more pronounced for the CKD replacement samples. The 5% sample demonstrated a reduction of 0.6% compared to the control, while the 10, 15, 20, and 30% CKD replacement had reductions of 6.9, 7, 23, and 28.4%, respectively.

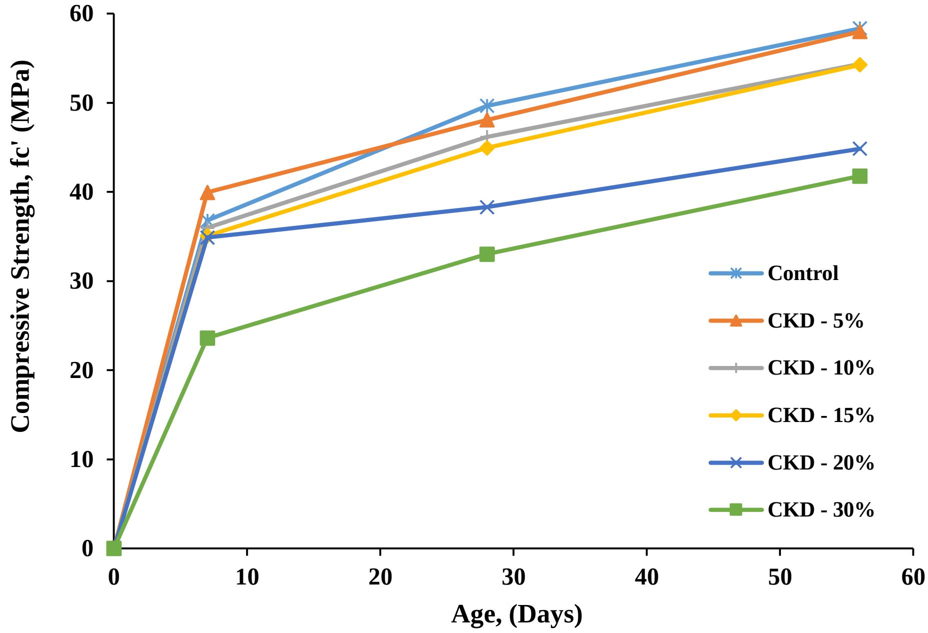

Figure 13. Effect of CKD on Compressive Strength of the Concrete.

The data clearly shows that lower CKD replacement ratios of 5 and 10% resulted in relatively small reductions in compressive strength compared to the control sample. However, as the CKD content percentage increased (15, 20, and 30%), the reduction in compressive strength became more significant. This comparison highlights the importance of considering the CKD replacement ratio when incorporating CKD into concrete mixtures. Lower replacement ratios can help minimize the reduction in compressive strength, whereas higher replacement ratios tend to lead to more substantial strength reductions.

4.1.3. Flexural Strength test (Modulus of Rupture)

The flexural strength test data provided in Fig. 14 allows for examining the influence of CKD replacement levels on the flexural strength of concrete samples at 28 days. Valuable insights can be gained by comparing the strength reduction observed among different CKD content percentages. Starting with the control sample, which represents 0% CKD content, a flexural strength of 5.07 MPa was recorded. When comparing this to the samples with CKD replacements, it becomes evident that the 5% CKD replacement sample experienced a minor strength reduction of only 1.6% with a flexural strength of 4.99 MPa. Similarly, the 10% sample exhibited a strength reduction of 5.3% with a flexural strength of 4.8 MPa.

However, as the CKD replacement percentage increased to 15, 20, and 30%, more substantial reductions in flexural strength were observed. The 15% sample demonstrated a strength reduction of 14.2% with a flexural strength of 4.35 MPa. Likewise, the 20% sample experienced a reduction of

17.2% with a flexural strength of 4.2 MPa. Finally, the 30% sample showed a similar reduction of 17.0% with a flexural strength of 4.21 MPa.

