DEVELOPMENT OF MORTAR FILLED HONEYCOMB SANDWICH PANELS FOR PERFORMANCE EVALUATION AGAINST REPEATED BALLISTIC IMPACTS

Structures Thesis Dissertation

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DEDICATION

I Dedicate this Research Work to My Research Supervisor Dr. Muhammad Usman, Dearest Husband, Adorable Son Muhammad Shees Hussain and My Loveliest Family.

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ABSTRACT

Growing security threats demand structures offering exceptional energy absorption and heat dissipation capabilities with minimum damage. Sandwich structures are adopted widely for resisting ballistic impacts. Honeycombs filled with composites propose significant resistance by energy absorption or heat dissipation due to localized encapsulated damage. Therefore, this research focuses on developing composite sandwich panels that can resist multiple ballistic impacts to a considerable degree. It constituted a core of Aluminum Honey Combs (AHC) Al3003 and Al5052 filled with cement mortar containing tire rubber dust (15%), iron powder (20%), glass powder (25%), and polyvinyl (PVA) fibers (1.5%) and wrapped with C-230 Carbon Fiber Reinforced Polymers (CFRP). These panels experimented with CEN 1063 standard in a controlled testing environment against 19 mm (640 J), 45 mm (1800 J), and 51 mm (3270 J) bullets. All samples resisted ballistic impacts of 19 mm and 45 mm with indentation within 25 mm Back Face Signature (BFS). However, ballistic impacts of 51 mm bullets pierced through and caused only localized damage maintaining structural integrity, compactness, and durability.

Keywords: Composite Sandwich Structure; Impact loading; Ballistic resistance; Aluminum Honey Comb (AHC); Sustainable materials

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CHAPTER 1

INTRODUCTION

1.1 General

Ballistic resistance of different materials has remained a point of interest for decades. In this modern era, various composite sandwich structures with exceptional properties are being adopted in the construction industry. A sandwich structure is a special class of composite materials that is fabricated by attaching, two thin but stiff skins to a thick core. The skins can be composite plies of GFRP, CFRP, Kevlar, or sheet metals while the core can be open and close structured foams like honeycombs, Polyethylene, and Polyvinylchloride, foams, Balsa Wood, and Synthetic Foams

1.2 Honey Comb Sandwich panels

Honeycomb sandwich panels are widely used in civil and military infrastructures like racing automobiles, aircraft, high-speed marine ships, high-speed trains, etc. due to their acoustic and energy absorption capabilities, high strength-to-weight ratio, and resistance to ballistic impacts.

1.3 Conventional Material Used against Ballistic Impacts

The conventional materials used against the ballistic impacts e.g. plywood, high-class wood, MS steel plates, and rolled homogenous require modification and up-gradation because of their cost, weight, non-reusability, import, and associated custom duty-related issues. Therefore, research in developing modified multi-purpose composite materials is necessary to pave a new avenue for more resistive innovations.

Since there is no significant research available in this specific field of the improvised composite aluminum honeycomb sandwich panels filled with different mortar mixtures. Previously, only the behavior of honeycomb core against impact loading has been analyzed, tested. Therefore, this research is based on the development of various composite sandwich panels filled with different cement mortar mixtures and their performance evaluation against multiple impact loading. The primary focus is on enhancing impact resistance as well as ensuring structural flexibility and integrity by using composite panels. The ductile inner core made up of AHC also provides an improved jointing mechanism.

1.4 Research Relevance to National Needs

Pakistan being a nuclear power country, require continuous R & D for strengthening its defence. One of the main objectives of this research is to utilize intellectual capital towards defence R & D. Thus, supporting our military organizations in achieving self-reliance and providing a solution or alternates to get rid of 'dependency syndrome'.

In general, its relevance is with the need and development of blast/ impact-resistant structures. In particular, it is with the strengthening of defence needs of our country.

1.5 Problem Statement

Developing Sandwich Panels that can resist multiple ballistic impacts keeping the integrity of the panels intact.

1.6 Identified Gap

- Development of locally reproduce-able and reusable structure that can resist multiple impacts
- Composite Sandwich Panels made up of CFRP Wraps and Aluminum Honeycomb core filled with various mortar mixes.

1.7 Research objectives

- To develop variety of improvised composite sandwich structures
- To evaluate response of the sandwich panels against multiple ballistic impacts.
- To compare the response of improvised composite panels.
- Development of a multi-purpose composite structure that can be modified and re-used for many similar purposes.

A step towards indigenous solution by aligning it with defence needs.

1.8 Thesis Progression

Thesis progression will be in the following manner:

- ✓ Chapter 1 will be introducing or discussing briefly about the research topic.
- ✓ Chapter 2 is about the Literature Review.
- ✓ Then the detailed adopted methodology will be discussed in Chapter 3

- ✓ Chapter 4 will be discussing the Testing or Experimentation done for this research work. It is based on the previous literature and bit innovation.
- ✓ In Chapter 5, the results obtained from the Experiments/ testing will be discussed elaborately in addition to the acknowledgement.
- ✓ All the above chapters will be followed by the References at the end.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This Ballistic resistance of different materials has remained a point of interest for decades[1]–[4]. In this modern era, various composite smart sandwich structures with exceptional properties are being adopted in the construction industry[5], [6].

Honeycomb sandwich panels are widely used in civil and military infrastructures like racing automobiles, aircraft, high-speed marine ships, high-speed trains, etc. due to their acoustic and energy absorption capabilities, high strength-to-weight ratio, and resistance to ballistic impacts [7]–[10]. Yahaya et. al [11] studied the response of Aluminum honeycomb sandwich panels against foam projectile impact. The response of blast-loaded sandwich structures, comprising mild steel plates and aluminum alloy honeycomb cores, was investigated by Nurick et al. [12]. The ballistic limit and energy absorption capability are directly affected by core density and thickness as concluded by Alasania et al [13]. Jamil et al. found that increasing the core thickness serves to increase the blast resistance of sandwich structure [14]. Dynamic mechanical behavior and energy absorption of aluminum honeycomb sandwich panels under repeated impact loads were studied by Zhang et al. [4]. Further, it is also recommended to use ductile material for improving the jointing mechanism [7].

Mortar replacement with wastes like iron powder, glass powder, etc. is useful for enhancing properties[15]–[18]. Orouji et al. [19] concluded that by using glass powder as a partial replacement, the compressive and flexure strengths of concrete increase significantly. Orouji et al. [19] also concluded that 1.5 percent fiber replacement also gives the best values of compressive and flexural strengths gain. Lee et al. [20] concluded that liquid crystal display (LCD) Glass Powder improved both concrete strength and durability. Usman et al. also found that use of steel fiber enhanced both ductile behavior and post peak behavior of concrete [21]. Abbassi et al. concluded that increasing rubber substitution from 10% to 50% significantly enhances deformation characteristics of concrete or ductility but significantly reduces its compressive strength [22]. Cui et al. observed significant improvement in strength. Specifically, with 20% Waste Iron Tailing Powders (WITP) replacement, 30.95% strength is improved [1].

2.2 Composite Sandwich Panel

A sandwich panel's structural performance is comparable to that of a traditional I-beam since it has 2 sheets on face. These two sheets on face resists lateral bending & in-plane loads while the core material of any type mostly resists shear loads (like flange and web of an I-beam). The concept is to use strong but thin layers for the face sheets and a light, soft, but substantial layer for the core. This causes the panel's total thickness to increase, which frequently enhances its structural qualities, such as its bending stiffness, and keeps its weight the same or even decreases it [23]. Composite Sandwich Structures is considered because of its excellent weight-to-strength ratio, great resistance to impact loading, and high energy absorption characteristics [24]–[28].

