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ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC): MATERIAL BEHAVIOR REVIEW FOR MILITARY FIELD PROSPECTS

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ABSTRACT

Late years, intensity of collapse buildings, facilities and other protection constructions from civilian even military have showing increasingly frequent. As ideas for the restoration of concrete structures, one part of defence technology, developments were carried out for the lightweight materials and frameworks. Mostly the research development of UHPC behavior respectfully increase with visibility at high level characterization, as major advantages of construction difficulties, increasing safety demands, raised the workability, created green environment, protection enhancement and cost with wisely on improving the efficiency of each material, however, its exactly linear for requirement of military construction assignment at the field.

Keywords: material behavior, military field, UHPC.

INTRODUCTION

Late years, intensity of collapse buildings, facilities and other protection constructions from civilian even military have showing increasingly frequent (Abbas, 2023). For those, some research of high-strength performance materials in case to preventing or protecting the main structure of constructions have developed (Ning, 2023).

In high-strength performance material case such as concrete, most of the development proved that ultra high performance concrete or UHPC has high level performance of material behavior compared to conventional concrete (Ning, 2023; Abadel, 2023). It means, promising as a protective materials and structures for military and civilian building (Ning, 2023).

While development lightweight materials on going (**Figure 1**) (Siengchin, 2023), linearly, it also effects the concrete materials behavior and increasing the characterization into superior (Amran, 2022). A view potential replacements of UHPC to conventional concrete application are, UHPC structural member designs more thinner and lighter, more durable, stronger but deformable of seismic load, high performing on structural repair and rehabilitation, and also its a good opportunity for defense construction structures (Jonnalagadda, 2023 and Akhnoukh, 2021).

Most of impressive caracterizations of UHPC are compressive and tensile strength under impact resistance (Ning, 2023; Abadel, 2023), improved toughness (Mettwally, 2022), high resilience and energy absorption (Jonnalagadda, 2023), strength and durability (Reeves, 2023). Other advantages, UHPC members more slim and even more low in weight than conventional concrete. Beside of the long-term viability of construction facilities (Abdal, 2023), by high durability, it would stress costs more effective considering of construction life cycle cost (Jonnalagadda, 2023). The durability itself could extended the service life and then enhance the sustainability (Gee, 2020).

Those high level achievements should be major advantages for engineering construction difficulties, especially on military field prospects.

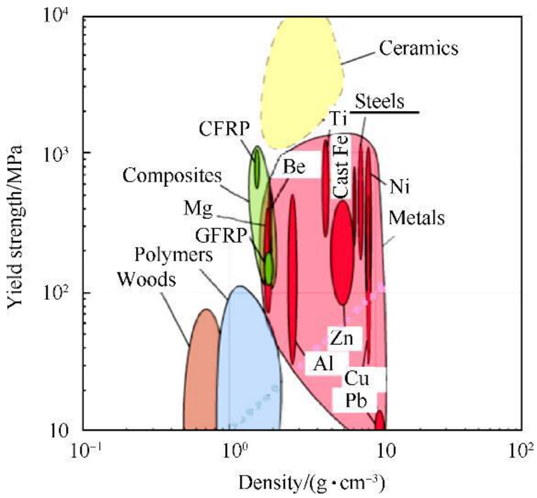

Figure 1. The Comparison of Each Lightweight Materials (Siengchin, 2023; Rana, 2014)

METHOD

All the reviewing result are using by literating a number of UHPC material behavior documents that are considered either important according to the requirement of military assignment prospects at the field in this modern era.

REVIEW RESULTS

Lightweight Concrete

While compressive strength of conventional concretes at 20 MPa until 55 MPa, UHPC compressive strength minimum around 150 MPa, its higher than conventional concrete maximum strength. There are two class manufactured of UHPC, Class 200 MPa and 800 MPa (Christ, 2023; Jonnalagadda, 2023; Amran, 2022; Akhnoukh, 2021).

The unit quantity cost design of UHPC shows that exceed than conventional concrete (Ortiz, 2013). The way optimizing the applications, on large scale or even lower scale projects, it needs reducing the thickness concrete or by changing the structural shapes (Ortiz, 2013), with still keeping the construction design specification.