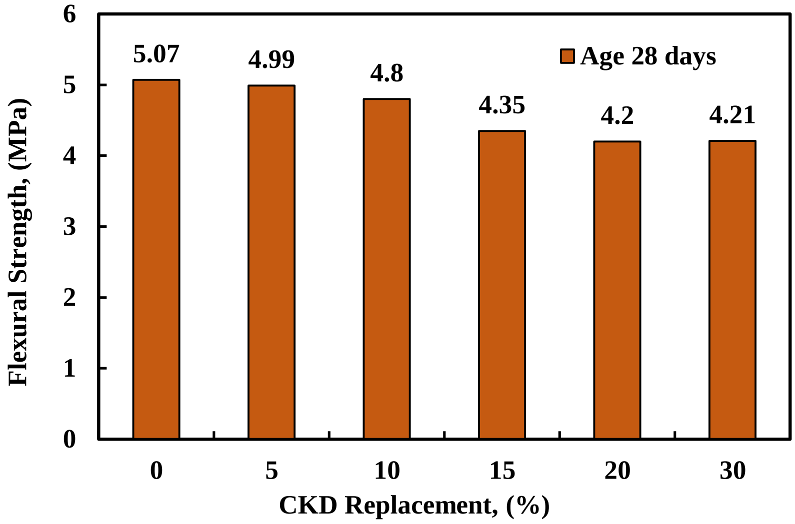

Figure 14. Effect of CKD on the Flexural Strength of the Concrete.

The data clearly illustrates that lower CKD replacement ratios, such as 5% and 10%, resulted in relatively minor reductions in flexural strength compared to the control sample. However, as the CKD content percentage increased to 15%, 20%, and 30%, the reduction in flexural strength became more significant.

Overall, the flexural strength test results demonstrate that incorporating CKD as a partial replacement for cement leads to a gradual decrease in the flexural strength of the concrete. The observed reduction in flexural strength implies a weakening effect on the concrete's ability to resist bending forces.

4.2. The Literature Data and Comparisons with Experimental Data

4.2.1. Compression Strength at 7 Days

The obtained data in Table 1 from the literature regarding compression strength at 7 days provides valuable insights into the relationship between CKD content and the resulting compressive strength of concrete at an early age. Statistical analysis of the data, as shown in Fig. 15, indicates that 71 data points were considered, with the mean compressive strength calculated as 26.1 MPa, indicating the average strength attained across the range of CKD replacement ratios. A standard deviation of 11.66 MPa suggests moderate variability in the dataset, indicating a dispersion of compressive strength values around the mean. The maximum recorded compressive strength was 46.7 MPa, while the minimum was 3.2 MPa. These values highlight the range of compressive strengths achievable when utilizing CKD replacements in concrete mixtures. The median compressive strength was determined to be 24.3 MPa, and the variance was calculated as 135.93.

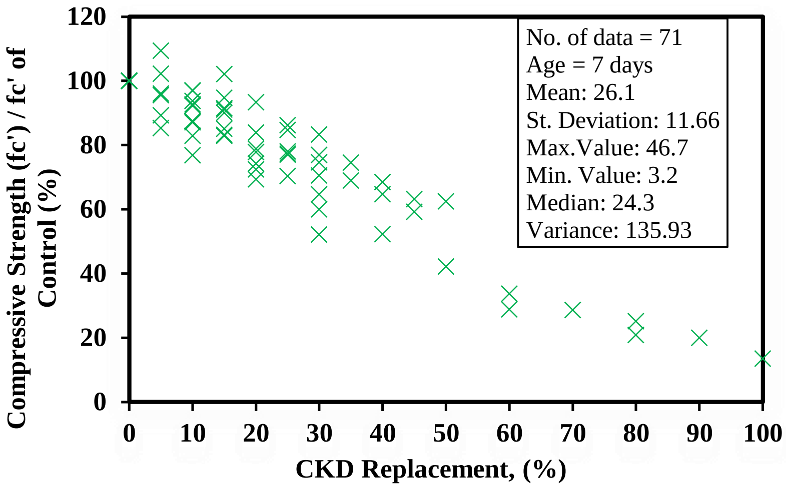

Figure 15. Statical Analysis of Compressive Strength for 7 Days, Collected from Table 1.

