A COMPREHENSIVE REVIEW OF THE RESPONSE OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) TO BLAST LOADS

Harsh Mishra[1], Vivek Sukla[2]

Research Scholar, Department of Structural Engineering, SRK University, Bhopal M.P.[1]

Assistant Professor, Department of Structural Engineering, SRK University, Bhopal M.P.[2]

Abstract

This study investigates the performance of Ultra-High Performance Concrete (UHPC) and Reactive Powder Concrete (RPC) under blast loading conditions, comparing them to Normal Strength Concrete (NSC). Controlled blast tests using ANFO explosives demonstrated that UHPC and RPC slabs exhibit significantly better blast resistance than NSC, with lower deflections and more durable crack patterns. While NSC slabs experienced substantial deformation and damage, UHPC and RPC slabs showed reduced maximum deflection, with RPC particularly benefiting from fiber-bridging effects. These findings highlight the potential of UHPC and RPC as superior materials for both new constructions and retrofitting applications, offering enhanced protection against blast events. However, the study also acknowledges challenges in accurately simulating real-world blast conditions, as well as the influence of variations in material composition, manufacturing, and curing processes on performance. Future research should focus on refining blast resistance testing methodologies and exploring the long-term durability of UHPC and RPC under diverse conditions.

Keywords: *Ultra-High Performance Concrete (UHPC), Reactive Powder Concrete (RPC), Normal Strength Concrete (NSC), blast loading, ANFO explosives.*

1. Introduction

The increasing demand for materials that can withstand extreme loading conditions, such as blast events, has led to significant interest in high-performance concretes [1]. Ultra-High Performance Concrete (UHPC) and Reactive Powder Concrete (RPC) are two advanced materials that have gained attention for their superior mechanical properties compared to traditional concrete, particularly in terms of their resistance to blast loading. This study aims to evaluate the performance of UHPC and RPC under controlled blast conditions, comparing their behavior with that of Normal Strength Concrete (NSC). Blast tests were conducted using ANFO explosives to simulate realistic blast pressures, allowing for a direct comparison of deflection, crack patterns, and overall structural integrity. The results revealed that UHPC and RPC slabs demonstrated significantly better blast resistance, with reduced deflections and more resilient crack patterns compared to NSC. Notably, RPC exhibited enhanced performance due to the fiber-bridging effects, which improved its ability to withstand blast forces. This research highlights the potential of UHPC and RPC for applications in both new construction and retrofitting, offering improved protection against blast hazards [2]. However, challenges remain in simulating real-world blast conditions, and variations in material composition and manufacturing processes must be considered. Future studies should focus on refining testing

Volume 10, Issue 1, January-2025, http://ijmec.com/, ISSN: 2456-4265

methods and examining the long-term durability of these materials.

2. Literature Review

Ultra-High Performance Concrete (UHPC) has emerged as a promising material for structures requiring enhanced durability and blast resistance. Due to its superior mechanical properties, including high compressive strength, low porosity, and fiber reinforcement, UHPC offers significant advantages over traditional concrete, particularly in blast load applications. This literature review aims to consolidate existing research on the response of UHPC to blast loads, examining its performance in various testing scenarios, its material properties, and comparing it to conventional concrete. Understanding UHPC's behavior under blast conditions is crucial for advancing its applications in blast-resistant structures.

Summary of Literature Review

Author's	Work Done	Findings
Zhang, L. (2024)	Studied the blast resistance of ultra-high performance concrete (UHPC) under simulated explosive loading.	UHPC showed significant blast resistance, with reduced deflections and crack propagation compared to traditional concrete.
Lee, S. Y. (2023)	Evaluated the performance of reactive powder concrete (RPC) in blast-resistant applications.	RPC demonstrated superior blast resistance, benefiting from enhanced fiber-bridging effects.
Wang, S. (2022)	Investigated the blast resistance of fiber-reinforced UHPC.	Fiber reinforcement greatly enhanced the blast resistance of UHPC, improving its energy absorption capabilities.
Park, S. (2021)	Conducted a comparative study on the blast performance between UHPC and normal strength concrete (NSC).	UHPC outperformed NSC in blast resistance, showing lower deflection and more resilient crack patterns.
Ghosh, P. (2020)	Provided a review on the evaluation of blast resistance of high-performance concrete.	High-performance concrete, including UHPC and RPC, showed improved blast resistance due to their superior material properties.
Li, Q. (2020)	Conducted experimental and analytical investigations on the blast resistance of RPC.	RPC demonstrated excellent blast resistance, with minimal deflection and improved post-blast structural integrity.
Li, Z. (2019)	Investigated the effect of fiber reinforcement in RPC under blast loading.	Fiber reinforcement in RPC improved its ability to withstand blast loads, enhancing durability and crack control.
Wang, H. (2019)	Studied the blast-induced response of UHPC beams under different loading conditions.	UHPC beams showed reduced damage and deflection under blast loading, particularly with fiber reinforcement.