Panels using conventional concrete are traditionally 6-to-8 inches thick, which makes them pretty heavy and cumbersome (Reeves, 2023), UHPC panels are no thicker than three inches and cure to a strength of 22,000 PSI in just 28 days (Reeves, 2023). Using tests and data from more than three decades of research, ERDC tested the UHPC panels, including simulating what would happen if the panels were struck by a barge. The results validated the exceptional strength and durability of the UHPC panel (Reeves, 2023). By eliminating the coarse aggregate, interfacial transition zone will be eliminate where the cementitious paste meets the aggregate particle. This zone is typically the weakest location in conventional concrete, and they don’t have that in UHPC (Reeves, 2023).

France’s St. Pierre La Cour bridge using 1 inch thick of UHPC precast panels deck, then Australia’s Shepherds Creek bridge superstructure supported by 1 inch thick of UHPC precast panels as

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reinforced concrete deck (Ortiz, 2013).

Cor-Tuf UHPC has a lifespan of 100+ years and is 10x stronger than traditional concrete (Cor_Tuf, 2024). Its engineered a 1-inch thick Ultra-High-Performance Concrete (UHPC) lid, by featuring two ribs and benefiting from an 8-day ambient curing process (**Figure 2**). This construction showcases remarkable flexural strength, enduring the weight of a GMC 3500 diesel vehicle across a 4-foot span with approximately 1 inch of bearing on each end. (Burgess, 2024).

Figure 2. A 1-inch Thick Ultra-High-Performance Concrete (UHPC) (Burgess, 2024) and Cor-Tuf UHPC Aplication on GW Memorial Bridge Project (Cor_Tuf, 2024)

Projectile Impact

Recently UHPC compared to normal one and shows the increasing of compressive strength, tensile resistance and toughness. This advancement of UHPC is quite well to be used in the design of structures subject to blast loads (Mettwally, 2022; Li, 2015).

Under impact resistance tests, there is research by comparing between UHPC and granite targets to find penetration depth also crater diameter differences then analyze by using finite element of ANSYS 16.0/LS-DYNA (Ning, 2023). Impact test, UHPC targets with 600 mm thick, the Ø35 mm caliber cannon of 35CrMnSiA (Ø30 mm) projectile was used, and as the results, when its conducted at UHPC targets, the velocities record at 216 m/s until 340 m/s, so projectile velocity design is controlled in range of 200 m/s to 350 m/s (**Table 1**). Then for the impact resistance test, projectile with diameter of 117 mm was used. (Ning, 2023).

Comparing with the granite targets, the reduce facts of crater diameter, UHPC targets are better than granite objects (**Tabel 1**) (Ning, 2023).

Table 1. Penetration Test Data

Types of Target	d [1] (mm)	m [2] (kg)	V [3] (m/s)	Depth of Penetration		Crater Diameter	
				h [4] (mm)	h/d	d_c (mm)	d_c/d
UHPC	30	1.001	216	145	4.83	200	6.67
	30	1.003	308	199	6.63	300	10
	30	1.003	341	223	7.43	320	10.67
Granite [32]	30	0.999	216	89	2.97	253	8.43
	30	1.002	226	74	2.47	370	12.33
	30	1.003	229	97	3.23	305	10.17
	30	0.999	300	122	4.07	363	12.1
	30	1.004	300	96	3.2	365	12.17
	30	1.005	322	122	4.07	513	17.1
	30	1.003	340	139	4.6	363	12.1

[1] projectile diameter; [2] projectile mass; [3] striking velocities; [4] depth of penetration.