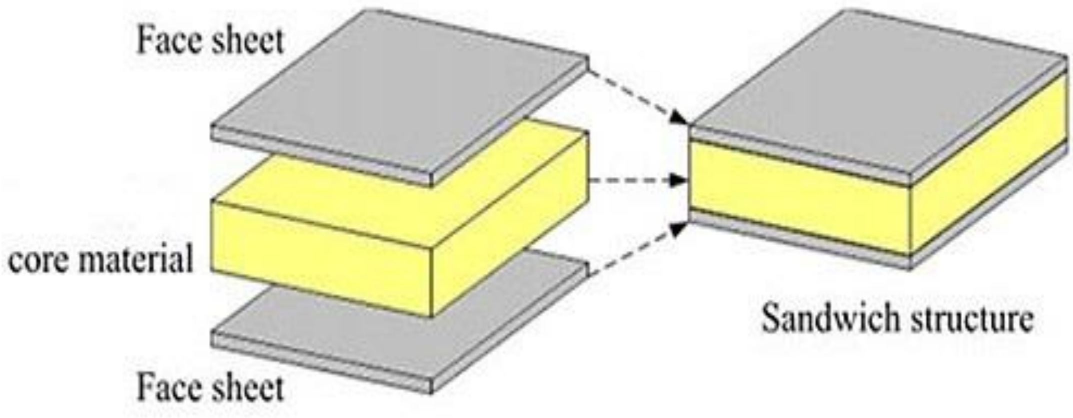

Figure 2.1: Composite Sandwich Panels[24]

2.3 Material Selection for Property enhancement

The concrete's compressive and flexural strengths are increased when glass powder is used to partially replace the fine aggregates. In concrete, the best percentage of glass powder is 25%, which raises the specimen's compressive strength by 11% after 7 days. The increased percentages are 25% and 20%, respectively, for specimens with ages of 28 and 90 days. Additionally, by just 25% glass powder addition, 3 percent flexural strength is increased. In concrete, the best strength ratings (both compressive and flexural) come from using 1.5% fiber in place of cement. The increase in compressive strength was 52% and the rise in flexural strength was 60% in the 28-day-old specimen. The compressive and flexural strengths are both reduced by 2% when the fiber fraction is increased. [19]

The deformation characteristics of concrete were greatly improved by adding more rubber to the mixtures of the evaluated samples. Rubber was partially incorporated in concrete structures in place of natural aggregates, which increased the material's ductility but significantly decreased its compressive strength. When 50% of the natural aggregate was replaced with rubber, this reduction in compressive strength could reach up to 80% [22].

The concrete air content is most dramatically influenced by rubber, while plastic (at low percentage) has negligible impact. Compared to other wastes, glass aggregate best improved the compressive and tensile strength of concrete. The stiffness of the corresponding waste particles has a direct impact on the stiffness of the composite concrete composition. Concrete elastic modulus was lower for low plastic and rubber stiffness materials and higher for glass stiffness materials due to glass's higher stiffness. Rubber and plastic are more ductile in concrete. Concrete that had glass added to it has superior durability characteristics. Concrete with rubber in it has a low permeability to oxygen but is more likely to absorb water and thus performs poorly in durability [29]

Liyun et al. outlines a unique mortar replacement (M) technique that would utilise waste solids and use less cement. In the experiment, the author used a method that substitutes waste iron tailing powders (WITP) for water, cement, and sand under continuous water/cement conditions and discovered that the strength growth may be greatly enhanced. In particular, a mortar with 20% WITP substitution can boost strength development by 30.95% [1].

2.4 Material Properties

2.4.1 Modulus of Toughness

Material’s ability to absorb elastic and plastic strain energy till fracture point” [19], [21], [30]. Toughness is taken as the area under the stress-strain curve until fracture/breakage point, as given below:

$$\text{Toughness} = \text{Area underneath the stress–strain } (\sigma\text{–}\varepsilon) \text{ curve} \quad (1)$$

$$\text{Toughness} = \sigma \times \varepsilon \quad (2)$$

$$\text{Toughness} = P/A \times \Delta L/L = (\text{MPa})\cdot(\text{unitless}) \quad (3)$$

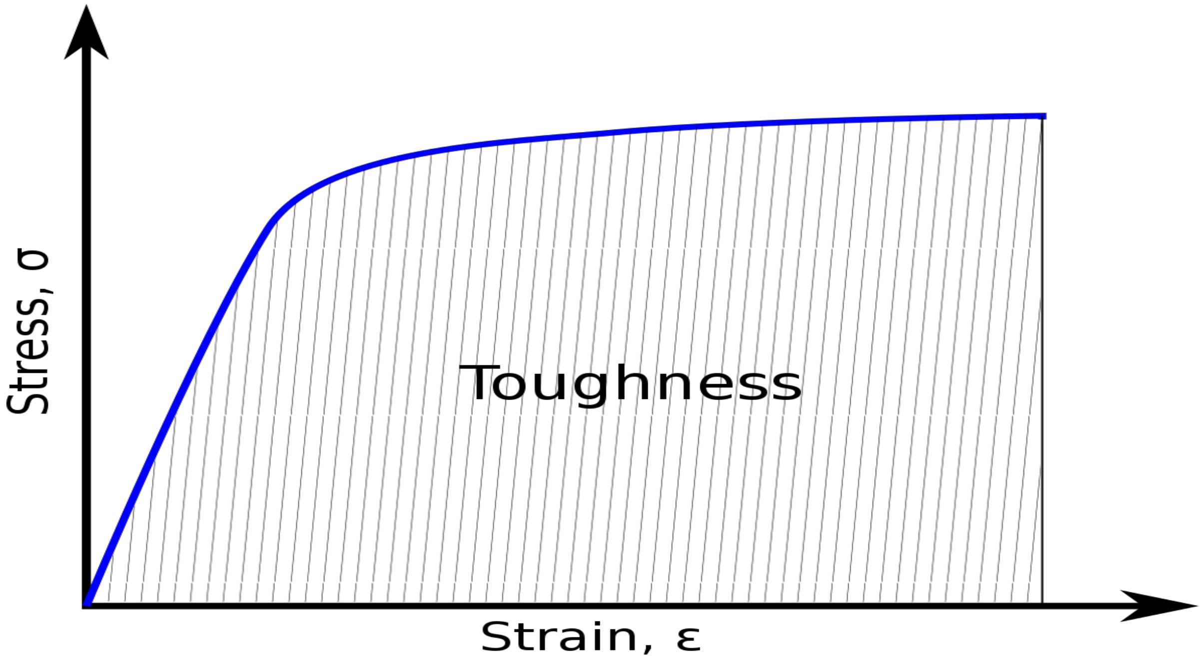

Figure 2.2: Modulus of toughness[22]

2.4.2 Strain rate effect on Compressive Strength

Strain rate affects concrete strength, and the degree of sensitivity is directly inverse to strain rate [30]. Experimental research is done to determine how strain rate affects compressive strength and stiffness. Traditional low strength, normal strength, and medium strength concrete mixtures have been studied. Additionally, research is done on how sensitive polypropylene fiber reinforced concrete mixes are when compressed. Different strain rate levels are used to examine the responses of the conducting concrete mixtures when compressed. The range of strain rate is intended to cover the predicted wide range of load application rates. The range from quasi-static to quick load application is simulated by these rates. The findings of this investigation demonstrated the tested concrete mixtures' susceptibility to compression

2.4.3 Compressive Strength / Hardness

The procedures for testing and determining the compressive strength of 2" cubes are described in ASTM C109 [31]. The idea of concrete qualities is provided by the compressive strength. The compressive strength. is the ability of material to resist load over cross-sectional area. Compressed materials shrink in size. Compressive strength is taken as ratio of load to cross-sectional area.

Compressive Strength = Load (P) / X-sectional Area (A) (4)

2.5 Composite Sandwich Panel Behavior

2.5.1 Ballistic impact resistance and high velocity impact

Honeycomb sandwich structures are widely used in civil and military infrastructures like racing automobiles, aircraft, high-speed marine ships, high-speed trains, etc. because of their great energy absorption capabilities, excellent resistance to ballistic and high strength-to-weight ratio [11–14]. Yahaya et. al [15] studied the response of Aluminum honeycomb sandwich panels against foam projectile impact. The response of blast-loaded sandwich structures, comprising mild steel plates and aluminum alloy honeycomb cores, was investigated by Nurick et al. [16]. The ballistic limit and capability of absorbing energy is directly affected by thickness and the density of core as concluded by Alasania et al [17]. Jamil et al. found that increasing the core thickness serves to increase the blast resistance of sandwich structure [18]. Dynamic mechanical behavior and energy absorption response of AHC sandwich panels under repeated impact loads were studied by Zhang et al. [3] .

2.5.2 Deformation in Metal Armors

When load is applied on material, it first deforms elastically and then plastically. The type of material, the force being applied, and the shape of the material all affect deformation [32]. When a material experiences a high-speed impact, the internal heat produced by friction and plastic deformation is not given enough time to dissipate, leading to a significant local temperature increase, extensive plastic distortion, and even failure. An engineering stress-strain graph for a typical ductile material is shown in Figure 2.3 and discusses various material responses under force.