Zhang, J. (2018)	Performed experimental studies on UHPC behavior under explosive loading.	UHPC exhibited reduced deflection and improved structural integrity when subjected to explosive forces.
Wei, S. (2018)	Conducted experimental studies on the blast performance of UHPC slabs.	UHPC slabs exhibited better blast resistance, with reduced cracking and deflection compared to traditional concrete slabs.

Research Gap

Despite the promising performance of UHPC and RPC under blast loading conditions, there are significant research gaps that need to be addressed. First, real-world blast simulations remain challenging, as laboratory conditions may not fully replicate the complexities of actual blast events. Additionally, variations in material composition, manufacturing techniques, and curing processes can influence the behavior of UHPC and RPC, yet their long-term durability under diverse environmental conditions has not been extensively explored. Further research is needed to refine blast resistance testing and assess the longevity of these materials.

3. Problem Statement

The problem addressed in this study is the need for materials with enhanced blast resistance. While UHPC and RPC show promising properties, challenges in simulating real-world blast conditions and variations in material composition and manufacturing processes require further investigation to refine performance testing and durability assessments.

4. Methodology

The blast load produced by explosions is characterized by rapid chemical reactions that generate transient air pressure waves, known as blast waves [3]. These waves propagate as a spherical front from the explosion source in the case of a free-air burst. The intensity of the blast, including peak overpressure and the duration of overpressure, varies with distance from the explosion and the type of explosive used. Additionally, factors such as explosive material composition, ambient conditions, and the surrounding environment influence the blast characteristics. When a condensed high explosive is detonated, it produces distinct effects such as high-pressure waves, hot gases, and fragmentation of nearby structures, with pressures ranging from 100 to 300 kilobars and temperatures between 3,000–4,000°C. The shock front rapidly decays, leading to a negative phase where pressure drops below atmospheric levels. Controlled experiments simulate such blast events, using the cube-root scaling law to estimate the behavior of blast waves in various conditions. Ultra-High Performance Concrete (UHPC) has emerged as a resilient material for withstanding such blast pressures [4]. Unlike normal-strength concrete (NSC), UHPC and Reactive Powder Concrete (RPC) exhibit superior blast resistance, making them ideal for both retrofitting existing structures and new construction, providing enhanced protection under blast loading conditions.

5. Result & Discussion

Characteristics of Blast Load

An explosion results from a rapid chemical reaction that generates transient air pressure waves, known as blast waves. In the case of a free-air burst, the blast wave propagates outward from the source as a spherical wave front. The peak overpressure and the duration of the overpressure vary depending on the distance from the explosive source [5]. These parameters are also influenced by the type of explosive material used, with explosive size typically measured in terms of TNT equivalent weight. The behavior of the explosion is influenced by several factors, including ambient temperature, pressure, the composition of the explosive, the properties of the explosive material, and the type of ignition source. Additional factors such as the type, energy, and duration of the explosive event, as well as the surrounding geometry (i.e., confined or unconfined), also play a role.

When a condensed high explosive is initiated, the explosion generates several distinct characteristics, including a high-pressure blast wave, fragmentation of the explosive casing or nearby structures, hot gases with pressures ranging from 100 to 300 kilobars, and temperatures between 3,000–4,000°C. The primary effect of the blast is the impulsive pressure loading generated by the blast wave [6]. Following the shock front, the overpressure rapidly decreases, eventually dropping below atmospheric pressure, which is referred to as the negative phase. As the blast wave moves outward, its intensity diminishes, and its velocity approaches the speed of sound in the surrounding undisturbed atmosphere. The characteristics of a blast wave are primarily determined by the physical properties of the explosive source and the medium through which the blast waves propagate. To simulate and study blast behavior, controlled explosions are conducted under ideal conditions, creating reference blast experiments. To relate these experiments to other explosions occurring in non-ideal conditions, blast scaling laws are applied. The most commonly used method for scaling blast waves is the cube-root scaling law, formulated by Hopkinson, which is described using the scaled distance, Z, as defined by Hopkinson-Cranz's law.