(Ning, 2023)

Table 2. Penetration Depth at Different Reinforcement Ratio

Reinforcement Ratio (%)	d (mm)	V (m/s)	Depth of Penetration	
			h (m)	h/d
0		200	0.4	3.4
0		300	0.64	5.5
0		400	0.88	7.5
0		500	1.05	9.0
1.15		200	0.35	3.0
1.15		300	0.56	4.8
1.15		400	0.75	6.4
1.15		500	0.90	7.6
2.3		200	0.34	2.9
2.3		300	0.54	4.6
2.3	117	400	0.69	5.9
2.3		500	0.81	6.9
3.45		200	0.33	2.8
3.45		300	0.50	4.3
3.45		400	0.64	5.5
3.45		500	0.75	6.4
4.6		200	0.30	2.6
4.6		300	0.42	3.6
4.6		400	0.53	4.5
4.6		500	0.61	5.2

(Ning, 2023)

Continuous, **Figure 3** shows composite structure of UHPC/granite, where the penetration depth seen decreases by increasing of the projectile angle, and it proving a relationship to depth of penetration and reinforcement ratio (**Tabel 2**). Otherside, more high of projectile velocity, more less trajectory to deflect (Ning, 2023).

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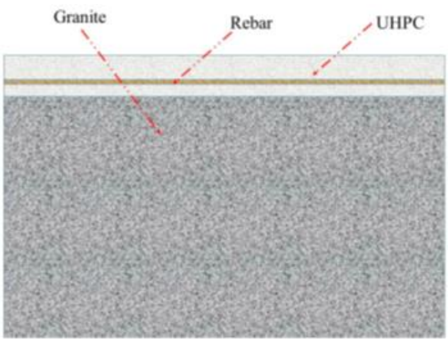

Figure 3. UHPC/Granite Composite Structure (Ning, 2023)

Another similar research about penetration resistance, there are UHPC and rock experimental within numerical simulation on the HPFRCC (Ning, 2023), it was shown that with the projectile velocity increase, depth of penetration and crater diameter also increased (Ning, 2023), and as the strength target increased, slight decrease was shown in depth of penetration (Park, 2023).

Dapper, 2021 researching feasibility protection enhancing of the ballistic on building structures, while material objects prepared from 100 MPa compressive strength UHPC elements, low content of cement then hybrid fibers inside. Plate specimens 500 x 500 mm with different various of thickness on 30 mm, 50 mm and 70 mm at 28 days. Its testing by Ballistic impact to assess the elements strength. There are some projectiles that been used, and the calibers are 380 SPL (Impact energy 270 J), 9mm (540 J), 12/70 (4000 J) and 7,62 mm (7420 J) (Dapper, 2021).

UHPC mixtures made from hybrid fiber variaties 1,5 % and 3,0 % to attained the Compressive Strength (Dapper, 2021). For the results, the 3.0 % variety recorded flexural strength with higher residual, the flexural toughness is 34,4 %, its greater than 1,5 % variety, and it shows affecting resistance to the ballistic impact. Plate shape with 70 mm thick as specimens and either fiber varieties 1,5 % or 3,0 % have ability on gunshot stoppable with energy of impact exceed of 7420 J and ensuring ballistic protection on level-III (**Figure 4**). Impact were tested with 7,62 mm of bullets caliber (7420 J) due to energy dissipation and absorption. Its recorded that fiber ratio in UHPC plate specimens doesn't had significant spalling effect and depth of penetration effect, except for the opportunity when it attained 7420 J equivalent of energy (Dapper, 2021).

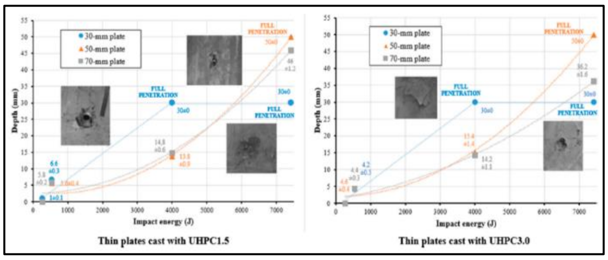

Figure 4. Depths of Fracture in UHPC Plates (Dapper, 2021)

The research from Anas, 2022, the using ABAQUS code on evaluating concrete slabs of UHPC, two-way NSC types performance, and SFRUHPC with steel and C-FRP as conventional tension reinforcements under falling weight (impact load) (Anas, 2022). where its generating 1035 N from dropping 105 kg weight at 2500 mm height and velocity impact of 7 m/s at the top mid-point slab surface while simulated by using ABAQUS Finite element (Anas, 2022).