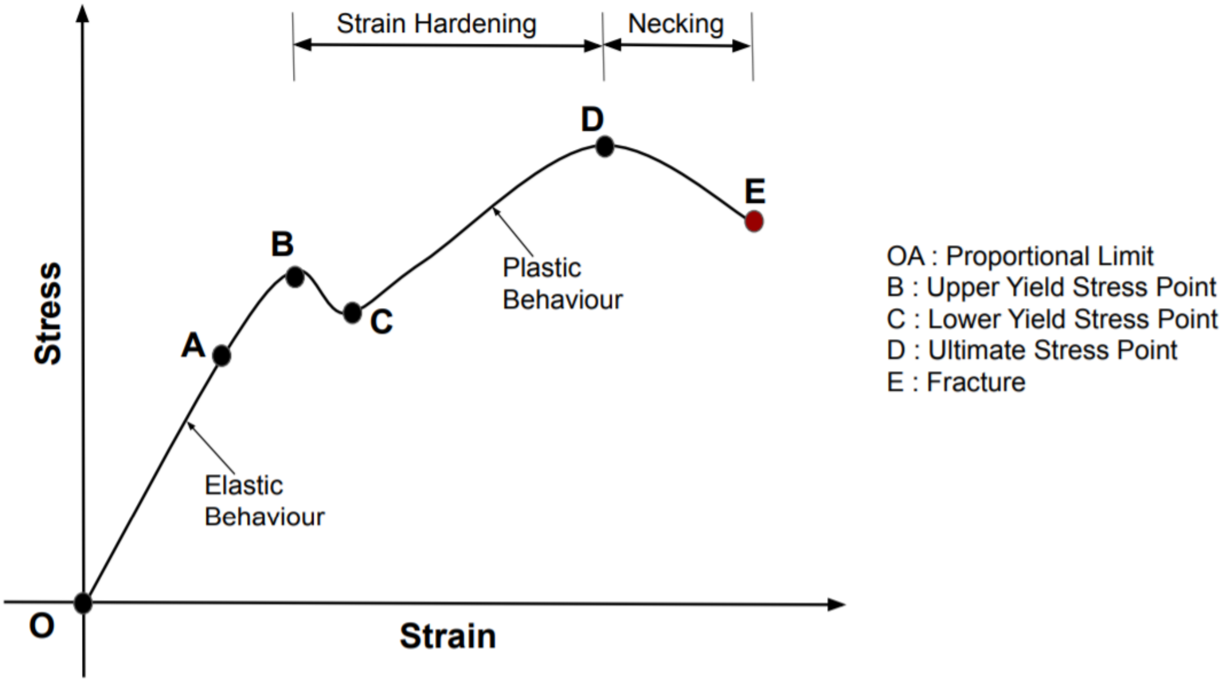

Figure 2.3: Stress strain graph of typical ductile material[22]

2.5.3 Failure mechanism in impact loading

When a high force is applied on a material for a very short interval of time, it is considered as Impact loading. The severity of impact load depends upon the weight and velocity of the impactor. When the body is hit by a projectile, kinetic energy of projectile is transferred to the body of target and converts into strain energy. This transfer of energy deforms the armor material and deformation depends upon the impacting projectile energy and their contact velocity [33].

2.6 BFS (Back Face Signature)

Performance evaluation standards for ballistic testing include BFS (Back Face Signature), commonly referred to as trauma. BFS, which is measured perpendicular to the backing material's surface, is the maximum depth of indentation that body armor can cause into ballistic backing material following impact. BFS is measured using a Vernier caliper and an 8 mm hemispherical probe [33], [34]. **Back face signature measurement:** A reasonable technique for estimating the BFS will be utilized. It will be exactly to ± 0.1 mm. On the off chance that utilizing a Vernier Caliper, it will have a 8 mm breadth hemispherical test. BFS estimation device focused on level surface of plate. BFS estimation device used to quantify the level over the plate surface of each shot community and the four checked estimation positions (estimations kept in millimeters (mm), recorded to one decimal spot).After all test shots have been played out, the board will be taken out from the support material plate. The BFS coming about because of each test shot will be estimated involving the top edges of the plate as a source of perspective point with a concurred estimation instrument. An estimation will then be taken at the most profound place of the BFS delivered by the shot. This will be rehashed for each shot area. BFS Assessments: All appraisals will be done as per the presentation evaluation rules. The hole will be surveyed from the body side of the protective layer. BFS values will be surveyed against the cutoff points determined in the Home Office Body Armour Standard (2017) [33].

CHAPTER 3

METHODOLOGY

3.1 Material Selection & Fabrication

The composite sandwich panels are prepared by filling the core of AHC with different types of mortar mix. Then after curing, the improvised core is wrapped with quadruple layers of CFRP wraps.

3.1.1 Aluminum Honeycomb

Aluminum 3003 and Aluminum 5052 are the most commonly used alloys in the aluminum industry[35]. However, the variances illustrate that even modest changes in the composition can have a significant impact on desirable attributes and uses. The primary ingredient in 3003 alloy type is Manganese (Mn) while in 5052 is Magnesium (Mg). Al 3003 is comparatively soft with moderate strength, while Al 5052 is relatively hard with higher strength. Mechanical properties of Aluminum Honeycomb panel are in **Table 3.1**:

Table 3.1:Mechanical Properties of Aluminum Honeycomb Panel

AHC Type	Elastic Modulus (ksi)	Elongation at Break	Ultimate Tensile Strength (ksi)	Yield Tensile Strength (ksi)
Al3003 (AL1)	10x10^3	4.5%	30	27
Al5052 (AL2)	9.9 x10^3	3.1%	44	37

Considering the factors affecting Impact resistance and Damage Tolerance, AHC of two types namely Al5052 (AL2) and Al3003 (AL1) which are procured from ‘Foshan Alucrown’ [36] have been selected in this research. Further, the technical specifications are as **Table 3.2**:

Table 3.2:Specifications of AHC

Cell Size	Core Thickness	Core Separation	Mass of AL1	Mass of AL2
25 mm	25 mm	1 mm	46 mg	36 mg

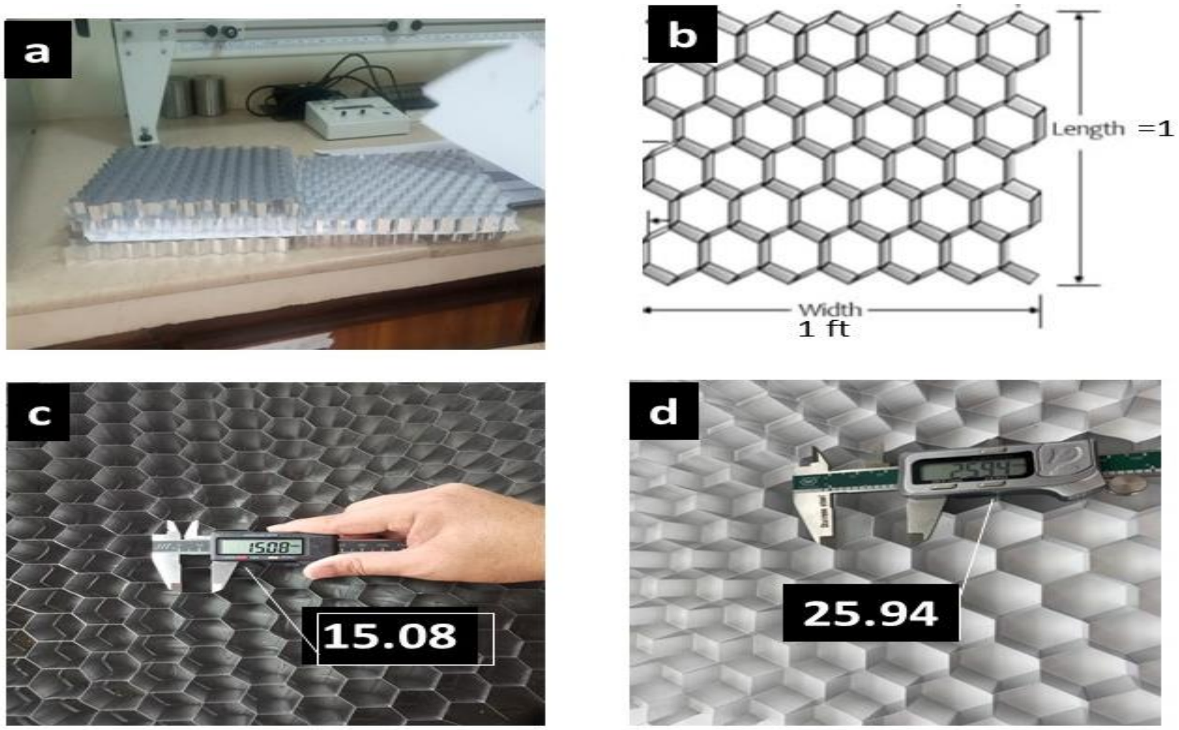

Figure 3.1:(a) Two Types of AHC i.e. AL3003 & AL5052 (b) 1 sq. ft. samples of AHC (c) Hexagonal side dimensions (d) Hexagonal diameter

3.1.2 Grout as a filler

Sika Grout®-114C without any substitution is used as a reference filler in AHC which is procured from Sika, Pakistan [37]. This grout is cementitious and general purpose. A non-shrink precision grout with has high ultimate strength and it flows freely. The properties of Sika Grout- 114C are tabulated in **Table 3.3**.