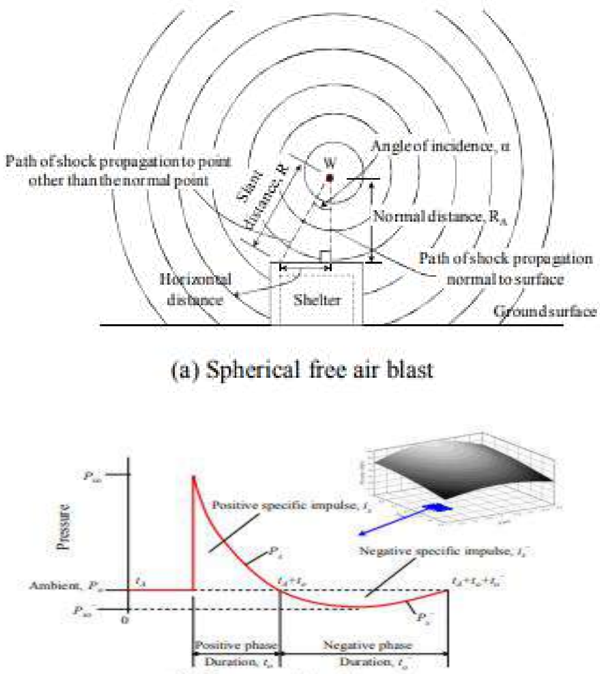


Figure 1 Spherical free air blast.

$$Z = R / E^{1/3} \ or \ Z = R / W^{1/3} \quad (1)$$

Where Z represents the scaling distance, R is the stand-off distance from the target structure, E is the total explosive thermal energy, and W is the charge weight in terms of the equivalent TNT amount [7]. The scaling distance, Z, is used to evaluate the characteristics of the blast wave in the context of a comprehensive review of the response of Ultra-High Performance Concrete (UHPC) to blast.

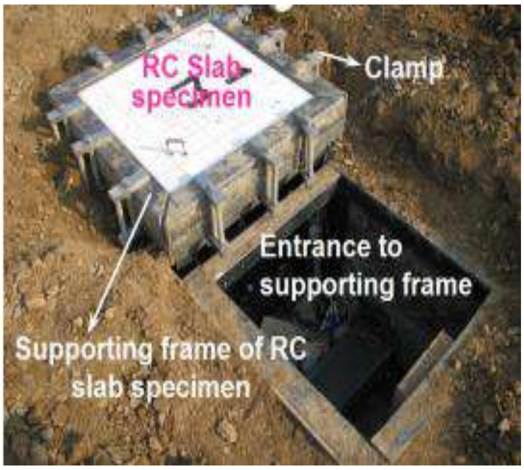
Research Trends

Concrete is generally recognized for its relatively high blast resistance compared to other construction materials. However, concrete structures that were not originally designed to withstand blast loads may require retrofitting during their service life to enhance their blast resistance. Retrofitting methods that involve attaching additional structural members or supports to increase blast resistance are often inefficient, as they incur additional construction costs and reduce usable space. Moreover, these methods do not significantly improve the overall structural resistance to blast loads. A more effective retrofitting approach would be the use of Ultra-High Strength Concrete (UHSC) or Reactive Powder Concrete (RPC) [8]. These materials would also be highly beneficial in new construction, as they can be used in reinforced concrete members. Research has shown that beams and plates made from high-strength concrete (HSC) exhibit better impact resistance compared to those made with normal-strength concrete (NSC). However, due to social and governmental constraints, studies comparing the blast resistance of different concrete types have been limited, resulting in an insufficient database regarding HSC's role as a blast-resistant material. Recently, several researchers have focused on static and impact capacity studies of fiber-reinforced concrete members under time-dependent loading conditions. However, studies on the impact and blast resistance of UHSC or RPC are largely absent, and research on blast-loaded HSC is scarce at best.

Blast Test Details

This study investigates the failure behaviors of reinforced Ultra-High Strength Concrete (UHSC) and Reactive Powder Concrete (RPC) slabs under blast loading conditions. The tests were conducted in two stages: preliminary and main tests, at the Agency for Defense Development in Korea [9]. During the preliminary test, a 35 lbs TNT charge was used on control specimens (NSC specimens). Following the trial tests, ANFO (Ammonium Nitrate Fuel Oil) 35 lbs was selected as the blast explosive for the main test stage.