Slabs that made of UHPC and SFR-UHPC concrete with either conventional steel or C-FRP reinforcing bars of 8 mm diameter, shown extraordinary performance in resisting applied falling-weight load, and in other part, the C-FRP bars slabs displayed slightly greater resistance than steel bars (Anas, 2022).

Table 3. Computational Results

Slab No.	Slab ID	α_y [*g]	Δ_y [mm]		Max^m. DDE [J]
			Slab	Re-bars	
S-1	S-NSC-Steel8	294.73	−27.31	−22.68	190.98
S-2	S-UHPC-Steel8	395.15 (−34)	−4.54 (83)	−4.12 (82)	92.77 (51)
S-3	S-SFRUHPC-Steel8	426.55 (−45)	−2.04 (93)	−1.86 (92)	62.15 (67)
S-4	S-NSC-CFRP4.66	245.70 (17)	−39.68 (−45)	−36.25 (−60)	203.86 (−7)
S-5	S-NSC-CFRP8	282.13 (4)	−24.89 (9)	−22.73 (−0.5)	173.21 (9)
S-6	S-UHPC-CFRP8	366.03 (−24)	−4.05 (85)	−3.68 (84)	87.11 (54)
S-7	S-SFRUHPC-CFRP8	388.92 (−32)	−1.80 (94)	−1.64 (93)	54.94 (71)

*Note: Entries in parenthesis are percentage decrease in displacement/DDE with respect to control model (S-NSC-Steel8); *g = acceleration due to gravity (9.81 m/s²); α_y = peak vertical acceleration; Δ_y = peak vertical displacement; DDE = damage dissipation energy.

(Anas, 2022)

Meanwhile, stiffness influencing the slabs peak acceleration and more high stiffness of the slabs displayed greater acceleration under impact load (Anas, 2022). **Tabel 3** and **Figure 5** shows slightly lower acceleration of NSC/UHPC/SFRUHPC slabs with C-FRP 8 mm diameter bars due to the lower C-FRP elastic modulus bars compared to the steel bars (Anas, 2022).

C-FRP rebars as steel rebars lieu have help slabs from decreasing scabbing severity and diagonal cracks. Other side, at the bottom face, concrete was ejected as low reinforcement ratio of 0,50 % then concrete strength of 29.70 MPa and contrarily. Steel rebars run into yield in NSC slab neither on UHPC/SFRUHPC however, the C-FRP bars didn't dispalyed yield then the NSC, even not with UHPC/SFR-UHPC following to the drop-weight load test. UHPC and SFR-UHPC slab with C-FRP 8 mm diameter rebars, respectfullly shows an extraordinary performance by enhancing absorption capacity of energy and slab cracks resistance (Anas, 2022).

Under certain conditions that fiber materials becomes expensive components on UHPC (Ragalwar, 2021). By steel wool cost 30–50% than steel fibers cost, therefore more optimum combination of steel fiber in UHPC reinforcement to be more practical and low cost (Ragalwar, 2021).

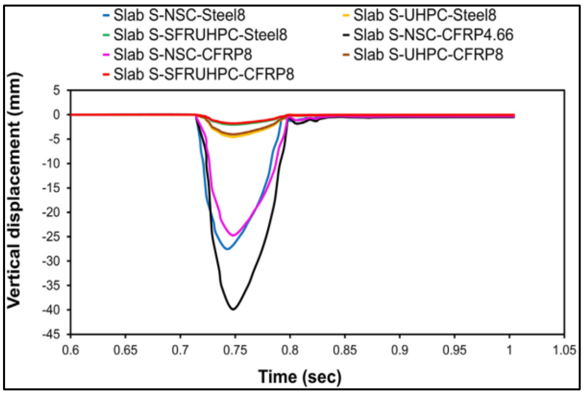

Figure 5. Slabs Displacement Time Plots (Anas, 2022)

High Temperature Permorfance

While thermal conductivity in conventional concrete has low therefor only surface exposed that tends to get tested (Adesina, 2021), but UHPC using bodies experimental test to evaluate its properties (Abid, 2017), such as aggregate type, rates of heat and cool, body dimensions, until strength of compression (Xiong, 2015; Christ, 2023). However, Bolina, 2020, which still using on cylindrical test bodies analysis as essential, to asseses the behavior of the structural element mixtures.