Table 3.3:Specifications of SikaGrout-114C

Compressive Strength (28 days) at w/p ratio 0.15	Tensile Adhesion Strength	Fresh Mortar Density	Maximum Grain Size	Mixing
65 N/mm2	≥ 1.5 N/mm2 (or concrete failure)	~2.20 kg/l (+25 °C)	~4 mm	Slow speed drill (maximum 500 rpm)

3.1.3 Composite Sandwich Panel Preparation

The mortar mix was prepared in Hobart Mixture keeping the water/grout ratio between 0.15-0.17 to achieve a higher compressive strength of around 65 N/mm2. Mortar mixtures of SikaGrout-114C were made along with the replacement of Rubber tire dust (15%) [22], Iron powder (20%) [1], Glass (25%) [19], Polyvinyl (PVA) fibers (1.5%) [19] of the same size as the grout i.e. sieve passing of 40 # or max. grain size 4 mm. These percentage replacements are taken from the previous research works. Waste materials e.g. glass powder, iron powder, tire rubber dust, etc. are graded by sieve analysis. An Aluminum Honeycomb of two types namely Al3003 (AL1) and Al5052 (AL2) are used. Five different mortar mixtures of SikaGrout-114C (g), Glass (G), Tire dust (T), Polyvinyl fiber (F), and Iron powder (I) were made.

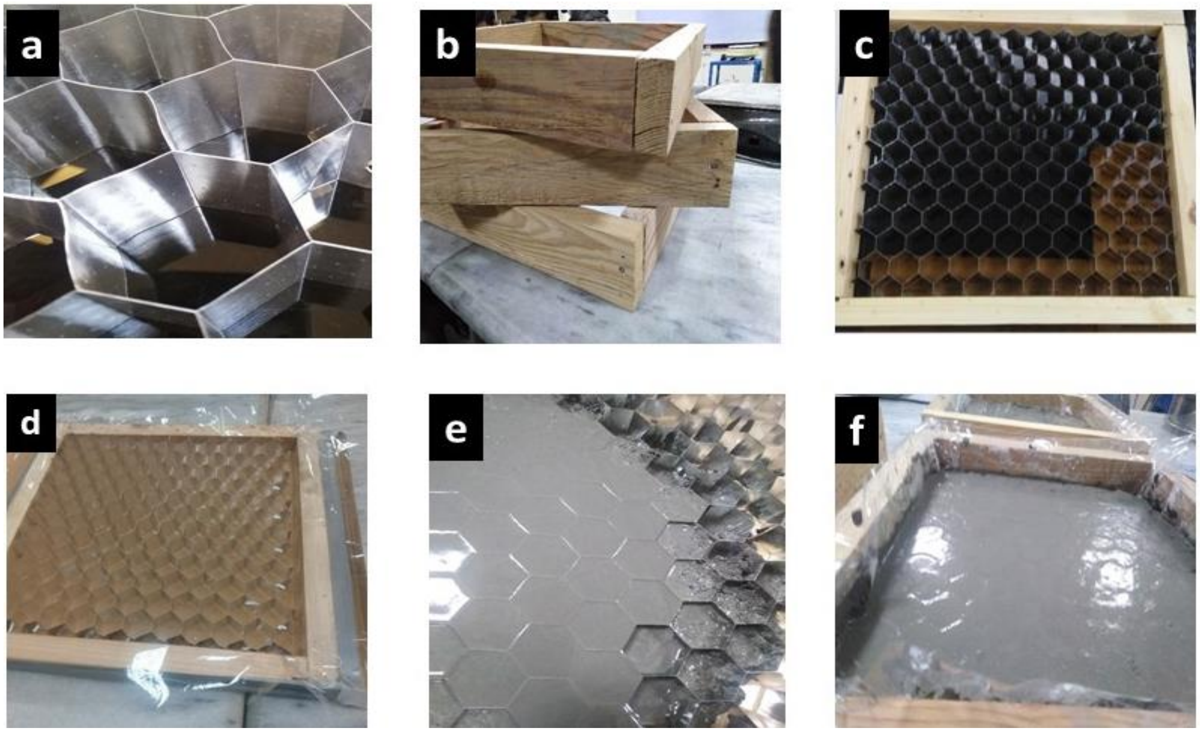

Figure 3.2:(a) Voids of AHC i.e. AL3003 & AL5052 (b) Wooden frames used for mortar filling (c) AHC fixed in wooden frames (d) Plastic sheet for kept before pouring mix (e) Mortar filling (f) Final Composite sample

One sample with AHC AL1 is filled with each mortar mixture and a total of 5 samples of one type i.e. AL3003 were prepared. The size of each sample is 1 square foot. Similarly, three samples of AHC core sandwich panel, of the same size i.e.1 ft. x 1 ft., were made for the second type AL2 which is also filled with various mortar mixtures. A total of 15 samples are made. Simultaneously, cubes of 2 in x 2 in x 2 in are made from each mortar mix. Total samples are 20. The samples are tested for toughness (stress-strain curve) and compressive strength.

Details of the composite sandwich panel samples are tabulated in **Table 3.4** along with the pictorial representation in **figure 3.3**.

Table 3.4:Nomenclature of Samples

AHC Type	Composite Material	Size	Sample No.	Nomenclature
Al3003 (AL1)	Grout	1 sq. ft.	01 No.	AL1 ref.
Al3003 (AL1)	Grout with 25% Glass (G)	1 sq. ft.	01 No.	AL1G
Al3003 (AL1)	Grout with 15% Tire Dust (T)	1 sq. ft.	01 No.	AL1T
Al3003 (AL1)	Grout with 1.5% Polyvinyl Fibers(F)	1 sq. ft.	01 No.	AL1F
Al3003 (AL1)	Grout with 20% Ironite (I)	1 sq. ft.	01 No.	AL1I
Al5052 (AL2)	Grout	1 sq. ft.	03 No.	AL2 ref.
Al5052 (AL2)	Grout with 25% Glass (G)	1 sq. ft.	03 No.	AL2G
Al5052 (AL2)	Grout with 15% Tire Dust (T)	1 sq. ft.	03 No.	AL2T
Al5052 (AL2)	Grout with 1.5% Polyvinyl Fibers(F)	1 sq. ft.	03 No.	AL2F
Al5052 (AL2)	Grout with 20% Iron powder (I)	1 sq. ft.	03 No.	AL2I

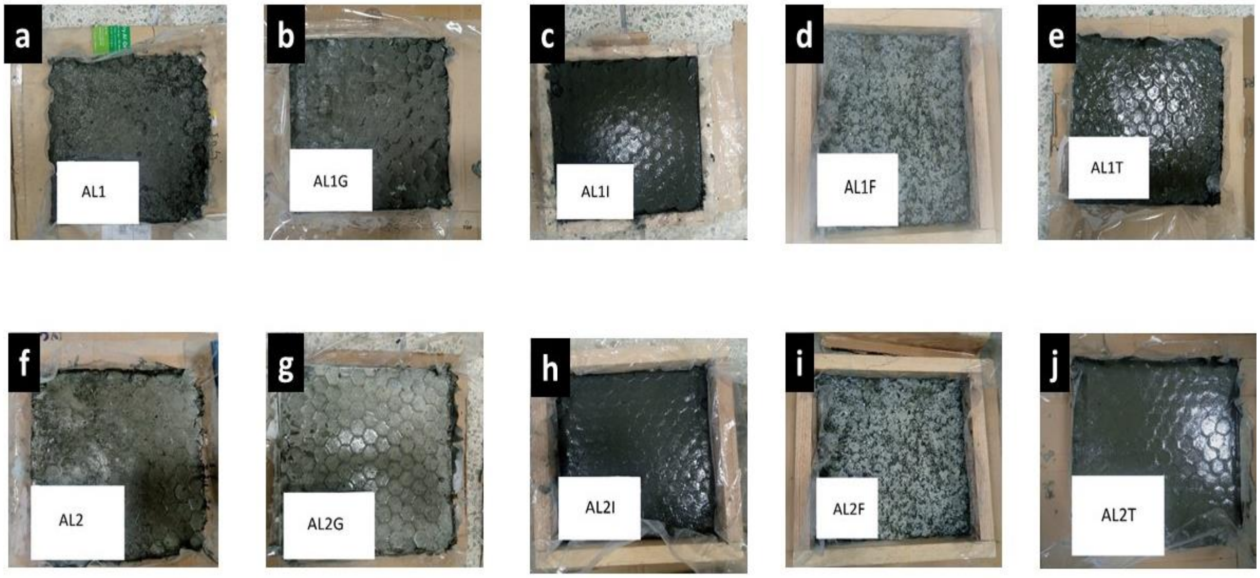

Figure 3.3: Composite samples (a) AL1(b) AL1G (c) AL1I (d) AL1F (e) AL1T (f) AL2 (g)AL2G(h)AL2I(i) AL2F (j)AL2T

3.1.4 Curing and Wrapping of Composite Sandwich Panel

All the Composite Sandwich Panel samples are cured for 28 days with jute bags/hessian cloth to attain maximum strength. After curing, the samples were wrapped quadrilateral i.e. each sample is wrapped four times at a 90-degree to the previous wrap with X-Wrap C230 which is a high-strength fabric made up of carbon fiber and is used for structural strengthening purpose. X-Wrap C230 is a uni-directional sheet which is particularly designed for the strengthening various structural members against impacts, tensile and shear forces. This sheet is used in conjunction with prime coat (primer) along with lamination resin. The technical details of the X-Wrap C230 CFRP are tabulated in **Table 3.5**.