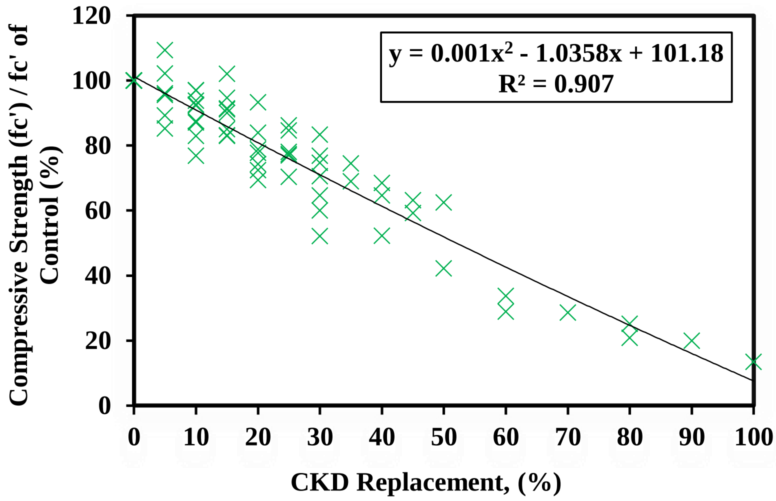

Figure 16. Non-linear Regression Model of Compressive Strength at Age 7 Days.

To further investigate the influence of CKD content on compressive strength at 7 days, an empirical equation using a non-linear regression model was derived based on the literature data. As illustrated in Fig. 16, this empirical equation demonstrates a strong correlation between the CKD content and the predicted compressive strength. The Eq. 1 is given by:

$$f'c_{p\,(7\,days)} = 0.0011\,(CKD)^2 - 1.0517\,CKD + 101.18 \quad (1)$$

where:

$f'c_{p\,(7\,days)}$ = Predicted compressive strength at 7 days, MPa

CKD = CKD content, %

The coefficient of determination (R^2) for this equation was found to be 0.904, indicating a significant relationship between the CKD content and compressive strength at 7 days. This empirical equation provides a practical tool for estimating the compressive strength of concrete with varying CKD percentages, aiding in concrete mix design decisions and early-age performance assessment.

The predicted compressive strength values based on the empirical equation with R^2 and RMSE of 0.90 and 2.36 MPa respectively, with error lines of -15 to 15% for the dataset, were depicted in Fig. 17. Table 7 contents the summarized the experimental data for compressive strength obtained in the laboratory, as well as the predicted strength values (Up to 30%) based on the empirical equation derived from the literature data. The comparison between the experimental data and the predicted strength values allows us to assess the accuracy of the empirical equation in estimating the compressive strength for different CKD replacement percentages.

Table 7. Experimental and Predicted Data for Compressive Strength at 7 Days.

Sample Name	CKD Content, (%)	Compressive Strength (MPa)		
		Exp. Data	Literature Data	
		7 days	Predicted Strength (%)	Predicted Strength (MPa)
Control	0	36.79	-	36.79
R - 5%	5	39.95	95.95	35.30
R - 10%	10	35.96	90.77	33.40
R - 15%	15	35.08	85.65	31.51
R - 20%	20	34.88	80.58	29.64
R - 30%	30	33.61	70.62	25.98

In comparing the experimental data with the literature data, several notable observations can be made. First and foremost, it's evident that the prediction results consistently yield lower compressive strength values than those experimental result by the test data. For instance, at a 5% CKD replacement, the experimental compressive strength stands at 39.95 MPa which was more than the control sample, while the literature predicts a lower value of 35.3 MPa (11.6% lower). Similarly, at 10% and 15% CKD replacement, the experimental strengths of 35.96 MPa and 35.08 MPa respectively outperform the literature predictions of 33.4 MPa (7.1% lower) and 31.51 MPa (10.2% lower). Similarly, for 20% replacement the experimental strengths of 34.88 MPa surpass the literature predictions of 29.64 MPa. Differently, for 30% replacement the experimental strengths of 23.61 MPa, it was lower the literature predictions of 25.96 MPa. In general, it can be seen that the predicted strengths are consistently lower than the experimental result except in 30% replacement.

