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Study of high-Performance concrete mixtures with residual Fluid Catalytic Cracking using Simplex-Centroid design method

Nghiên cứu bê tông tính năng cao sử dụng xúc tác FCC thải bằng phương pháp thiết kế Simplex-Centroid

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ABSTRACT

This study investigates the properties of high-performance concrete (HPC) mixtures, including residual fluid catalytic cracking (RFCC). Using the Simplex-Centroid Design Methodology, the RFCC is optimized by partly replacing silica fume and quartz powder in a high-performance concrete mixture. The study investigates both the benefits and drawbacks of RFCC implementation in HPC. Although RFCC enhances compressive strength, its water absorption characteristics may decrease flowability. The analysis results show that adequate RFCC proportioning can minimize variations in compressive strength, whereas adding silica fume is essential to preserving the compressive strength of HPC containing RFCC.

Keywords: RFCC; HPC; simplex centroid design; compressive strength; and slump flow.

TÓM TẮT

Bài báo đã nghiên cứu khảo sát thuộc tính của hỗn hợp bê tông tính năng cao (HPC), sử dụng chất xúc tác FCC thải (RFCC). Áp dụng phương pháp thiết kế Simplex-Centroid, lượng RFCC thay thế một phần silicafume và bột đá có trong hỗn hợp bê tông tính năng cao được tối ưu hóa. Bài báo khảo sát điểm mạnh và hạn chế của việc tái sử dụng RFCC trong HPC. Mặc dù RFCC giúp tăng cường cường độ nén nhưng khả năng hút nước nhiều của nó có thể làm giảm độ chảy xoè. Kết quả phân tích cho thấy tỷ lệ RFCC thích hợp có thể giảm thiểu sự thay đổi cường độ nén, và việc bổ sung silicafume là cần thiết để duy trì cường độ nén của hỗn hợp bê tông HPC có RFCC.

Từ khoá: RFCC; HPC; phương pháp simplex centroid; cường độ nén và độ chảy xoè

1. INTRODUCTİON

Since the 1990s, high-performance concrete (HPC) has gained significant traction in construction projects, and its usage is now widespread globally. In 1993, the American Concrete Institute (ACI) provided an extensive definition for HPC, describing it as concrete that meets specific performance and consistency criteria beyond what conventional materials and construction practices can typically achieve. These performance benchmarks may include improvements in placement and compaction to prevent segregation, long-term mechanical strength, early-age durability, resilience, dimensional stability, or longevity, especially in harsh environmental conditions [1].

Since the introduction of high-performance concrete (HPC) [2], its excellent mechanical properties and durability have attracted the attention of scholars in the field of engineering materials [3]. Its engineering application has significantly reduced structures' self-weights, improved their spans, strengths, and durability, and extended their service lives[4, 5]. Because of these advantages, HPC has considerable potential for the construction of buildings[6], bridges [7], and tunnels [8], as well as for marine engineering [9] and military engineering. The mechanical behavior and durability of HPC affect its service life in engineering applications. Moreover, the flowability of HPC significantly affects its hardened properties [10].

High-performance concrete (HPC) is engineered to possess greater durability and, when necessary, higher strength than standard concrete. HPC blends typically consist of the same basic materials found in traditional concrete blends, but their proportions are meticulously adjusted to meet the structural and environmental demands of the project. Concrete is considered high-strength when it achieves a specified compressive strength of 8000 psi (55 MPa) or higher. This threshold was chosen because it signifies a strength level that warrants special attention in concrete production and testing processes and potentially necessitates unique structural design considerations.

High-strength concrete is a critical material in modern construction, prized for its enhanced durability, structural performance, and versatility. In pursuing sustainable construction practices, there is an increasing demand for optimizing raw materials and reducing the environmental impact of concrete production. One significant aspect of this endeavor is managing waste generated during the production of high-strength concrete, particularly the waste generated from the residue fluid catalytic cracking (RFCC) catalysts.

