International Journal of Academic Engineering Research (IJAER)
ISSN: 2643-9085
Vol. 9 Issue 10 October - 2025, Pages: 42-46

Impact of Replacement Levels for Drill Cuttings on the Curing Age–Strength Development Relationship in Concrete.

Tochukwu A. Ihedioha[1], Maxwell I. Chikwue[2], Okay O. Okoroafor[3] Gladys.U. Asonye[4] Uzochukwu E. Uzoh[5], Ufomba J. Chukwudi[6]

[123456]Department of Agricultural and Biosystems Engineering, Federal University of Technology Owerri. PMB 1526 Owerri Imo State, Nigeria.

Email: tochukwu.ihedioha@futo.edu.ng, mchikwue@yahoo.com, okore.okorafor@futo.edu.ng, gladys4asonye@gmail.com, uzochukwu.uzoh@futo.edu.ng, chudyjohn@gmail.com

08036618459, 08064315919, 08023743452, 08030531299, 08067684643, 07035344438

Abstract: *The rising demand for cement in the construction industry has intensified environmental and sustainability concerns due to its high energy requirements and substantial CO_2 emissions. This study investigates the influence of treated drill cuttings as partial replacements for cement on the curing age–strength development relationship of concrete. Ordinary Portland Cement (OPC, grade 42.5R), river sand, and crushed granite were used as major constituents, while thermally treated and finely ground drill cuttings obtained from oil drilling operations served as supplementary cementitious material.*

Concrete mixes were designed at a 1:2:4 ratio (cement:sand:coarse aggregate) with a water–binder ratio of 0.60. Cement was replaced with drill cuttings at 5%, 7.5%, 10%, 12.5%, and 15% by weight. Fresh concrete was thoroughly mixed, and its workability was determined using the slump test in accordance with BS EN 12350. Cube specimens measuring 150 × 150 × 150 mm were cast in three layers, each compacted by tamping, demoulded after 24 hours, and cured in potable water for 7, 14, 28, 60, and 90 days. Compressive strength tests were carried out in accordance with BS EN 12390-3 using a compression testing machine. Results showed that compressive strength increased with curing age for all mixtures, confirming sustained hydration and pozzolanic activity. The control attained the highest strength (14.76 N/mm² at 90 days), while the 5% and 15% replacement levels achieved comparable long-term strengths, maintaining over 80–90% of the control values. The notable strength gain beyond 28 days indicated a secondary pozzolanic reaction, where reactive silica from the drill cuttings combined with calcium hydroxide to form additional calcium–silicate–hydrate (C–S–H) gel. This study concludes that the incorporation of treated drill cuttings up to 15% as a cement replacement produces sustainable concrete with satisfactory mechanical performance and long-term strength development. The findings promote the valorization of oil-field waste as a viable eco-friendly material for greener concrete production and circular economy advancement in construction.

Keywords: Drill cuttings, compressive strength, curing age, pozzolanic reaction, sustainable concrete.

1. Introduction

Concrete is the most widely used construction material globally, forming the backbone of modern infrastructure. However, its primary binder—Ordinary Portland Cement (OPC)—is a major contributor to environmental degradation. Cement production is responsible for approximately 8% of global CO_2 emissions, as the manufacture of one ton of cement typically releases nearly one ton of carbon dioxide into the atmosphere (Mehta, 2022). Beyond its carbon footprint, cement production is energy-intensive, relying heavily on fossil fuels and high-temperature kilns that further contribute to global warming. Consequently, the search for supplementary cementitious materials (SCMs) that can partially replace cement without compromising concrete performance has become a global priority (Aïtcin, 2016).

Several SCMs, such as fly ash, silica fume, rice husk ash, metakaolin, and ground granulated blast-furnace slag (GGBS), have been widely studied and successfully used to improve the sustainability and performance of concrete (Neville, 2011; Ghosh, 2010). These materials contribute to strength development through secondary hydration reactions, enhance durability, and reduce the embodied carbon of concrete. In recent years, attention has shifted toward the reuse of industrial by-products and drilling wastes as alternative SCMs to further promote environmental conservation and waste management.

Drill cuttings, a waste product generated during oil and gas exploration, are produced in large quantities and often disposed of through landfilling or open dumping, posing environmental risks such as soil and water contamination. When properly treated, however, drill cuttings contain siliceous and aluminous compounds that can exhibit pozzolanic behavior similar to conventional SCMs. Mostavi et al. (2015) evaluated thermally treated drill cuttings as a partial cement replacement and reported acceptable compressive strength up to 10% substitution. Similarly, Dawood et al. (2017) and Huang et al. (2018) found that thermal treatment enhances the pozzolanic activity of drill cuttings by eliminating hydrocarbons and improving chemical reactivity. Tuncan et al.