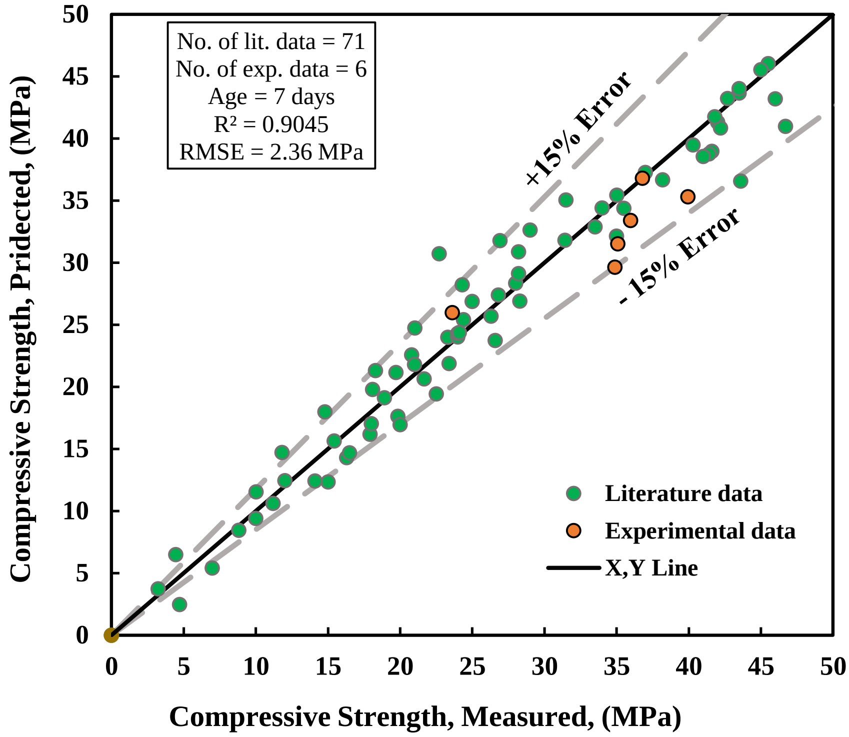

Figure 17. Relation Between the Measured and Predict Compressive Strength at 7 Days.

4.2.2. Compression Strength at 28 days

The obtained data in Table 1 on compression strength from the literature provides valuable insights into the relationship between CKD content and the resulting compressive strength of concrete. The statistical analysis of the data, as shown in Fig. 18, reveals that 108 data points were analyzed at 28 days. The mean compressive strength was calculated as 34.91 MPa, indicating the average strength attained across the range of CKD replacement ratios. The standard deviation of 13.74 MPa suggests moderate variability in the dataset, indicating a dispersion of compressive strength values around the mean. The maximum compressive strength recorded was 59.5 MPa, while the minimum value was 2.7 MPa; these values highlight the wide range of compressive strengths achievable when utilizing CKD replacements in concrete mixtures. The median compressive strength was determined to be 34.35 MPa, and the variance was calculated as 188.91.

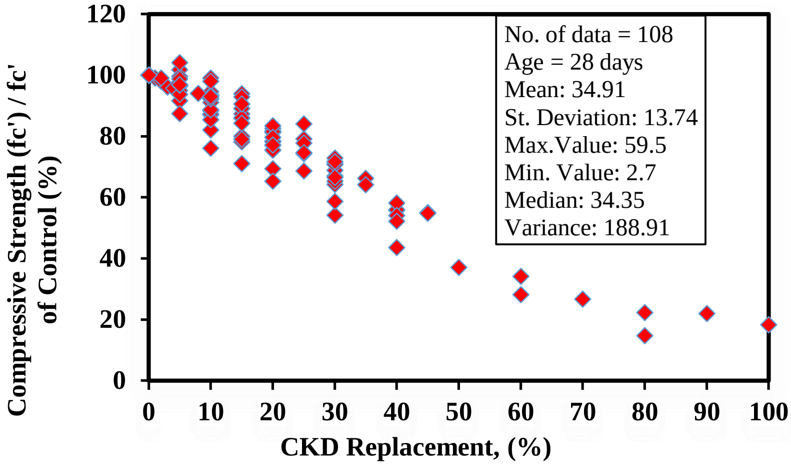

Figure 18. Statical Analysis of Compressive Strength at 28 Days, Collected from Table 1.