Table 3.5 - Table 5:Technical Specifications of CFRP C230 Wraps

Sheet weight	Carbon content	Net effective thickness	Modulus of elasticity	Tensile strength	Fiber orientation
230g/m2	95%	0.125mm	240 GPa	4000 MPa	0° (longitudinal, unidirectional)

The Composite Sandwich Panel are cleaned and prepared by sandblasting or grinding to remove all the contaminations and provide a mechanical key. The variations of level in the surface of composite panels are checked by using 300mm straight edge. In any direction, 1mm deviation over a distance of 300mm is the maximum permissible deviation. The surface with sharp edges or undesired undulations are grounded precisely for making it smooth. Initially, the Primer is applied over filled aluminum honeycomb. Then, Lamination Adhesive was mixed and applied over it. Immediately after applying the Lamination Adhesive, the CFRP C230 sheet was laid on the surface and pressed in position using suitable hand lay-up (washer) roller. Similarly, each layer of laminating resin and carbon fiber sheet is applied. After wrapping each layer, the Sandwich panels are kept at a controlled temperature of 30-35 degrees Centigrade for 7 days to cure the CFRP. Hence, it attained maximum strength.

Figure 3.4:(a) Mixing of binders (b) Application of resin/ adhesive (c) Cutting of CFRP (d) Hand roller removing undulations (e) Fixing CFRP with hand roller (f) CFRP wrapped sample

The specification of Composite Sandwich Panels is tabulated below in **Table 3.6**;

Table 3.6:Specifications of Composite Panel

Panel Weight	Panel Thickness	Structural Strength	Wrap Stacking
5-6 kg/ft^2	26 mm	17200 MPa	0°,45°,90°,135°,180°, 225°,270°,315°,360° (Anticlockwise) (Yong Xiao, 2018)

3.2 Testing of samples

3.2.1 Toughness and Compressive Strength testing of cubes

15 samples of 2 inches cubes (1 cube for each mortar mixture) are tested for 7 days, 21 days, and 28 days' compressive strength using ADR Touch Pro Compressive Testing Machine. The samples achieved 28 days compressive strength of around 10 ksi.

Figure 3.5: ADR Touch Pro Compressive Machine

05 samples of cubes (1 cube for each mortar mixture) were tested for 3 days' stress-strain curve i.e. toughness using Universal Testing Machine (UTM) wherein the strain rate can be set between 0.0005 mm /minute to 1000 mm / minute. The UTM Shimadzu has a limitation of maximum loading i.e.100KN force at max, that is why only 3 days of cured samples are tested in the machine. Whereas, the strength of concrete is strain rate sensitive. Also, the degree of sensitivity is directly proportional to strain rate [38]. Keeping this in consideration, the strain rate was kept at 0.001 mm /mm per minute to obtain a representative stress-strain curve.

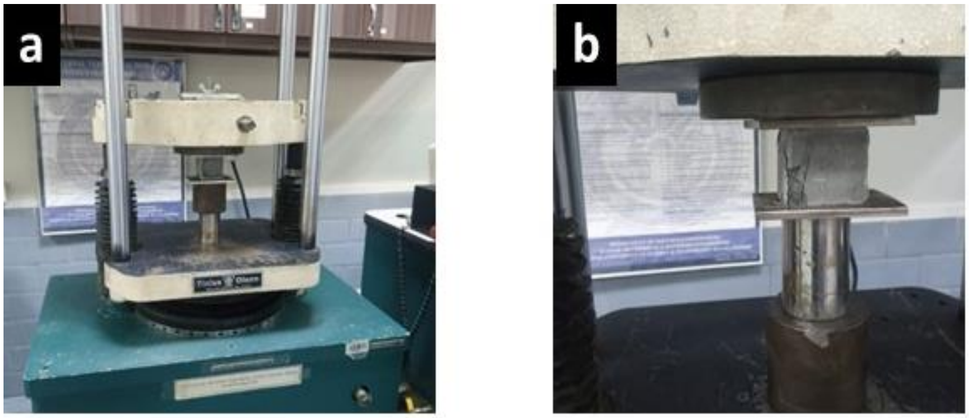

Figure 3.6:(a) UTM (SHIMADZU 100 KN) AG-Plus Universal Testing b) Sample testing

3.2.2 Ballistic Testing of Composite sandwich panels

European Committee for standardization created EN 1063, or CEN 1063 for measuring the protective strength of bullet-resistant glass [39]. The 3 bullets of the 19 mm, 45 mm, and 51 mm were fired as per CEN 1063 standard on each sample in the controlled testing environment to check against the resistance and the impact, and BFS of each sample. The details are tabulated in **Table No. 3.7**.

Table 3.7:Fired Bullet Details

Class	Weapon	Bullets	Weight (g)	Range (m)	Velocity (m/s)	Impact Energy	Shots
BR2	Handgun	9×19mm	8,0 ± 0,1	5,00 ± 0,5	400 ± 10	640 J	3
BR5	Rifle	5.56×45mm	4,0 ± 0,1	10,00 ± 0,5	950 ± 10	1800 J	3
BR6	Rifle	7.62×51mm	9,5 ± 0,1	10,00 ± 0,5	830 ± 10	3270 J	3

As per CEN 1063 [39], 3 bullets are to be fired at the distance of 120 mm / 6 inches in a triangular pattern in order to measure the resistance against the impacts as shown below.

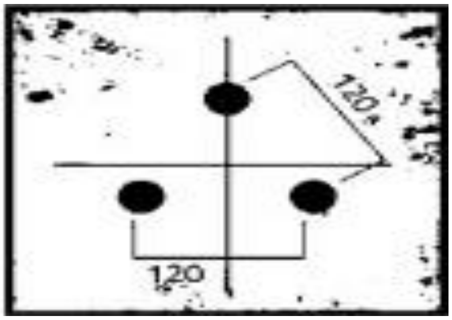

Figure 3.7: CEN 1063 Standard

The samples were prepared by marking as per the standard and then clamped on a stand-like arrangement. The bullets were fired through Computer Numerically Controlled (CNC) setup consisting of gun, shield and laser arrangement in a controlled environment where the bullet velocities and energies were constantly monitored. Three bullets of 19 mm were shot first, followed by 3 shots of 45 mm in the same pattern. Both bullets resisted the impact and the BFS was measured simultaneously after the shot. Afterwards, 3 bullets of 51 mm were fired and all pierced through the samples. These pictorial views give the reader a better idea of the testing arrangement.