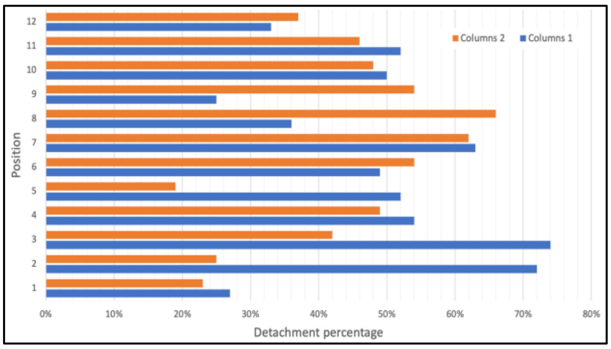

Figure 6. Columns Spalling After Exposure
(Christ, 2023)

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The curing period of 180 days to researched as a low condition that encountered approximate from probability of a real structure burning at early ages (Christ, 2023). The UHPC used as subjects two columns with superplasticizer additive without add water, reinforced only with fibers then evaluated columns exposed behaviors to elevated temperatures, spalling measuring on a real scale and even melting condition (Christ, 2023).

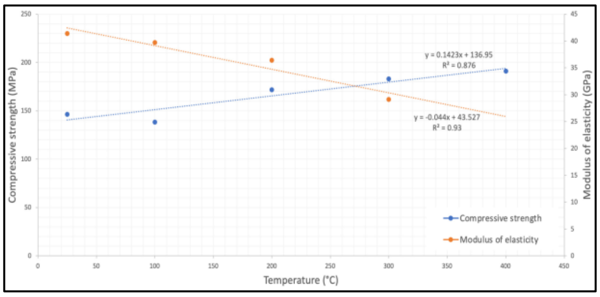

Figure 7. Compressive Strength and Elasticity Modulus Variations by Temperatures (Christ, 2023)

The results are, UHPC high strength displayed high displacement and more spalling compared to the conventional concretes (at lower water and cement ratios) (Christ, 2023). Alevated temperatures, UHPC columns expose suffered from external degradation due to spalling (**Figure 6**). At above 400˚C, increasing shown in compressive strength that exceed to 30,5 % but, the elasticity modulus also density shown decreased (**Figure 7**), with peak reductions recorded 30% and 6%,. When heating approximately 600˚C, concrete performance progressively showing less due to falling degradation from quartz sand aggregate and grows cracks then spalling. (Christ, 2023).

Due to the fact that UHPC elements design could extremely thin, then this will effect in the mass of heat absorption being lessed and the element thermal capacity is reduced (Kodur, 2022; Ullah, 2022). In this case, UHPC is not recommended for structure applications at high temperature. In the specific part of heat capacity, UHPC is slightly lower compared to the conventional (Kodur, 2022; Ullah, 2022).

UHPC HT (High Temperture resistant) binder systems were developed for extreme temperatures in the cement, steel, glass and power plant industries (Hyper, 2024). Based Technical Data Sheet properties of UHPC Cast HT to Mortar HT are Density (kg/m^3 / lb/ft^3) 2800/175 to 2800/175, Compressive Strength (MPa) 130 to 130, Flexural Strength (MPa) 19 to 22, Max. Service Temperature (°C/°F) 1200/2192 to 1200/2192 (WPE-DK, 2023).

Seismic Behavior

High resilience and energy absorption characteristics, UHPC perform structures advantages in high seismic zones (Jonnalagadda, 2023; Buck, 2013). Comparing with conventional concrete structures, UHPC design by its slim and lesser in weight, has ability to reduce the seismic forces (Jonnalagadda, 2023; AlHamaydeh, 2022).

On one research, UHPC that filled by FRP tube columns, presented high ductile behavior with the significant of compressive strength (Tian, 2021). As one of composite structure, UHPCFSTs performing superior strength behaviors, durability and ductility compared with UHPC without confinement. But, those are depending on seismic performance (Cai, 2023).