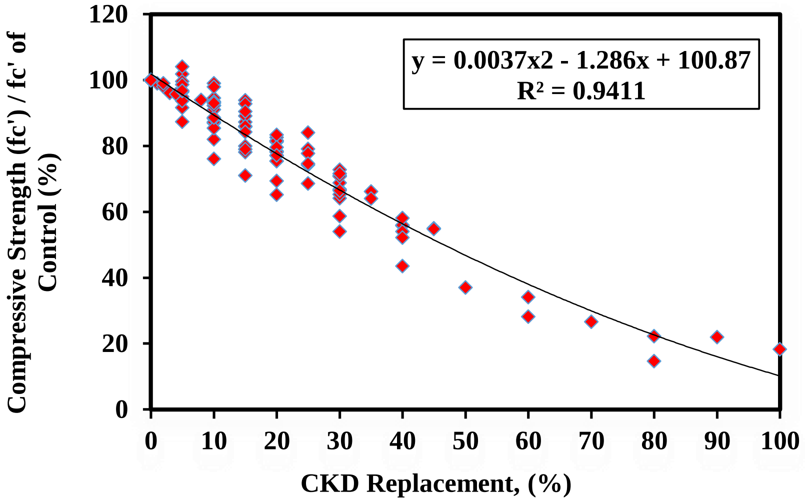

Figure 19. Non-Linear Regression of Compressive Strength at Age 28 Days.

To further investigate the relationship between CKD content and compressive strength, the non-linear regression model was used to drive an empirical equation based on the data obtained from the literature. The equation Eq. 2, illustrated in Fig. 19, demonstrates a high degree of accuracy in predicting the compressive strength based on different percentages of CKD. The empirical equation is given as:

$$f'c_{p\,(28\,days)} = 0.0037\,(CKD)^2 - 1.286\,CKD + 101.87 \quad (2)$$

where:

$f'c_{p\,(28\,days)}$ = Predicted compressive strength at 28 days, MPa

CKD = CKD content, %

This equation's coefficient of determination (R^2) was 94.1%, indicating a strong correlation between the CKD content and compressive strength. This empirical equation provides a practical tool for estimating the compressive strength of concrete with varying CKD percentages, allowing for informed decision-making during the concrete mix design process. The predicted compressive strength values based on the empirical equation with yielding an R^2 value of 0.94 and an RMSE of 2.39 MPa. Error lines ranging from -15% to 20% encompass the dataset, were depicted in Fig. 20. Table 8 illustrates the experimental data for compressive strength at 28 days obtained from the laboratory, and the predicted strength values (Up to 30%) based on the literature data. Let's compare the experimental data and the predicted strengths for different CKD replacements.

Table 8. Test and Predicted Data for Compressive Strength at 28 Days.

Sample name	CKD Content, (%)	Compressive Strength (MPa)		
		Exp. Data	Literature Data	
		28 days	Predicted Strength (%)	Predicted Strength (MPa)
Control	0	49.65	-	49.65
R - 5%	5	48.08	95.53	47.43
R - 10%	10	46.18	89.38	44.37
R - 15%	15	44.94	83.41	41.41
R - 20%	20	38.3	76.63	38.05
R - 30%	30	33.02	65.62	32.58

In summary, our prediction results consistently show lower compressive strength values compared to experimental results. For example, at a 5% CKD replacement, our experiments recorded a compressive strength of 48.08 MPa, which was 3.2% lower than the control sample but surpassed the literature's predicted value of 47.43 MPa (1.4% lower).

Similarly, at 10% CKD replacement, our experiments yielded compressive strengths of 46.18 MPa, representing a 7% reduction compared to the control sample, yet still outperforming the literature's predicted value of 44.37 MPa (a 3.9% reduction). Likewise, at 15% CKD replacement, our strength was 44.94 MPa (9.5% lower than the control), exceeding the literature's 41.41 MPa (7.9% lower) prediction.

Differently, for the 20% and 30% replacement sample, the experimental result shows a compressive strength of 38.3 MPa and 33.02 MPa respectively, while the predicted strengths slightly lower than the experimental results of 38.05 MPa and 32.58 MPa respectively.