The RFCC process plays a vital role in the petrochemical industry, facilitating the conversion of heavy hydrocarbons into valuable products such as gasoline and diesel fuel. However, this process generates a substantial quantity of RFCC, which, if not managed efficiently, poses environmental challenges and impacts the overall sustainability of construction projects [11]. By strategically incorporating this waste material into concrete mixes, we can reduce the demand for traditional raw materials, such as cement and aggregates, while providing an environmentally responsible solution for managing RFCC waste.

Quartz powder comprises less than 0.075 mm particles, while silica fume comprises ultra-finely particles with diameters ranging from 0.15 to 0.20 µm. The particle diameter of RFCC is less than 0.1 mm [12]. This research examines the potential of using RFCC as a substitute for silica fume and quartz powder. The study aims to optimize the utilization of RFCC waste in high-strength concrete by partially replacing silica fume and quartz powder.

In order to achieve this objective, a simplex-centroid design process is used to determine the optimal amounts of RFCC, silica fume, and quartz powder. The desired slump flow of the mixture should exceed 35 cm while maximizing the compressive strength. An analysis of the test results on concrete mixes designed using the simplex-centroid design process reveals many advantages and disadvantages of implementing RFCC in HPC.

2. SIMPLEX-CENTROID DESIGN METHODOLOGY

Simplex-centroid design (SCD) is an alternate design that allows the estimation of all coefficients in the special cubic model [13]. Given that the number of optimum components is n and the proportion of the i^th^ component is x_i in a mixture, the number of considered distinct points is 2^n-1, and the proportion of each component is limited by:

$x_i \geq 0, i = 1,2,3,\dots,n;$ and $x_1 + x_2 + \cdots + x_i \dots + x_n = 1$

The $2^n - 1$ measurements in the simplex centroid design are composed of n pure component composites, C_n^2 binary mixtures with equal proportions, C_n^3 ternary mixtures with equal proportions, and so forth, finally leading to an n-component mixture with equal proportions.

Figure 1 displays the SCD for the three mixture components, with n = 3. There are a total of seven mixtures, each consisting of equal proportions. These mixtures include pure component mixtures, binary mixtures, and a ternary mixture. For mixtures consisting of pure components, there are three n-component mixtures: (1,0,0), (0,1,0), and (0,0,1). Binary mixes consist of three combinations with equal proportions of n-components: (1/2,1/2,0), (1/2,0,1/2), and (0,1/2,1/2). In a ternary mixture, a component is present in equal proportions of 1/3.

In a mixture experiment, the controllable variable x_i must adhere to the foundational constraint that the sum of components is 100%. In real issues, additional limits may exist, such as establishing a maximum or minimum limit for each component. In this case, the SCD should be modified. The mixture experiment design with lower and upper bound constraints has been solved using pseudo-components. The actual experiment region is the polygon within the pseudo-region, as illustrated in Figure 3, under the constrained conditions.

The design points within the simplex centroid design method conform to the polynomial:

$$y = \sum_{i=1}^{p} \beta_i x_i$$

In this case, there are three components designed for the mixture experiment. The polynomial could be rewritten as follows:

$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3,$

the constrain $x_1 + x_2 + x_3 = 1$.

The polynomials are derived for all investigated mixture properties and are used to identify an optimal mixture.

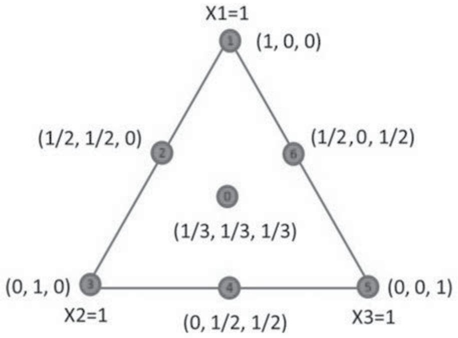


Figure 1. The scheme for the simplex-centroid design

3. EXPERIMENTAL INVESTIGATION

The experimental materials are typically used for High-Performance Concrete (HPC). They comprise PC50 cement, Silica fume, fine sand, quartz powder, RFCC, superplasticizer admixture, and water.