(2016) and Ibuchukwu and Nwakaudu (2012) also confirmed that utilizing drill cuttings in cement-based materials can significantly reduce environmental pollution and contribute to sustainability in oil-producing regions.

While these studies demonstrated the potential of drill cuttings in concrete production, most of them focused primarily on 28-day compressive strength, providing limited insight into long-term strength development and curing behavior. The relationship between curing age and strength gain—a critical factor for assessing pozzolanic activity—remains largely unexplored for drill cuttings. Extended curing ages (60 to 90 days) often reveal the delayed hydration and secondary reactions characteristic of pozzolanic materials, yet this dimension has been largely omitted in earlier works.

This study therefore addresses this knowledge gap by investigating the influence of drill cuttings replacement levels on the curing age–strength development relationship of concrete. Treated drill cuttings were used to replace cement at 5%, 7.5%, 10%, 12.5%, and 15% by weight, and compressive strength was evaluated at curing ages of 7, 14, 28, 60, and 90 days. The novelty of this research lies in its comprehensive long-term analysis of drill-cuttings-blended concrete, the establishment of an age–strength correlation, and the identification of an optimum replacement level that balances early and late strength performance. Additionally, this study demonstrates the feasibility of transforming oil-field waste into a value-added cementitious material, offering a dual benefit of reducing cement consumption and mitigating environmental pollution through sustainable waste valorization.

2. Materials and Method

2.1 Materials

Ordinary Portland Cement (OPC) grade 42.5R was used as the main binder. River sand served as fine aggregate, and crushed granite (20 mm maximum size) as coarse aggregate. Drill cuttings were obtained from an oil drilling site, oven-dried at 500°C for 3 hours, and thermally treated to remove hydrocarbons. The treated cuttings were then ground and sieved through a 75 µm sieve to obtain a fine pozzolanic material. Potable water was used for mixing and curing.

2.1.1 Equipment Used

- Weighing balance (accuracy ±0.1 g)
- Concrete mixer
- Slump cone apparatus (for workability test)
- 150 mm × 150 mm × 150 mm steel cube moulds
- Curing tank filled with clean water
- Compression testing machine.

2.2 Method

Concrete was batched at a mix ratio of 1:2:4 (cement:sand:coarse aggregate) and a constant water–binder ratio of 0.60. Cement was replaced by drill cuttings at 0% (control), 5%, 7.5%, 10%, 12.5%, and 15% by weight.

2.2.1 Batching and Mixing:
Materials were weighed according to mix proportions. The dry components (cement or cement–cuttings blend, fine aggregate, and coarse aggregate) were mixed thoroughly until uniform. Water was gradually added and mixed until a homogeneous mixture was achieved.

2.2.2 Workability Test:
The slump test was performed using a standard cone in accordance with BS EN 12350 to determine the consistency of the concrete.

2.2.3 Casting of Specimens:
Fresh concrete was poured into cube moulds in three layers, each layer tamped 25 times using a steel rod to eliminate air voids. The top surface was leveled and smoothed.

2.2.4 Demoulding and Curing:
The specimens were left in the moulds for 24 hours at room temperature (20–25°C). After demoulding, cubes were submerged in a curing tank containing potable water maintained at ambient temperature until the designated testing ages of 7, 14, 28, 60, and 90 days.

2.2.5 Compressive Strength Test:
After curing, the cubes were removed, surface-dried, and tested for compressive strength using a compression testing machine

following BS EN 12390-3. The load was applied continuously at a rate of 0.6 N/mm²/s until failure. Compressive strength was calculated as:

Fc = $\frac{P}{A}$ to obtain the compressive strength values.

Where Fc = Compressive Strength of the Concrete Cube

P = Load at Failure

A = Cross Sectional Area of Cube

The mean of three specimens was recorded for each curing age and replacement level.

3. Results and Discussion

This section presents and interprets the results obtained from the experimental investigation on concrete incorporating treated drill cuttings as a partial replacement for cement. The discussion covers the mix proportions, workability characteristics, and compressive strength development at different curing ages.

3.1. Mix Design.

The concrete was designed using a 1:2:4 mix ratio (cement : fine aggregate : coarse aggregate) and a constant water–binder ratio of 0.60. Ordinary Portland Cement (OPC) was replaced with treated drill cuttings at proportions of 5%, 7.5%, 10%, 12.5%, and 15% by weight of cement. The mix proportions used for the experimental work are presented in Table 1.