Blasting Test Setup: To eliminate three-dimensional effects, reinforced concrete (RC) slab specimens were placed level with the ground surface. A steel frame was constructed and buried in the ground, as shown in Figure 2(a). To prevent distortion of the supporting frame during blast loading, stiffeners spaced 250mm apart were installed along the frame's walls. Rubber pads, matching the width and length of the steel angle legs, were placed between the angles and the test specimen to ensure uniform support conditions. The explosive used for the test was spherical ANFO, held in place by a wooden horizontal bar [10]. Figure 2(b) illustrates the test specimen setup with the 35 lbs ANFO (equivalent to 28.7 lbs TNT) explosive charge. The stand-off distance between the specimens and the explosive's center was consistently maintained at 1.5 meters.



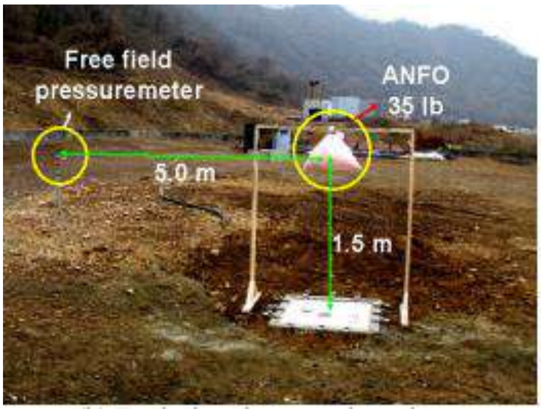


Figure 2 Overview blast setup: (a) Buried supporting frame, (b) Explosive charge and specimen

Table 2 Mix proportion of normal strength concrete (NSC)

Max. Size of Binder (kg)	FA (kg)	Coarse Aggregate (mm)	Target Strength (MPa)	Slump (mm)	W/B (%)	S/a (%)	Water (kg)	Cement (kg)	Fly-ash (kg)	S1 (kg)	S2 (kg)	CA (kg)	AE (kg)
25	24	100	49.8	47.7	163	294	33	616	264	957	2.45		

Table 3 Mix proportion range of Ultra High Strength Concrete (UHSC)

W/B (%)	S/a (%)	Water (kg)	Binder (kg)	FA (kg)	CA (kg)	AE (%)
< 20	< 39.1	< 140	< 1300	< 450	< 700	1~3

Table 4 Mix proportion range of Reactive Powder Concrete (RPC)

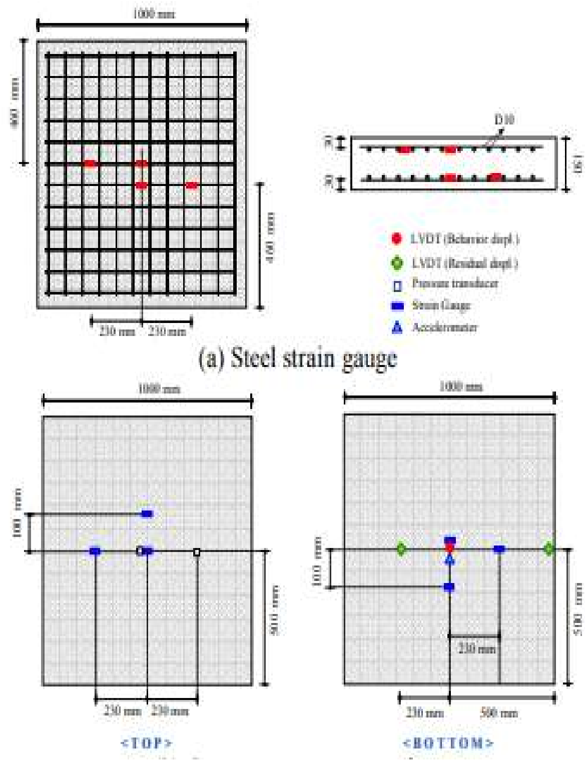
W/B (%)	Cement (kg)	Water (kg)	Silica Fume (%)	FA (kg)	Filler (2.2~200 ㎛)	Admixture (%)	Steel Fiber (%)
< 20	< 800	> 200	10~30	800~1000	200 kg	1~3	2