PC50 cement

This study utilizes PC50 cement. This type of cement has a compressive strength of 29.7 MPa at three days and 55.2 MPa at 28 days, which is suitable for HPC.

Silica fume

Silica fume is a byproduct of the production of silicon or silicon alloys in electric arc furnaces. Quartz is heated to 2000°C in an electric furnace that utilizes wood particles, coal, or coke. Silica fume is generated when fume condenses and oxidizes in the vicinity of the furnace's summit. The purity of silica fume depends on the quantity of silica [14]. Silica fume is ultra-finely pulverized, with particle diameters ranging from 0.15 to 0.20 µm. Consequently, to obtain workability, concrete necessitates increased water and a superplasticizer [15].

Quartz sand

The fine white sand used in the experiment is fine-grained, clean, and free from impurities and foreign matter. The sand has particle diameters ranging from 0.15 to 0.3 mm.

Quartz powder

The Quartz powder, usually limestone powder, has particle diameters smaller than 0.075 mm. The addition of limestone filler to Portland cement alters the kinetics and mechanism of cement hydration in a number of aspects. Calcite (calcium carbonate: $CaCO_3$) is the main mineral that makes up limestone. High concentrations of calcium and/or magnesium carbonate and tiny amounts of other minerals are found in large quantities in limestone, which occurs naturally and is widely distributed.

Superplasticizer admixture

In this study, we utilized ADVA CAST 5388V admixture. This is a high-range water-reducing polymer admixture designed explicitly for concrete production.

Water

The water used for concrete mixture preparation is laboratory tap water. This water ensures cleanliness, the absence of impurities, and no chemical mixtures that could affect the concrete setting process or reduce the strength of the concrete structure during use.

RFCC

RFCC waste is a catalyst in the petroleum cracking process, and after multiple processes, it loses its activity and becomes RFCC waste (Figure 2). The RFCC spent catalyst significantly improves the compressive strengths due to its relatively strong pozzolanic property. [16].

Figure 2. Residue fluid catalytic cracking

Mix design and sample preparation

In this investigation, RFCC partially replaced quartz powder and silica fumes. The volume of quartz powder and silica fume in one cubic meter of concrete is 0.169 m^3, as determined by the conventional mixture proportion of HPC. The Simplex Centroid Design methodology is used to determine the test mixture compositions, which are subject to a volume constraint of 0.169 m^3 for RFCC, quartz powder, and silica fume, as illustrated in Figure 3.

Table 1 summarizes the material proportions of the mixtures under consideration, in which the mixtures were named CI-CV. Each mixture corresponds to a single point in Figure 3. The materials changing proportions are silica fume, Quartz powder, and RFCC, while the unchanged materials are cement, Quartz sand, superplasticizer, and water.

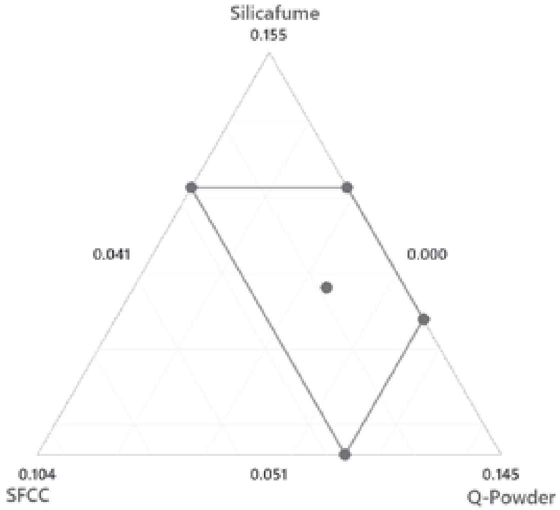


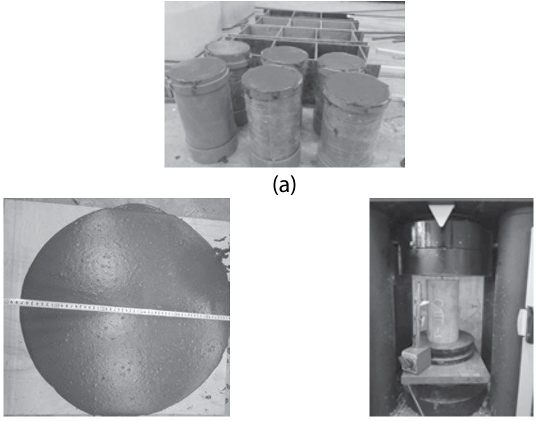
Figure 3. Design concrete mixture compositions