Cai, 2023 researching the UHPCFSTs seismic behaviors by the combinations of axial compression and lateral cyclic. By considering the thickness effects of steel tube, its also investigate from the ratios of axial compression and height-to-width. Hysteretic UHPCFSTs model established by machine learning algorithm, where UHPCFSTs hysteretic behaviors are predictable in satisfaction (Cai, 2023).

Result recorded that UHPCFSTs performing preferential deformation capacity with exelent capacity of energy dissipation, and it also serving ability as a remarkabel choices in areas with high seismic load intensity (**Figure 8) (**Cai, 2023).

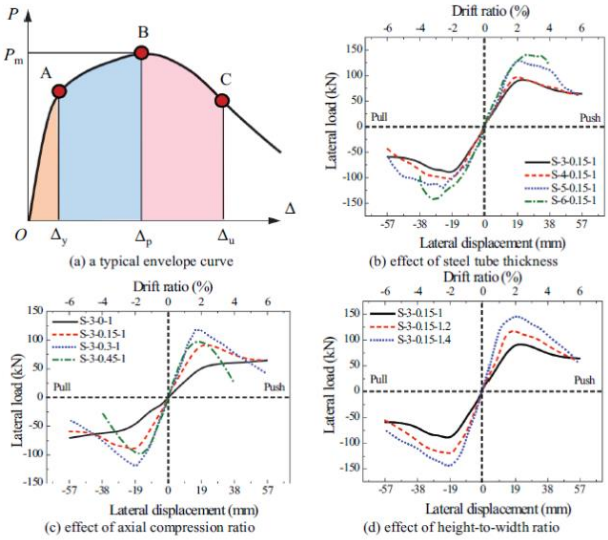

Figure 8. Envelope Curves Specimens (Cai, 2023)

The increasing of steel tube thickness then enhancing height-to-width ratios, its improving seismic behaviors of UHPCFSTs. The determining of its height-to-width ratio should be controlled in term of seismic design in order to keep the stiffnesses (**Figure 9**) (Cai, 2023).

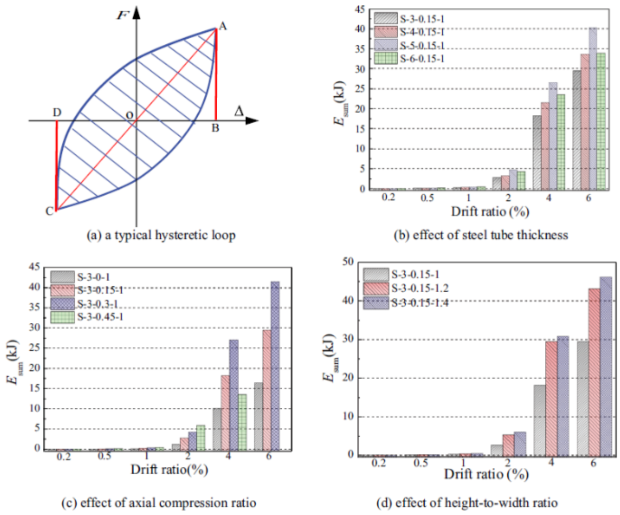

Figure 9. Cumulative Dissipated Energy and Drift Ratio (Cai, 2023)

AlHamaydeh, 2022 in research that UHPC model with 185 MPa (the models consist of 150 MPa, 185 MPa and 220 MPa) was recommended in tall builldings as terms of seismic performance compared to high-strength concrete of 60 MPa. At lateral load resistance, due to dead load structure decrease, UHPC structure elements are required and its lower cost of foundation design.

CONCLUSIONS

Mostly the research development of UHPC behavior respectfully increase with visibility at high level characterization, as major advantages of construction difficulties, increasing safety demands, raised the workability, created green environment, protection enhancement and cost with wisely on improving the efficiency of each material, however, its exactly linear for requirement of military construction assignment at the field.

Beside those, other development was carryout on establish frameworks in order to optimizing materials used in UHPC applications, there such as Concrete Observations Repository and Predictive Software – Structural and Thermodynamical Integrated Framework (CORPS-STIF) as a UHPC structural models fundamental in the future (Howard, 2021).

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