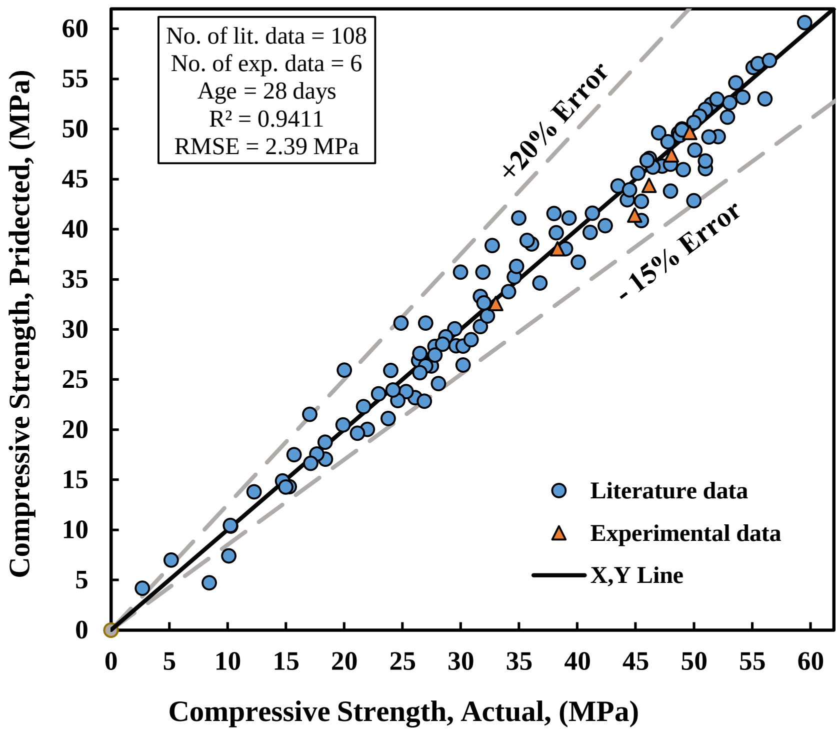

Figure 20. Relation Between the Measured and Predict Compressive Strength at 28 Days.

4.2.3. Flexural Strength Test (Modulus of Rupture)

The data obtained from the literature regarding flexural strength at 28 days provides valuable insights into the relationship between CKD content and the resulting strength characteristics of concrete. As shown in Fig. 21, statistical analysis indicates that 42 data points were considered, with an average flexural strength of 3.54 MPa and a standard deviation of 1.36 MPa. The maximum recorded flexural strength was 7.12 MPa, while the minimum was 0.97 MPa. The median flexural strength was determined to be 3.3 MPa, and the variance was equal to 1.84.

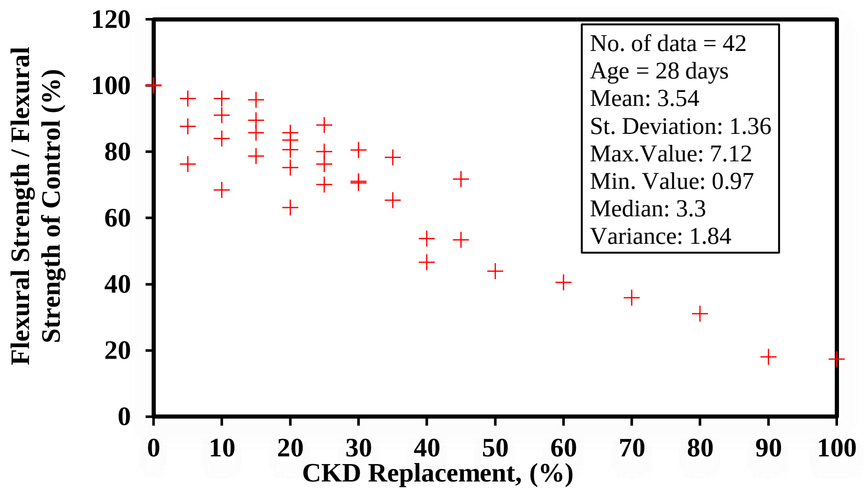

Figure 21. Statical Analysis of Flexural Strength at 28 Days, Collected from Table 1.