Experimental specimens measuring 100mmx200mm were used for compression tests. There was a total of five mixed designs. Each mix design had three specimens. Before testing, the compression specimens were ground flat on both ends to prevent localized damage caused by poor contact between the specimen and the steel plates. The specimens were cast using PVC pipe molds and poured from the top, as depicted in Figure 4a.

Table 1. Mixture composition in cubic meters

Mixtures	CI	CII	CIII	CIV	CV
Water (kg)	188	188	188	188	188
Superplasticizer (Kg/m^3)	24	24	24	24	24
Silica fume(kg/m^3)	265	265	208	113	190
Cement PC50 (kg/m^3)	794	794	794	794	794
RFCC (kg/m^3)	79	0	39	79	0
Quartz powder (kg/m^3)	109	201	223	292	292
Quartz sand (kg/m^3)	881	881	881	881	881
RFCC/ Cement (%)	10	0	5	10	0
Silica fume/ Cement (%)	33	33	26	14	24

Furthermore, Figure 4b illustrates the concrete mixture's remarkable self-consolidating capacity by illustrating its slump flow during a slumping flow test. The testing instrument is a multipurpose testing device that is capable of conducting compression tests. The highest load capacity of the compression testing machine is 3000 kN, as illustrated in Figure 3c.


(a)

(b) (c)

Figure 4. Test process: (a) Sample preparation, (b) Slump flow test, and (c) Compressive strength test.

3. EXPERIMENTAL RESULTS

Slump flow

A concrete mix's self-flow distance is tested. Pour concrete into a cone on an impermeable plate for the test. The cone is raised vertically to release concrete after filling. The tester will measure the concrete diameter for flow. Self-consolidating concrete mixes undergo flow testing often. The wetness of these mixtures makes slump testing harder. Flow tests also determine whether concrete can fill forms without vibration, especially in reinforced projects. High-performance concrete exhibits good flowability, a mini-slump flow of 160 mm [17, 18].

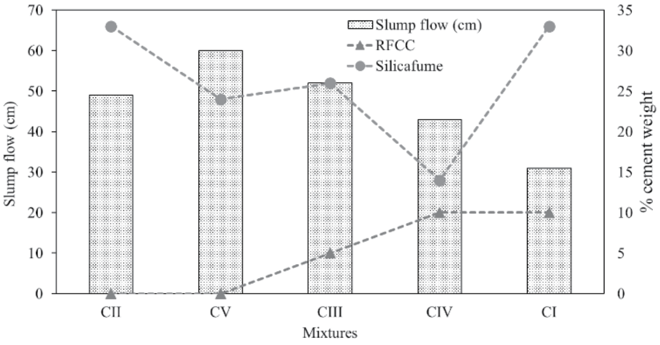


Figure 5. Slump flow of test mixtures

The slump flow information for the quartz powder and silica fume, which RFCC has replaced, is depicted in Figure 5. The figure also includes the percentage of silica fume and RFCC in the concrete mixtures. The flow changes of CI-CV range from 31 cm to 60 cm. It is important to note that the mixture CI reaches a low point at 31 cm, whereas the mixture CV reaches its maximum at 60 cm.

The graph demonstrates an upward trend of slump flow along with the decreasing proportion of silica fume in concrete mixes without RFCC. This is evident from the slump flow values seen in the cases of CII and CV. In addition, the slump flow reduces as the proportion of RFCC increases, regardless of the variety of silica fume in the concrete mixtures. The slump flow values of CV, CIII, CIV, and CI support this. The results indicate that RFCC demonstrated a notable ability to absorb water compared to silica fume, decreasing the slump flow of the mixtures.