Specimen Manufacturing and Details: For relative and absolute comparisons, specimens made of UHSC, RPC, and NSC were cast as RC slabs with dimensions of 1,000 × 1,000 × 150 mm [11]. These slabs were reinforced with D10 mesh-type reinforcement (71.33 mm^2) spaced 82 mm apart. The steel reinforcement ratio for the NSC and UHSC specimens was identical, and the RPC specimens included 2% by volume of short steel fibers. The mix proportions for NSC, UHSC, and RPC are summarized in Tables 2, 3, and 4, respectively. Additionally, 100 × 200 mm cylindrical specimens were prepared for compressive and tensile strength testing at the Hyundai Institute of Construction Technology. Two specimens were tested for NSC, while four specimens each were tested for UHSC and RPC. The average compressive strengths of NSC, UHSC, and RPC were 25.6 MPa, 202.0 MPa, and 203.0 MPa, respectively. Specimens with compressive strengths deviating by more than 15% were excluded from the analysis. The tensile strength of RPC was approximately 2.3 times greater (21.4 MPa) than that of NSC (2.2 MPa) and UHSC (9.21 MPa), due to the incorporation of 2% by volume of short steel fibers in RPC [12].

Measurement Outline: The free-field incident pressure was measured 5 meters from the center of the test slab specimens, while the reflected pressure on the concrete specimen was recorded at the center of the top surface and 230 mm from the center, corresponding to 1/3 of the specimen's diagonal length. Strain was measured using 6 mm strain gauges attached to the reinforcing steel in the tensile region, and 30 mm strain gauges were placed on the concrete surfaces (top and bottom) as shown in Figure 3. For retrofitted specimens, FRP strain gauges were used on the bottom surface instead of concrete strain gauges. Additionally, Linear Variable Differential Transformers (LVDTs) were placed at the specimen's center to measure the maximum and residual displacements

Table 5 Measured blast pressure.

SPECIMEN	Con WEP	NSC2	UHSC1	UHSC2	RPC1	RPC2
Charge	ANFO 35lbs	ANFO 35lbs	ANFO 35lbs	ANFO 35lbs	ANFO 35lbs	ANFO 35lbs
Environment Temp. (°C)	-	5	8	NR	-9	NR
Humidity (%)	-	Up 51	56	NR	39	NR
Center Pressure (MPa)	17.02	NR	NR	16.92	NR	21.99
Impulse (MPa- msec)	2.42	NR	NR	3.87	NR	2.83
230mm Pressure (MPa)	16.53	26.58	NR	18.76	22.62	22.1
Reflect Pressure Impulse (MPa- msec)	2.38	3.26	NR	3.02	2.03	22.41
Free Field Peak Overpressure (MPa)	0.17	0.161	0.249	0.191	0.16	0.191
Pressure Impulse (MPa- msec)	0.205	0.23	0.191	0.23	0.229	0.21



(b) Gauges on concrete surface.

Figure 3 Location of measuring sensor

A strain measurement was taken 230 mm from the center, corresponding to approximately one-third of the specimen's diagonal length. To measure strain, 6mm strain gauges were attached to the reinforcing steel at the tensile region, and 30mm strain gauges were installed on the top and bottom surfaces of the concrete, as shown in Figure 3. For retrofitted specimens, FRP strain gauges replaced the concrete strain gauges on the bottom surface. Additionally, Linear Variable Displacement Transducers (LVDTs) were placed at the center of the specimen to measure both maximum and residual displacements.

Blast Test Results

UHSC and RPC RC slabs were tested for blast resistance. The preliminary tests used an NSC RC slab to determine the blast cracking behavior and required explosive charge for the main tests [13].

Blasting Tests: ANFO 35lbs was used for the main tests, producing a pure pressure-type explosiowith high pressure, temperature, noise, and energy, as shown in Figure 4.

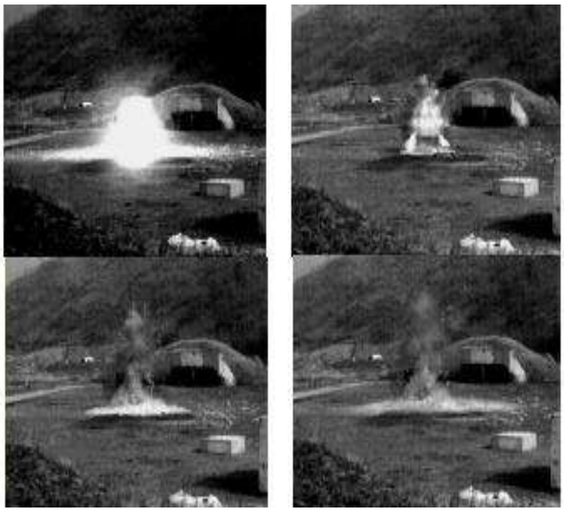


Figure 4 Explosive scene by ANFO 35lbs.