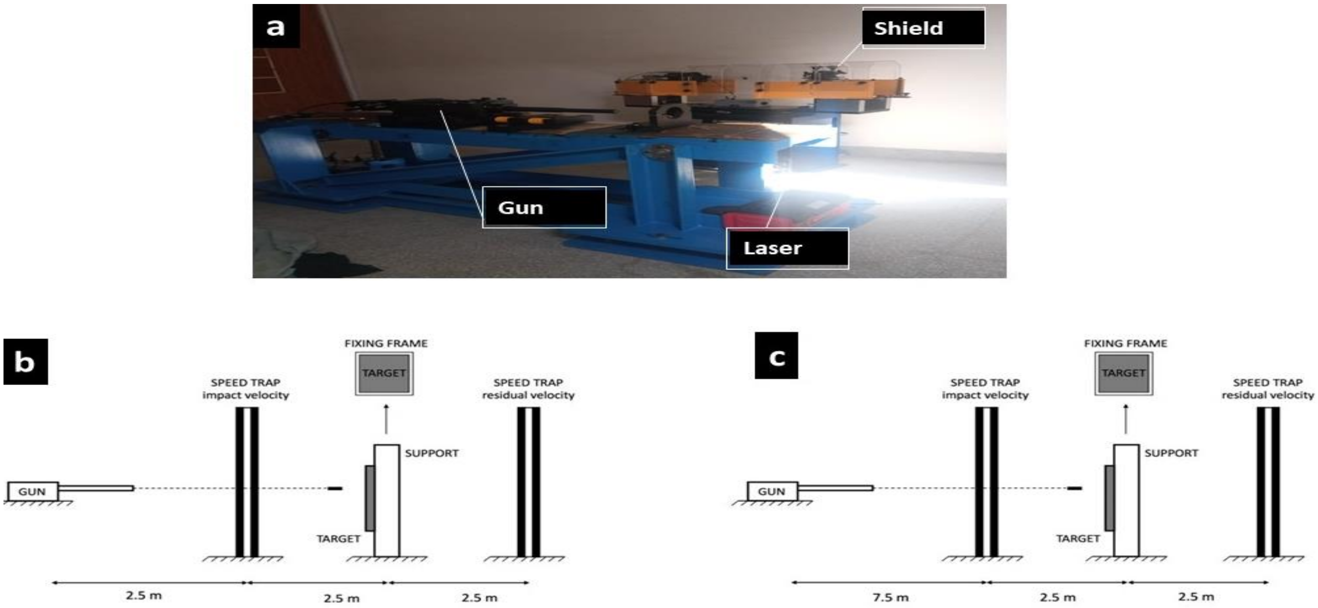

Figure 3.8:(a) Controlled Testing Equipment b) Schematic Presentation of Testing for 9 x19mm bore shot (c) Schematic Presentation of Testing for 7.62 x51 and 5.56×45mm mm bore shot

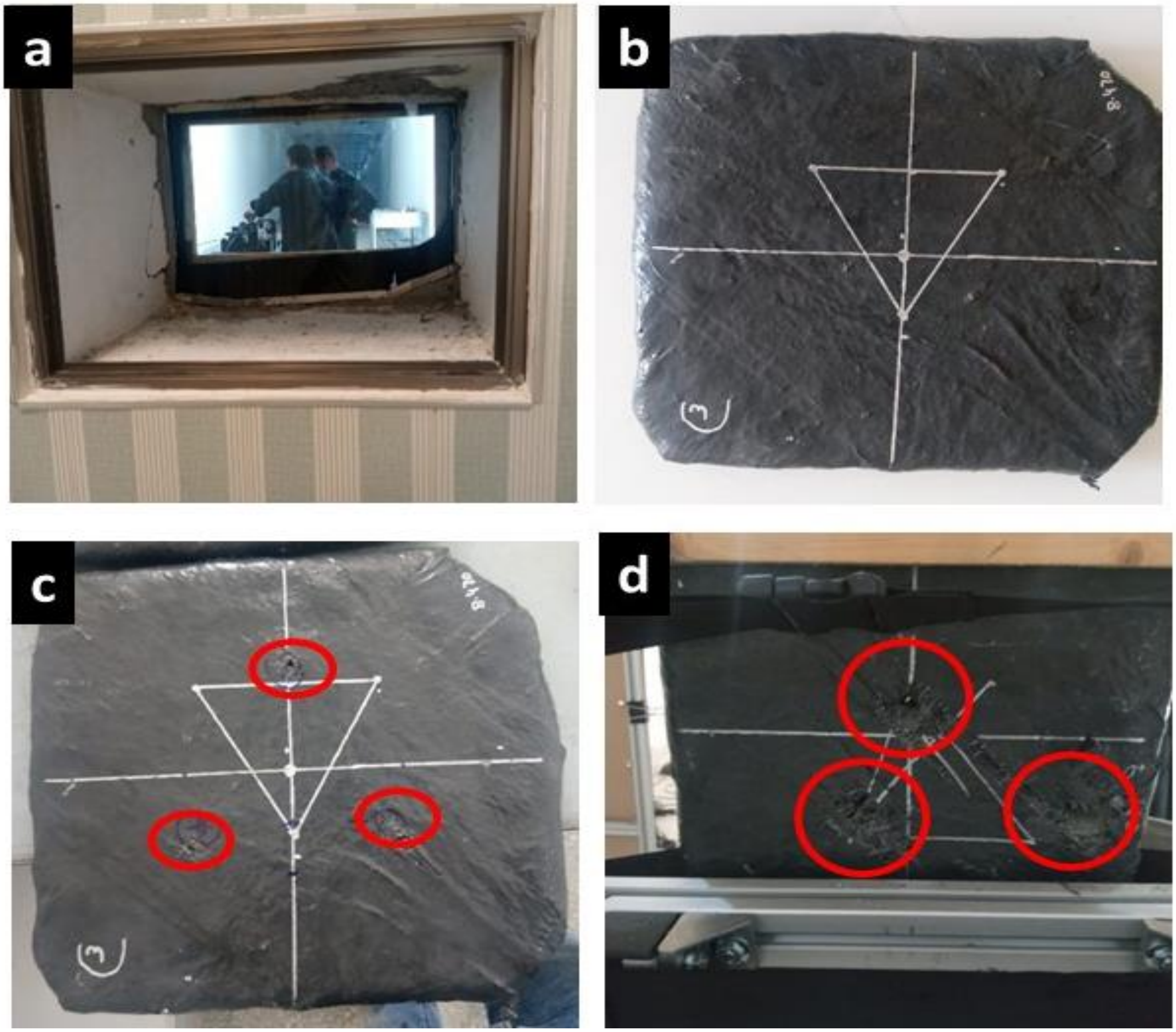

Figure 3.9:(a) Viewing Window of the testing tunnel b) Post-firing 9 mm bullet – indicating negligible BFS effect on the sample (c) Post-firing 45 mm bullet – indicating smaller surface indent and smaller BFS (d) Post-firing 51 mm bullet–piercing through the sample

CHAPTER 4

RESULTS AND DISCUSSI4ONS

3.3 Compressive Strength

15 samples of cubes (1 cube for each mortar mixture) were tested for 7 days, 21 days, and 28 days' compressive strength. The grout samples achieved 28 days of compressive strength of around 60.45 MPa. With the replacement of waste materials, i.e., iron powder, tire dust, glass powder, and Polyvinyl (PVA) fibers in the grout., the peak compressive strength has improved for all samples except the grout sample with tire dust. The peak compressive strength has relatively been compromised by the addition of tire/rubber dust. The results achieved are in conformity with previous researches [15]–[17]. The overall behavior of the stress-strength curve i.e., toughness also improved for all samples except the sample with tire dust. The same can be seen in the graph below in Figure 4.1 while the results are tabulated in **Table 4.1**, respectively.

Table 4.1: Compressive Strength of Samples

Sample Description	3 days Compressive Strength (MPa) (Peak Values from Stress-Strain Curve)	7 days Compressive Strength (MPa)	21 days Compressive Strength (MPa)	28 days Compressive Strength (MPa)
AL (Ref.)	24.60	39.98	58.43	60.45
ALI	22.30	37.24	60.96	63.80
ALT	20.39	35.13	53.42	57.10
ALG	28.28	43.96	65.17	69.50
ALF	38.88	61.18	90.34	93.55