Compressive strength

Figure 6 depicts the compressive strength of the examined mixes after 28 days. The compressive strengths range from 61.8 MPa to 83.5 MPa, meeting the strength requirements for high-performance concrete (HPC). Unlike mixture CIII, which has a minimum value of 61.8 MPa, mixture CI has the highest value of 83.5 MPa.

The graph demonstrates a clear correlation between the decreased proportion of silica fume in concrete mixes without RFCC and the decrease in compressive strength. The compressive strength values of CII and CV support this. In addition, the compressive strength of the concrete mixtures increases as the proportion of RFCC increases, regardless of the variability of silica fume. The compressive strength values of CV, CIII, CIV, and CI support this. The results indicate that RFCC demonstrated the ability to absorb water and reduce the slump flow while simultaneously increasing the compressive strength of the concrete mixes.

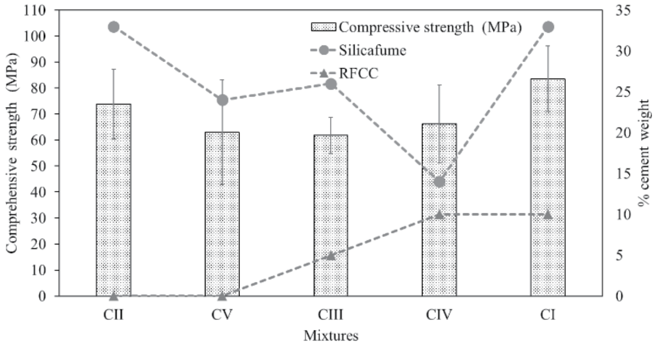


Figure 6. Compressive Strength

RFCC influences compressive strength and slump flow

Figure 7 and Table 2 supply data on the compressive strength (in MPa) and slump flow (in cm) values of the five mixtures of concrete that were investigated. Additionally, the horizontal axis of Figure 7 illustrates the proportion of RFCC in the concrete mixture (see Table 1).

The graph depicted in Figure 7 provides an obvious graphical illustration of the impact of including RFCC on the water absorption capacity, slump flow, and compressive strength of the concrete mixes. It demonstrates that adding RFCC led to an increase in water absorption capacity, a decrease in slump flow, and an improvement in compressive strength. The standard deviation of the compressive strength of CI (10% RFCC) is 12.6, which is lower than the standard deviations of CII (13.4) and CV (20.1). CII and CV are concrete mixes that do not contain RFCC. It suggests that adding RFCC to concrete mixes might decrease the variability in compressive strength as long as an appropriate quantity of RFCC is used.

Table 2. Compressive strength and Slump flow test results

Mixtures	Compressive strength (MPa)	Compressive strength standard deviation	Slump flow (cm)
CI	83.5	12.6	31.0
CII	73.8	13.4	49.0
CIII	61.8	6.9	52.0
CIV	66.2	15.0	43.0
CV	62.9	20.1	60.0

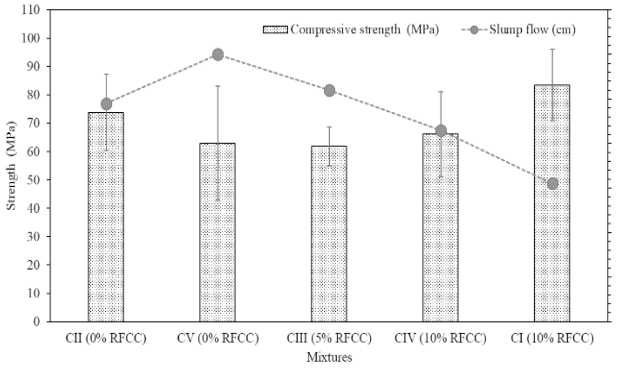


Figure 7. The relationship between Compressive Strength and Slump flow

4. OPTIMIZATION OF THE RFCC IN HPC MIXTURES

Based on the Simplex-Centroid Design Methodology, the optimum point could be estimated according to desired conditions. The obtained optimum point is selected based on the constraint of slump flow and compressive strength. The slump flow should be higher than 35cm, while the compressive strength is the highest value. The optimum prediction point exhibits a compressive strength of 79 MPa and a slump flow of 38.8 cm, as shown in Figure 7.