Measured Blast Pressure Results: In the preliminary stage, TNT debris damaged the pressure gauge, preventing data collection. However, free field and reflected pressures from ANFO 35lbs were measured (Figure 5, Table 6), with results aligning well with ConWEP data.

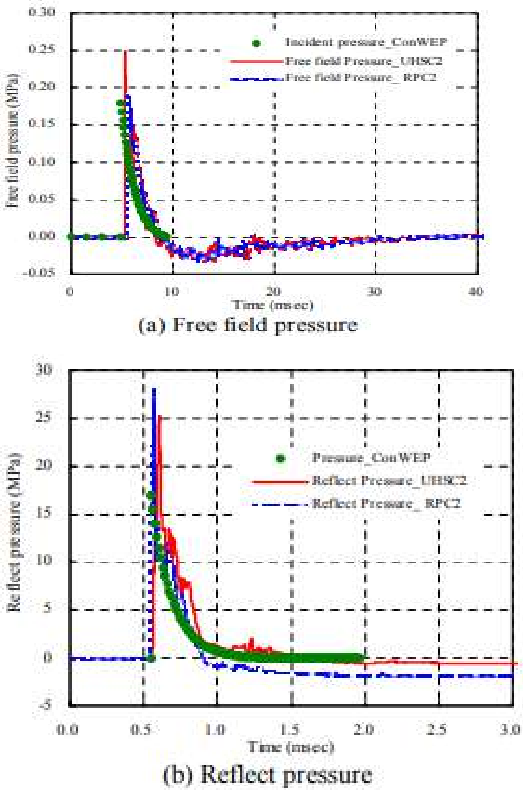


Figure 5 Measured pressure on specimens (ANFO 35lbs).

Tested Specimen Examination: Surface examination of the specimens revealed varying crack patterns: NSC slabs had a turtle-back pattern, UHSC slabs showed macro-cracks near yield lines, and RPC slabs displayed one-directional macro-cracks with fiber-bridging effects (Figure 6).

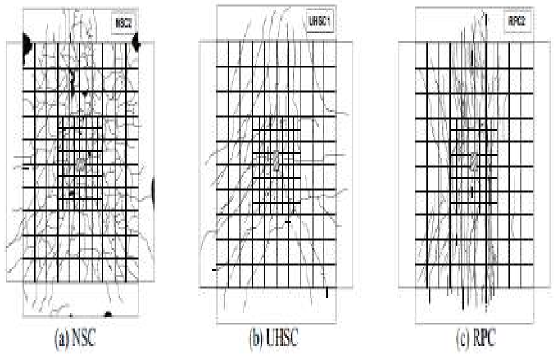


Figure 6 The crack pattern of blasted specimens.

Deflection Measurements: Deflection measurements (Table 7) showed that NSC had the highest maximum deflection (18.57mm), followed by UHSC (12.83mm) and RPC (11.91mm). UHSC showed a greater residual deflection reduction (57.23%) compared to RPC (52.29%). If the hysteresis of the moisture isotherm is considered, two distinct relations—evaporable water versus relative humidity—must be used, depending on the direction of variation. When comparing the displacements of NSC, UHSC, and RPC specimens, RPC specimens show less displacement at the center, indicating superior blast resistance. This is likely due to the short steel fibers in the RPC specimens, which limit crack opening through crack bridging and control.

Acceleration Measurements from Blast Test: Specimen behavior under blast loading can typically be analyzed using LVDT and accelerometer data. If LVDT data is unavailable or inaccurate, acceleration data can be used. Figures 8(a)–(c) show the acceleration measurements for NSC, UHSC, and RPC specimens, with accelerations ranging from 1,000 to 2,500g. These measurements include both

International Journal of Multidisciplinary Engineering in Current Research - IJMEC

Volume 10, Issue 1, January-2025, http://ijmec.com/, ISSN: 2456-4265

specimen acceleration and impulse acceleration. For one UHSC specimen, the sensor detached during the blast, leading to inaccurate data. RPC specimens exhibited high-frequency vibrations due to the absence of reinforcement, suggesting reinforcement affects specimen behavior under blast loading [14].