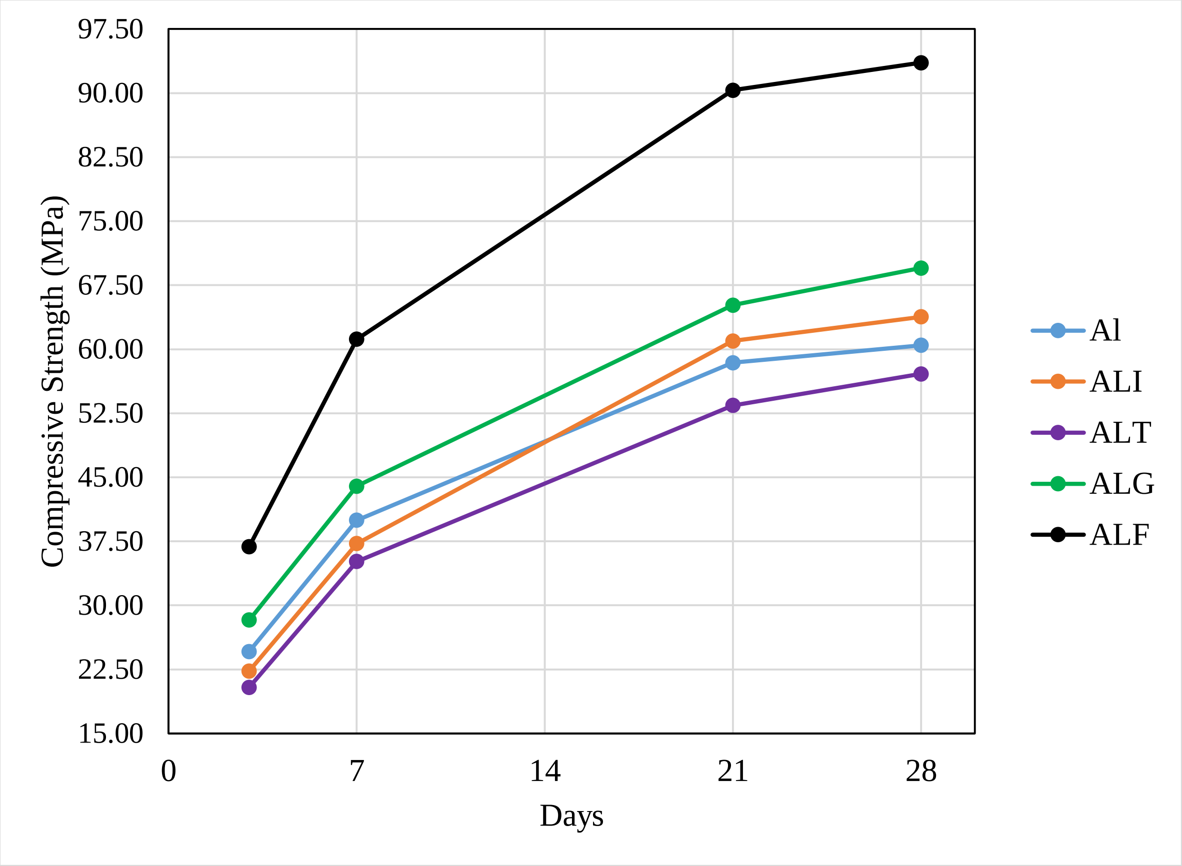

Figure 4.1: Comparison of Compressive Strengths of different mortar mixes

3.4 Toughness

05 samples of the cube (1 cube for each mortar mixture) were tested for 3 days' stress-strain curve i.e., toughness using Universal Testing Machine. The UTM had a limitations of max. loading i.e., 100 KN, that is why only 3 days of cured samples could be tested for max. stress i.e., 100 KN / 50 x 50 mm^2 = 40 MPa. The strain-controlled loading rate was set at 0.001 mm / mm per minute and the loading continued till the physical failure of the sample. The area under the stress-strain curve has been calculated in excel sheets by adding all trapezoidal areas between small intervals of strains i.e., 0.001 mm/mm per minute. Further, it can be seen from the graphs that the area under the stress-strain curve i.e., toughness has improved with the replacement of different materials in the grout mortar mixture except for the tire dust which may be due to some abnormality or error in sample preparation. An increase in toughness is directly linked to more energy absorption/dissipation capacity of the AHC Composite Sandwich Panels. It indicates more ductile

behavior and better performance against multiple ballistic impacts. The 3- days stress-strain curves for all sample cubes are drawn together below in Figure 4.2 for better comparison.

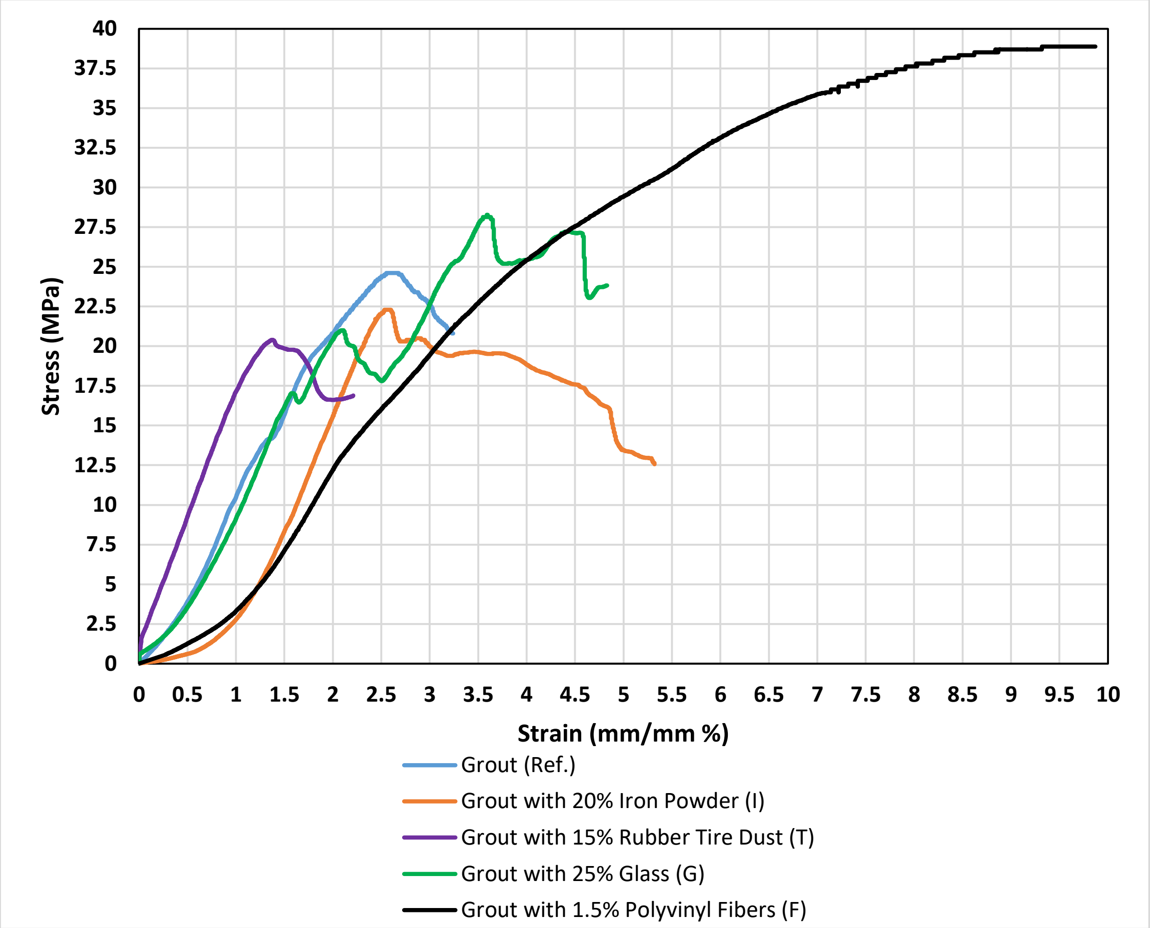

Figure 4.2: Comparison of 3- days Stress-Strain Curve for different mortar mix cubes

This grout sample is taken as referenced samples because the other samples have been prepared by different material replacements in this grout mortar mixture. The graph in Figure 11 represents the 3- days Stress-Strain Curve. Cube of grout which attained the maximum stress of 24.6 MPa. The toughness obtained by calculating the area under the stress-strain curve is 48.68 MPa-mm/mm % and the maximum strain taken by the sample is around 3.24 mm/mm %. The 28- day compressive strength of the grout cube is 60.45 MPa as shown in Figure 4.1.

The grout with 20% Iron Powder (I) cube sample has attained the 3 days' maximum stress of 22.3 MPa which is 9.35% less than the referenced cube. However, 28 days' maximum compressive strength is 63.80 MPa which is 5.54% higher than the referenced cube. The toughness obtained is

70.28 MPa-mm/mm % which is 43.8% higher than referenced cube and the maximum strain taken by the sample is around 5.32 mm/mm % which is also 64.2% higher than the referenced cube.

The grout with 15% Rubber Tire Dust (T) cube sample has attained the 3 days' maximum stress, 28 days' maximum compressive strength, toughness, and maximum strain of 20.38 MPa, 57.10 MPa, 31.65 MPa-mm/mm %, and 2.21 mm/mm % respectively which is 17.15%, 5.54%, 35.25% and 31.8% less than referenced cube respectively. There is significant loss observed in both maximum stress and toughness against the expected increase in toughness which may be due to anomaly in sample preparation or error in testing. It can also be substantiated that the 28 days of compressive stress of the cube showed a comparable lower decrease in strength. Further, all AHC Composite Sandwich Panel with this type of mortar mixture filling behaved in a similar manner as compared to other mortar mixture fillings.

The grout with a 25% Glass (G) cube sample has attained the 3 days' maximum stress, 28 days' maximum compressive strength, toughness, and maximum strain of 28.28 MPa, 69.50 MPa, 86.03 MPa-mm/mm %, and 4.83 mm/mm % respectively which are 14.96%, 14.98%, 76%, and 49.1%. All the values are higher than referenced cube respectively. All properties of this sample showed improvement.