However, decreasing the amount of silica fume decreases the compressive strength of the identified optimal point. Limiting the usage of silica fume is suggested due to its comparatively high cost compared to other components in the concrete mix. Concrete mix with RFCC utilizes silica fume as an essential ingredient in their concrete mixture to enhance its compressive strength.

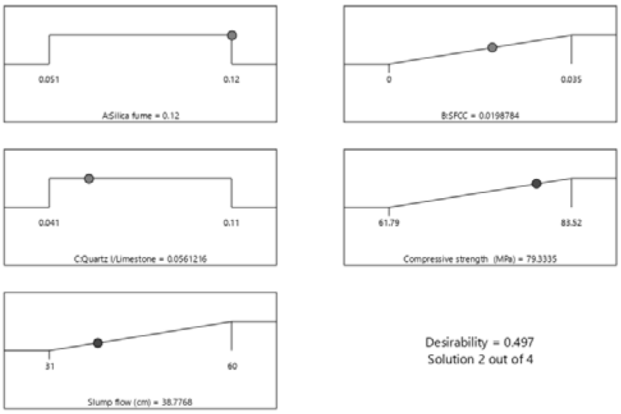


Figure 8. Solutions prediction

Figure 8 presents the optimum point in the explored zone. The optimum point corresponds to silica fume, RFCC, and Quartz powder weight: 265, 45, and 149 kg per cubic meter of concrete mix, respectively. In this instance, RFCC corresponds to 6% of the weight of cement in the concrete mixture.

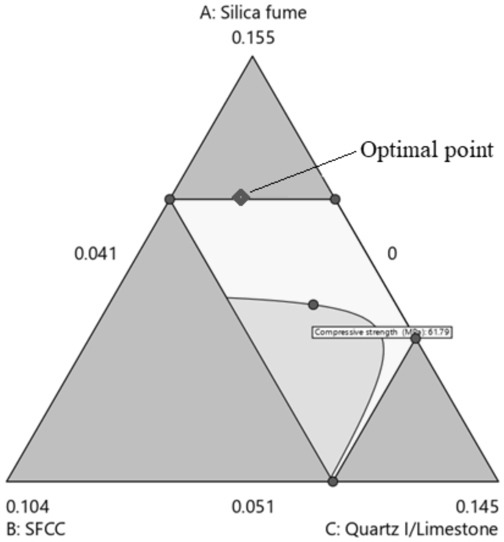


Figure 9. Optimal prediction point

Additional investigation and testing are necessary to determine the benefits and drawbacks of using RFCC in high-performance concrete.

5. CONCLUSION

Firstly, the compressive strength of the RFCC-based mixtures exhibits significant variability, ranging from 48.69 MPa to 92.43 MPa. Secondly, slump flow measurements across the RFCC-based mixtures vary from 31.00 cm to 60.00 cm. This variability underscores the influence of mixture proportions of constituent materials partly replaced by RFCC on concrete strength and slump flow. Notably, several mixtures, including CI-CV, demonstrate compressive strengths exceeding 60 MPa and the slump flow exceeding 35 cm, which meets the criterion for high-performance concrete.

The research indicates that using RFCC in concrete mixes has various benefits and drawbacks. The addition of RFCC to concrete mixes demonstrated its ability to absorb water and reduce the flow of the mixture while simultaneously enhancing the compressive strength. Incorporating RFCC into concrete mixes can reduce the variability in compressive strength, provided that the correct amount of RFCC is used. The concrete mixture containing RFCC has silica fume as a crucial component to improve its compressive strength.

REFERENCES

[1] M. Narmatha and D. Kala, "METAKAOLIN –THE BEST MATERIAL FOR REPLACEMENT OF CEMENT IN CONCRETE," *International Journal of Advanced Research,* vol. 4, pp. 1690-1696, 07/31 2016.