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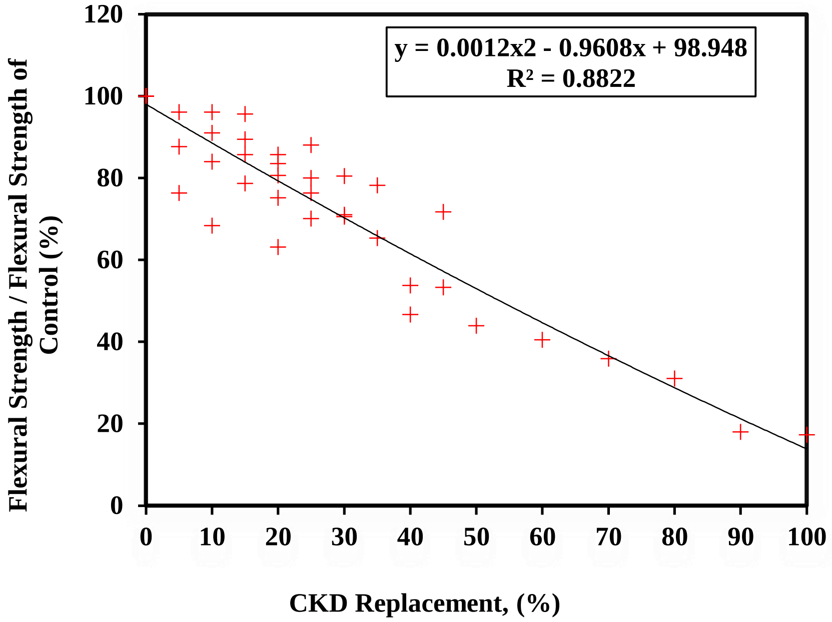

Figure 22. Non-Linear Regression of Flexural Strength at Age 28 Days.

To further explore the impact of CKD content on flexural strength at 28 days, an empirical equation (using a non-linear regression model) was derived based on the literature data. As illustrated in Fig. 22, this empirical equation demonstrates a significant correlation between the CKD content and the predicted flexural strength. The equation Eq. 3 is given by:

$$\boldsymbol{f_{p.\,rp} = 0.0014\,(CKD)^2 - 0.9846\,CKD + 99.75} \qquad (3)$$

where:

$f_{p.\,rp}$ = Predicted flexural Strength at 28 days, MPa.

CKD = CKD content, %.

The coefficient of determination (R^2) for this equation was found to be 0.8822, indicating a strong relationship between the CKD content and flexural strength at 28 days. This empirical equation provides a practical tool for estimating the flexural strength of concrete with varying CKD percentages, aiding in concrete mix design decisions and structural performance evaluation. The predicted flexural strength values based on the empirical equation with yielding an R^2 value of 0.89 and an RMSE of 0.36 MPa. Error lines ranging from -20% to 20% encompass the dataset were illustrated in Fig. 23. Table 9 depicts the laboratory experimental data for flexural strength at 28 days, alongside the corresponding predicted strengths based on literature data. Let's examine the relationship between the experimental data and the predicted strengths for different CKD replacements.

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Table 9. Test and Predicted Data for Flexural Strength at 28 Days.

Sample Name	CKD Content, (%)	Flexural strength (MPa)		
		Exp. Data	Literature Data	
		28 days	Predicted Strength (%)	Predicted Strength (MPa)
Control	0	5.07	-	5.074
R - 5%	5	4.99	94.86	4.813
R - 10%	10	4.8	90.04	4.569
R - 15%	15	4.35	85.30	4.328
R - 20%	20	4.2	80.62	4.091
R - 30%	30	4.21	71.47	3.626

In summary, our predictions consistently show slightly lower flexural strength values compared to the experimental data. For instance, at a 5% CKD replacement, our empirical equation indicates a flexural strength at 4.81 MPa, which is 3.7% less than the experimental result (4.99 MPa). Similarly, with a 10% CKD replacement, our equation yields a flexural strength at 4.57 MPa, representing a 5% reduction compared to the experimental result of 4.80 MPa. Interestingly, at a 15% CKD replacement, the flexural strength showed only a slight difference (neglectable) between the predicted equation and experimental results.

Differently, for 20 % CKD replacement sample demonstrated experimental result of flexural strength of 4.2 MPa, whereas the predicted strength was 4.09 MPa. Lastly, 30% displayed an experimental result flexural strength of 4.21 MPa, with a predicted strength of 3.63 MPa (13.7 % lower). It is noteworthy that the predicted strengths consistently appeared lower than the corresponding experimental results, indicating a conservative estimation or underestimation of flexural strength when using the empirical equation.