Table 1. Mix Design for Mix Ratio of 1:2:4

Constituent material	0% DC	5% DC	7.5% DC	10% DC	12.5% DC	15% DC
Cement (kg)	1.2	1.14	1.11	1.08	1.05	1.02
Drill cuttings (kg)	0.0	0.06	0.09	0.12	0.15	0.18
Sand (kg)	2.3	2.3	2.3	2.3	2.3	2.3
Gravel (kg)	4.6	4.6	4.6	4.6	4.6	4.6
W/B ratio	0.60	0.60	0.60	0.60	0.60	0.60
Total water (kg)	0.66	0.66	0.66	0.66	0.66	0.66

Note. DC = Drill Cuttings.

The total binder content was maintained at a constant level for all mixes to ensure uniformity. Fine and coarse aggregates were batched by weight, and mixing was performed manually until a consistent color and uniform texture were achieved.

3.1.2. Workability of Concrete

The workability of fresh concrete was determined through slump testing in accordance with BS EN 12350-2. The results revealed a progressive reduction in slump with increasing replacement of cement by treated drill cuttings. This behavior is attributed to the fine texture and high surface area of the drill cuttings, which increased the water demand and reduced the fluidity of the mix.

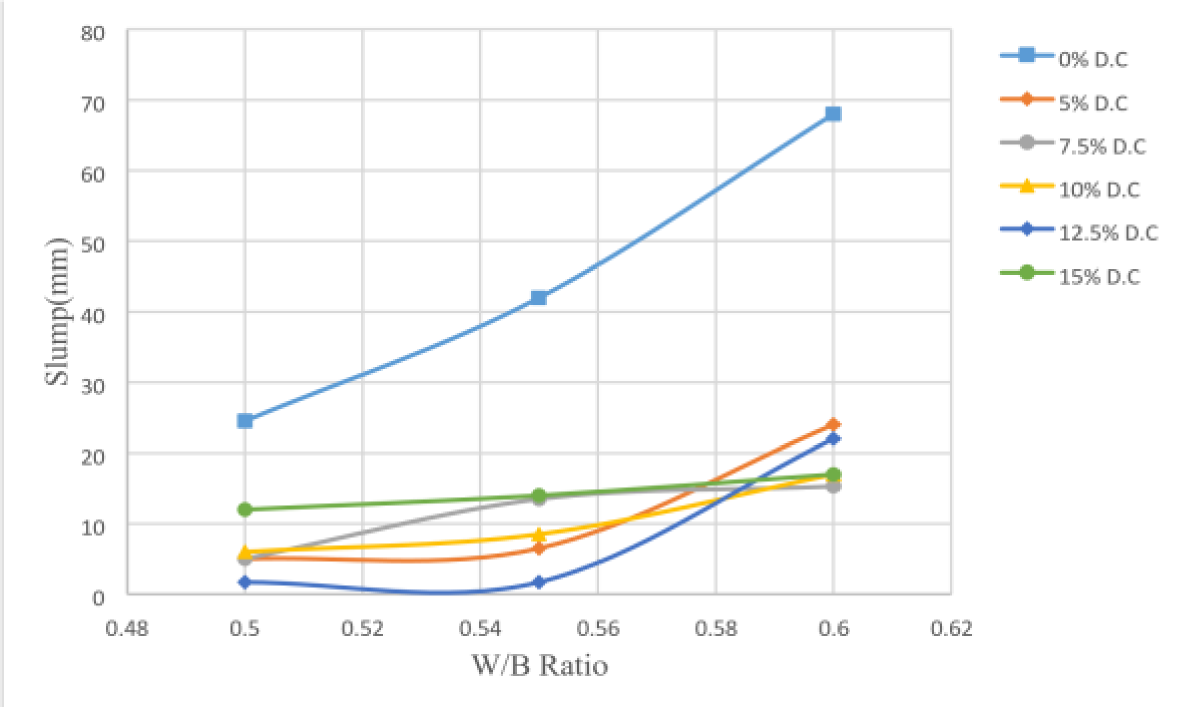


Figure 1. Variation of slump at different water-binder ratio with drill cuttings replacement level

The decline in workability agrees with findings by Mostavi et al. (2015) and Huang et al. (2018), who reported that incorporating treated drill cuttings and other fine pozzolanic materials reduces concrete's slump. Nonetheless, all mixes remained workable and suitable for normal-weight concrete applications.