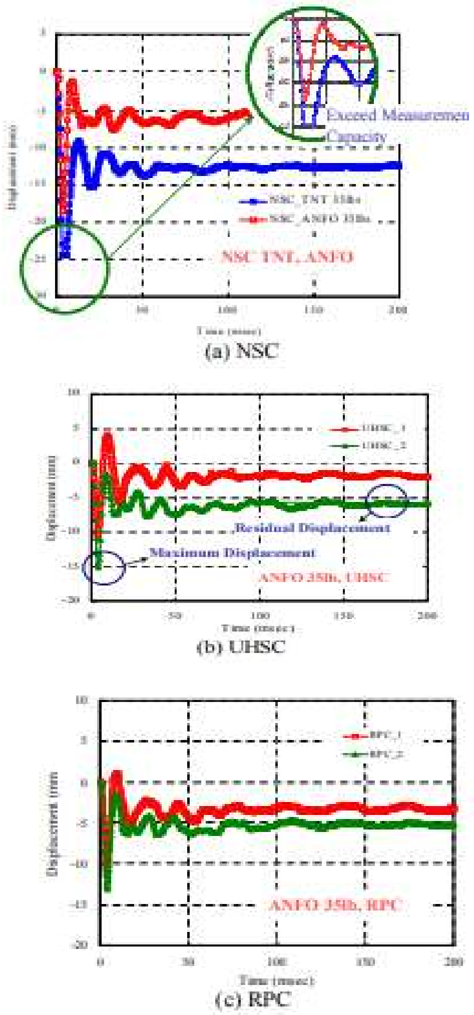


Figure 7 Displacement behavior of concrete specimen center point under blast loading.

Blast Design and Analysis Process: Based on the blast tests, a blast design and analysis process is proposed. First, building and owner requirements are necessary to determine the blast resistance capacity of the target structure. Blast loading on each component and the resistance capacity can be derived from test results or research. Once materials and structural systems are selected, deformation limits can be assessed using analysis methods such as High Fidelity Physics Based (HFPB) models, Single-Degree-of-Freedom (SDOF), or Multi-Degree-of-Freedom (MDOF) methods. Design details should ensure the deformation limit is met based on analysis results.

Table 7 Measured blast test results.

SPECIMEN	NSC1	NSC2	UHSC1	UHSC2	RPC1	RPC2
Charge	TNT 35lbs	ANFO 35lbs	ANFO 35lbs	ANFO 35lbs	ANFO 35lbs	ANFO 35lbs
Max. Displacement (mm)	Over 25	18.565	10.517	15.14	10.73	13.09
Average of Max. Disp. (mm)	-	18.565	12.829	11.91	-	-
Retrofit Effect (%)	-	-	30.9	35.85	-	-
Residual Displacement (mm)	12.26	5.79	1.86	5.86	3.202	5.41

Volume 10, Issue 1, January-2025, http://ijmec.com/, ISSN: 2456-4265

Average of Residual Disp. (mm)	-	9.025	3.86	4.306	-	-
Retrofit Effect (%)	-	-	57.23	52.29	-	-
Steel Top Strain	16012	5964	2796	2832	-	-
Steel Bottom Strain	15998	28113	6711	7553.6	-	-
Concrete Top Strain	NR	11848	4502	12821	11198	24214
Concrete Bottom Strain	16007	NR	16025	18081	NR	4903