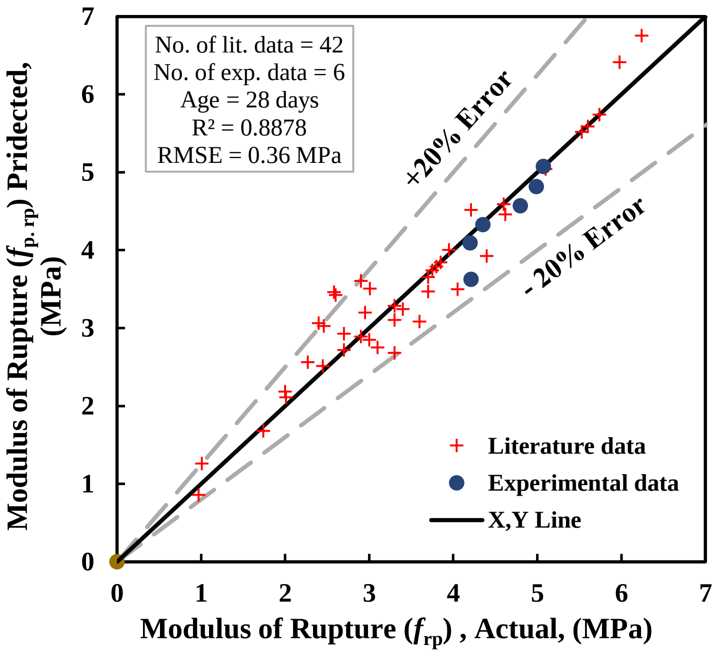

Figure 23. Relation Between the Measured and Predict Flexural Strength at 28 Days.

5. Conclusions

This study investigated the effect of CKD content on various properties of concrete. The major sections analyzed included slump, compression strength at 7 and 28 days, splitting tensile test, flexural strength test, empirical equations, and comparing test and literature data.

1. As the CKD content in the concrete mixture increased, there was a noticeable decrease in slump and workability. When 5% of cement was replaced with CKD, the slump and workability decreased by 11%. However, when 30% of CKD was used as a replacement, the slump and workability decreased significantly by 61%.
2. The optimal CKD replacement content for concrete cured at 7 and 28 days was 15% and 10%, respectively. At 7 days, the compressive strength of concrete was reduced by 4.6% with the replacement of 15% CKD, while at 28 days, the compressive strength was reduced by 7% with 10% CKD replacement.
3. The ideal proportion of CKD replacement in cured concrete at 28 days for flexural strength was 10%. When 10% of the cement was substituted with CKD, the flexural strength decreased by 5.3%.
4. Empirical equations were used to predict concrete properties with varying CKD content. Although predicted strengths were lower than actual results, these equations showed good correlations for compressive and flexural strengths. This makes them practical tools for estimating mechanical properties despite discrepancies between predictions and actual outcomes.

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مراجعة وتقييم تأثير غبار فرن الأسمنت على الخواص الميكانيكية المختلفة للخرسانة

الخلاصة: تظل صناعة الأسمنت قطاعاً بالغ الأهمية على الرغم من التقدم في العلوم والصناعة. ومع ذلك، فإن إنتاج الأسمنت يولد منتجات ثانوية كبيرة، بما في ذلك غبار فرن الأسمنت (CKD)، مما يؤدي إلى مخاوف بيئية. تهدف هذه الدراسة إلى تقييم تأثير CKD على الخواص الميكانيكية للخرسانة. يتضمن الاستقصاء خصائص مثل الركود وقوة الانضغاط وقوة الانحناء. يملأ البحث الفجوات المعرفية الحالية ويقدم رؤى حول فوائد وقيود دمج CKD في الخلطات الخرسانية. تشير النتائج إلى أن زيادة محتوى CKD يقلل من الركود وقابلية التشغيل. نسب استبدال CKD المثلى بنسبة 15 ٪ في 7 أيام و10 ٪ في 28 يومًا تعطي مقاومة ضغط مرضية. بالإضافة إلى ذلك، تقل قوة الانحناء بنسبة 5.3٪ مع استبدال الأسمنت بنسبة 10٪. توضح المعادلات التجريبية المستندة إلى بيانات الأدبيات وجود علاقة بين محتوى CKD وقيم القوة المتوقعة. تعمل هذه المعادلات كأداة عملية لتقدير خصائص الخرسانة بنسب CKD متفاوتة. يساهم هذا البحث في ممارسات البناء المستدامة من خلال توفير رؤى حول استخدام CKD وتعزيز الممارسات الصديقة للبيئة.

الكلمات الدالة: غبار فرن الأسمنت (CKD) ، الخرسانة ، الخواص الميكانيكية ، النمذجة ، التحليل الإحصائي.