[2] W. Meng, M. Valipour, and K. Khayat, "Optimization and performance of cost-effective ultra-high performance concrete," *Materials and Structures,* vol. 50, p. 29, 08/01 2016.

[3] W. Mansour, M. Sakr, A. Seleemah, B. Tayeh, and T. Khalifa, "Development of shear capacity equations for RC beams strengthened with UHPFRC," *Computers and Concrete,* vol. 27, pp. 473-487, 05/28 2021.

[4] S. Hanipah, F. Mohamed Nazri, R. Putra Jaya, N. K. Baharuddin, and B. Abu, "Evaluation of Bond Strength between Fire-Damaged Normal Concrete Substance and Ultra-High-Performance Fiber-Reinforced Concrete as a Repair Material," *World Journal of Engineering,* vol. 13, pp. 1-8, 10/03 2016.

[5] B. Tayeh, B. H. Bakar, M. A. Megat Johari, and Y. Voo, "Utilization of Ultra-high Performance Fibre Concrete (UHPFC) for Rehabilitation - A Review," *Procedia Engineering,* vol. 54, pp. 525–538, 12/31 2013.

[6] C.-C. Hung and C. H. Yen, "Compressive Behavior and Strength Model of Reinforced UHPC Short Columns," *Journal of Building Engineering,* vol. 35, p. 102103, 12/01 2020.

[7] A. Semendary, W. Hamid, E. Steinberg, and I. Khoury, "Shear friction performance between high strength concrete (HSC) and ultra high performance concrete (UHPC) for bridge connection applications," *Engineering Structures,* vol. 205, p. 110122, 02/15 2020.

[8] Q. Meng *et al.*, "Steel/Basalt Rebar Reinforced Ultra-High Performance Concrete Components against Methane-Air Explosion Loads," *Composites Part B: Engineering,* vol. 198, p. 108215, 07/01 2020.

[9] Q. Song, R. Yu, Z. Shui, S. Rao, D. Fan, and X. Gao, "Macro/micro characteristics variation of ultra-high performance fibre reinforced concrete (UHPFRC) subjected to critical marine environments," 11/08 2020.

[10] T. Jirout, A. Krupica, and A. Kolomijec, "CFD Analysis of Ultra-High-Performance Concrete Rheological Tests," *Fluids,* vol. 9, p. 45, 02/11 2024.

[11] D. D. Do, H. M. Bui, and C.-S. J. S. C. O. W. Tran, "Residue Fluidized Catalytic Cracking in Lightweight Polystyrene Concrete: A Sustainable Construction Solution," p. 100003, 2024.

[12] A. Allahverdi and M. J. C. S. Mahdavan, "Durability performance of rfcc spent catalyst-blended portland cement paste exposed to sea water attack," vol. 57, no. 4, pp. 305-312, 2013.

[13] Y. Chen *et al.*, "Preparation and performance of the ultra-high performance mortar based on simplex-centroid design method," vol. 15, pp. 3060-3077, 2021.

[14] M. Mazloom, A. Ramezanianpour, J. J. C. Brooks, and c. composites, "Effect of silica fume on mechanical properties of high-strength concrete," vol. 26, no. 4, pp. 347-357, 2004.

[15] M. Panjehpour, A. A. A. Ali, R. J. I. J. o. S. C. E. Demirboga, and Technology, "A review for characterization of silica fume and its effects on concrete properties," vol. 2, no. 2, 2011.

[16] A. Allahverdi, M. N. Shahrbabaki, M. Ghezelasheghi, and M. J. B. d. I. S. E. d. C. y. V. Mahinroosta, "Sulfate resistance of RFCC spent catalyst-blended Portland cement," vol. 58, no. 3, pp. 103-114, 2019.

[17] J. Du *et al.*, "New development of ultra-high-performance concrete (UHPC)," vol. 224, p. 109220, 2021.

[18] V. Perry and P. Eng, *What Really is Ultra-High Performance Concrete? -Towards a Global Definition*. 2018.