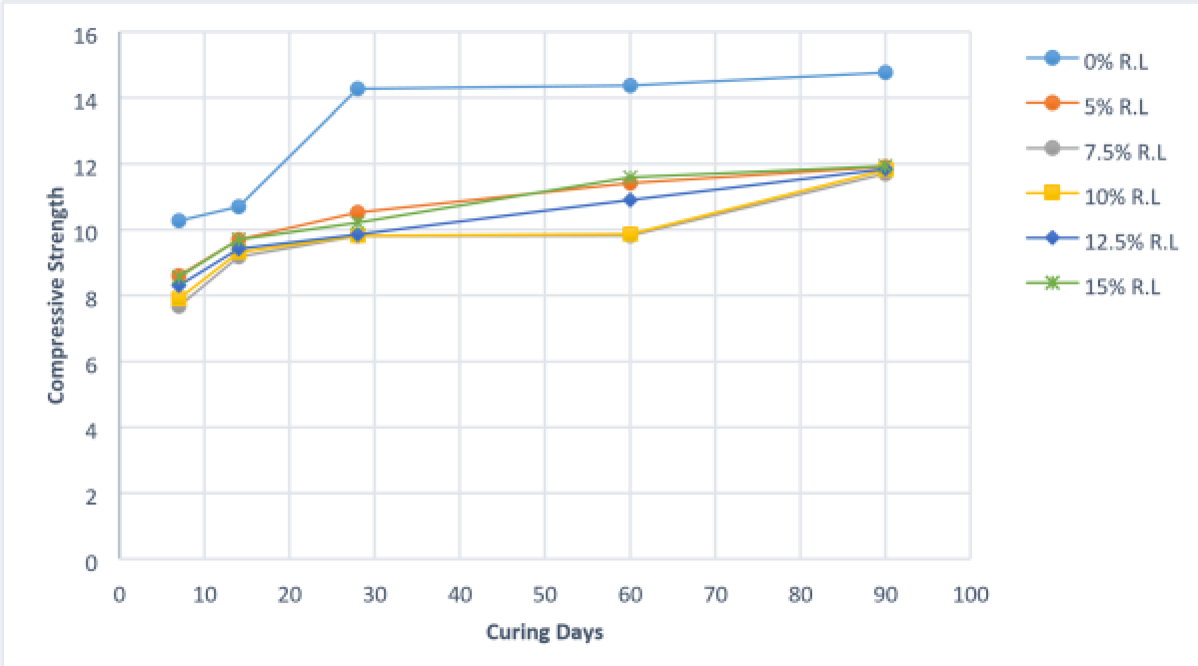
3.1.3 Compressive Strength of Concrete

Compressive strength tests were conducted at curing ages of 7, 14, 28, 60, and 90 days in accordance with BS EN 12390-3:2009. The results are summarized in Table 2.

Table 2. Compressive strength of concrete at different replacement levels of drill cuttings at 7, 14, 28, 60, and 90 days curing time

Curing Time (Days)/Replacement Levels (%)	0 %	5%	7.5%	10%	12.5%	15%
7	10.27	8.6	7.67	7.9	8.3	8.56
14	10.7	9.57	9.17	9.31	9.42	9.7
28	14.27	10.52	9.8	9.81	9.85	10.21
60	14.37	11.42	9.81	9.86	10.9	11.59
90	14.76	11.91	11.7	11.81	11.84	11.93

Figure 2. compressive strength versus Curing age of concrete mixes (All mixes exhibit continuous strength gain; 5% and 15% replacement levels show comparable long-term performance to the control.)



3.2 Discussion

The compressive strength of all mixes increased progressively with curing age, confirming the continuation of hydration and the pozzolanic activity of treated drill cuttings. At 7 days, the control mix achieved 10.27 N/mm², while the 5% and 15% mixes attained 8.60 N/mm² and 8.56 N/mm², respectively, showing a slight early-age strength reduction due to reduced cement content and slower hydration.

At 28 days, the control mix recorded the highest strength of 14.27 N/mm². The 5% replacement achieved 10.52 N/mm², and the 15% replacement reached 10.21 N/mm², representing strength reductions of approximately 26–33% relative to the control. However, these levels remain within acceptable limits for general structural applications.

Long-term results demonstrated a notable increase in strength between 28 and 90 days for the drill cuttings mixes. The 5% mix gained 13.2% additional strength (from 10.52 to 11.91 N/mm²), while the 15% mix improved by 22.4% (from 10.21 to 11.93 N/mm²). This indicates delayed pozzolanic reactions between the amorphous silica and alumina in the drill cuttings and calcium hydroxide from cement hydration, forming additional calcium–silicate–hydrate (C–S–H) that enhances the matrix.

Although higher replacement levels (10% and 12.5%) exhibited lower overall strengths, they continued to gain strength with prolonged curing, confirming the extended pozzolanic reactivity of the treated material. The results align with studies by Dawood et al. (2017) and Tuncan et al. (2016), who reported similar delayed but sustained strength growth in concretes containing thermally treated drill cuttings.

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