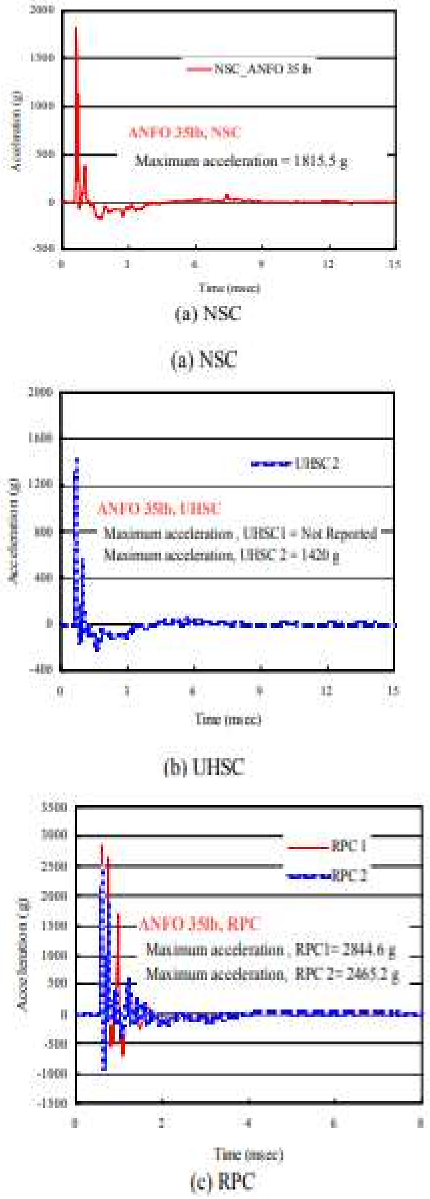


Figure 8 Specimen acceleration under blast loading

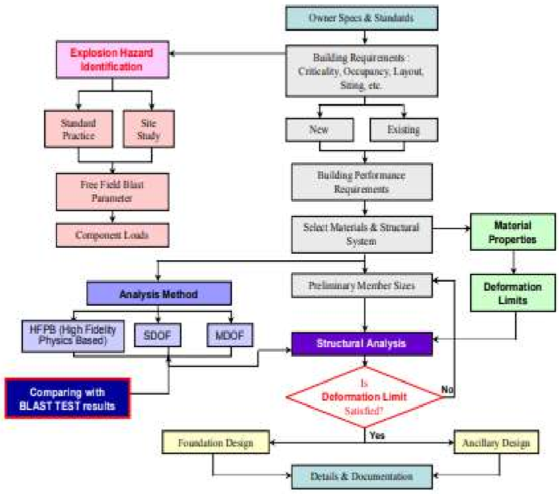


Figure 9 Blast design and analysis process

6. Conclusion

In conclusion, the study of Ultra-High Performance Concrete (UHPC) and Reactive Powder Concrete (RPC) under blast loading conditions reveals their superior performance compared to Normal Strength Concrete (NSC). Controlled blast tests with ANFO explosives demonstrated that UHPC and RPC slabs exhibit enhanced resistance to blast pressures, evidenced by lower deflections and more durable crack patterns. While NSC slabs experienced significant deformation and damage, UHPC and RPC slabs showed reduced maximum deflection, with RPC benefiting from fiber-bridging effects. The results indicate that UHPC and RPC offer promising materials for retrofitting and new constructions, providing improved protection against blast events. However, the study acknowledges the challenges in simulating real-world blast conditions and the potential impact of variations in material composition, manufacturing, and curing processes. Future research should focus on further refining blast resistance testing and exploring the long-term performance of UHPC and RPC under diverse conditions.

Future Scope

- Assess long-term performance under various environmental and loading conditions.
- Explore how different compositions of UHPC and RPC impact blast resistance.
- Investigate optimal manufacturing and curing techniques for consistent performance.
- Combine UHPC and RPC with other materials for enhanced blast protection.
- Study the cost-effectiveness of UHPC and RPC in retrofitting and new constructions.

7. Reference

1. Zhang, J., & Zhang, L. (2024). Blast resistance of ultra-high performance concrete under simulated explosive loading.
2. Lee, H. W., & Lee, S. Y. (2023). Performance evaluation of reactive powder concrete in blast-resistant applications.
3. Zhou, X., & Wang, S. (2022). A study on the blast resistance of fiber-reinforced ultra-high performance concrete.
4. Kim, Y., & Park, S. (2021). Comparison of blast performance between UHPC and NSC: A numerical and experimental study.
5. Rao, P. K., & Ghosh, P. (2020). Evaluation of blast resistance of high-performance concrete: A review.
6. Xu, S., & Li, Q. (2020). Blast resistance of reactive powder concrete: Experimental and analytical investigation.
7. Liu, W., & Li, Z. (2019). Investigation on the effect of fiber reinforcement in reactive powder concrete subjected to blast loading.
8. Zhang, L., & Wang, H. (2019). Blast-induced response of ultra-high performance concrete beams under different loading conditions.
9. Li, X., & Zhang, J. (2018). Behavior of ultra-high performance concrete under explosive loading: An experimental study.
10. Guo, L., & Wei, S. (2018). Experimental study on the blast performance of ultra-high performance concrete slabs.
11. Hamed, S., & Kumar, S. (2017). Comparative study on the performance of ultra-high performance concrete under blast loading.
12. Li, Y., & Sun, J. (2017). Investigation on the blast resistance of reactive powder concrete beams: Experimental and numerical analysis.
13. Wang, X., & Chen, L. (2016). Blast resistance of ultra-high performance concrete panels with different fiber reinforcement configurations.
14. Feng, Q., & Zhang, L. (2016). Experimental study of blast performance of reactive powder concrete plates.