The grout with a 1.5% Polyvinyl Fibers (F) cube has attained the 3 days' maximum stress of 38.88 MPa which is 58% higher than the referenced cube. 28 days' maximum compressive strength is 93.55 MPa which is also 54.8% higher than the referenced cube. The toughness obtained is 249.43 MPa-mm/mm % which is 410% higher than the referenced cube. This cube sample has shown the highest increase in toughness. The maximum strain taken by the sample is around 9.87 mm/mm % which is also the highest among all cube samples and 204% higher than the referenced cube. It can also be established that besides better toughness and higher strain, there is a smooth transition in a stress-strain curve which indicates the ductile nature of the sample. The different aspects of the graphs are summarized hereunder in **Table 4.2**.

Table 4.2: Comparison of properties of different mortar mixes

Sample Description	3 Days Peak Compressive Stress (MPa)	28 Days Peak Compressive Stress (MPa)	Toughness (3 days Stress-Strain Curve) (MPa – mm /mm)	Maximum Strain (3 days Stress-Strain Curve) (mm / mm %)
Grout (Ref.)	24.6	60.45	48.88	3.24
Grout with 20% Iron Powder (I)	22.3 (-9.35%)	63.80 (+5.54%)	70.28 (+43.8%)	5.32 (+64.2%)
Grout with 15% Rubber Tire Dust (T)	20.388 (-17.15%)	57.10 (-5.54%)	31.65 (-35.25%)	2.21 (-31.8%)
Grout with 25% Glass (G)	28.28 (+14.96%)	69.50 (+14.98)	86.03 (+76%)	4.83 (+49.1%)
Grout with 1.5% Polyvinyl Fibers (F)	38.88 (+58%)	93.55 (+54.8%)	249.43 (+410%)	9.87 (+204.6%)

The cube samples with Glass Dust (G) and Polyvinyl fiber (F) have shown a great gain in 3 days' peak stress, 28 compressive strengths, toughness, and strain. The highest percentage increase in both toughness and strain % is observed in grout with a 1.5% Polyvinyl fiber (F) cube sample. There is significant loss observed in both maximum stress and toughness against the expected increase in toughness of cube samples with Tire rubber dust (T).

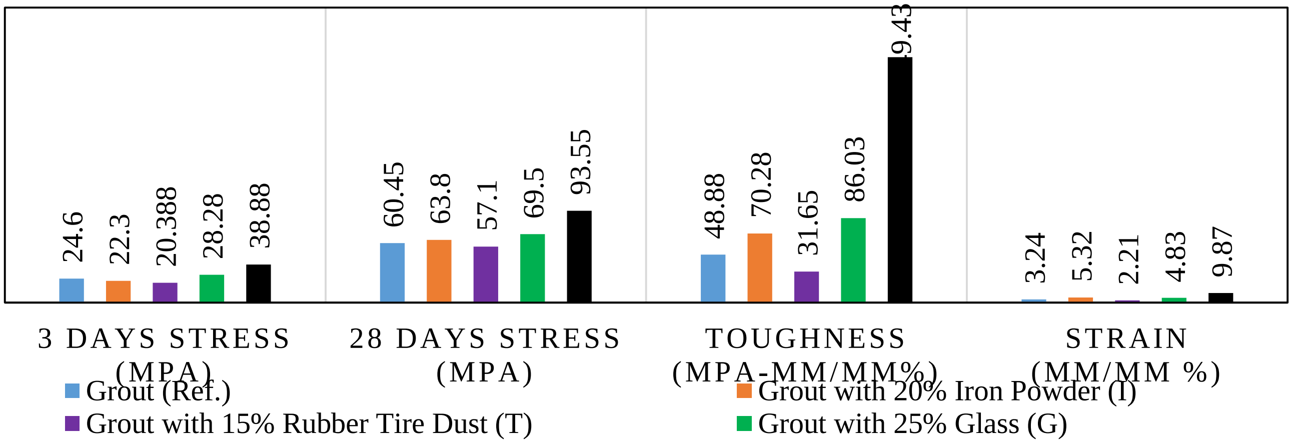

Figure 4.3: Comparison of properties of different mortar mixes

3.5 BFS due to Ballistic testing

After impact, the maximum depth of indentation made by armor body into ballistic backing is known as Back face signature or trauma. It is always measured perpendicular to the surface of panel or backing material. The Maximum Mean BFS measurements need not be exceeded 25 mm for the 5.56×45mm shots [33]. The BFS of all the samples was measured by the Vernier Calipers depth scale. All samples resisted 19 mm and 45 mm shots with a maximum BFS of 14 mm. 9×19mm shots produced negligible BFS indentation on all the composite sandwich panel samples. The composite sandwich panel of AL1 produced a relatively higher BFS than AL2.

For 5.56×45mm shots; the composite sandwich panel of AL1 having composite material of polyvinyl fiber core and tire rubber dust produced the BFS in the range of 12 and 14 mm respectively while the other samples with a composite core of glass, iron powder, and grout produced the BFS in range of 5-8 mm. However, the composite sandwich panel of AHC AL2 having composite material of polyvinyl fiber core and rubber dust bore the average BFS of 10 and 12 mm while the other samples with a composite core of glass, iron powder, and grout bore the average BFS of 6mm, 6.5 mm and 5 mm respectively. The BFS results are presented below in bar chart.

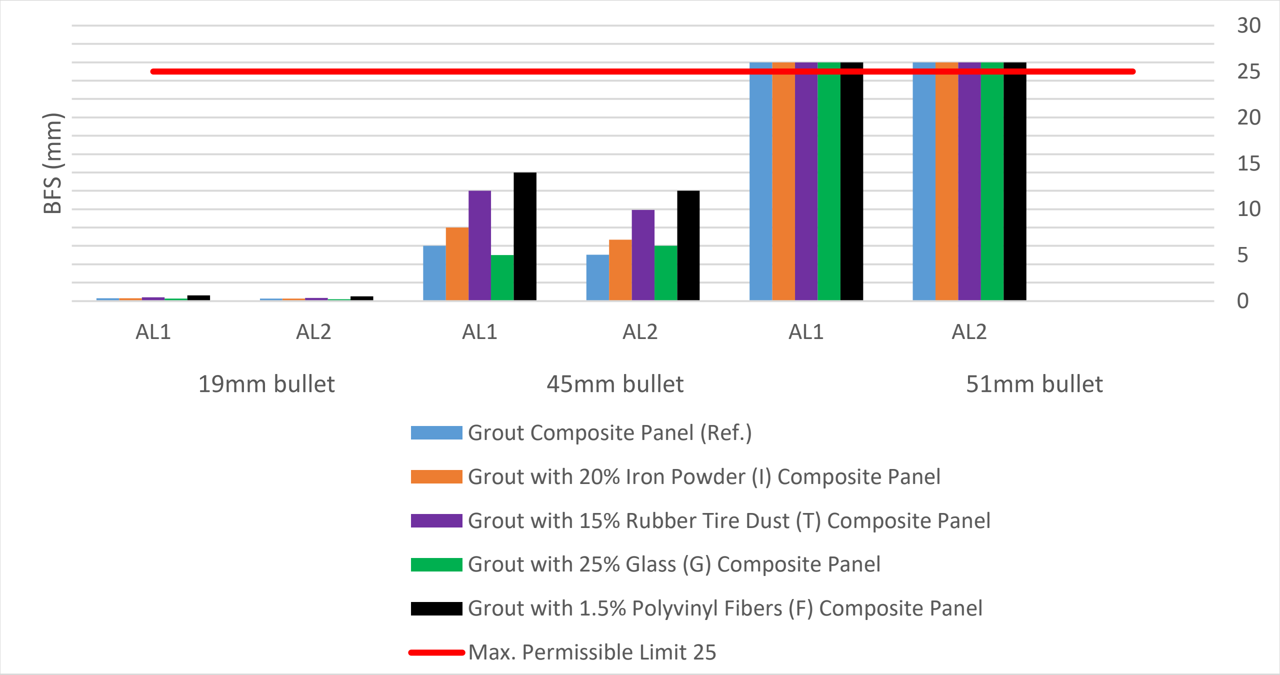

Figure 4.4: BFS of different Composite Sandwich Panels

None of the samples provide the resistance/protection against the 7.62×51mm bore shot i.e., 3270 J Impact Energy. Perforation is a term that refers to the instance when a projectile passes through an armor (National Institute of Justice Guide: Body Armor- 0101.06) [40]. 51 mm bullets pierced through the samples but only a single cell of AHC was damaged with each bullet perforation, thus the integrity of the composite sandwich panel remained intact.

As it is evident from the bar chart that the composite sandwich panel of AL1 produced a relatively higher BFS than AL2 which is mainly due to the overall higher ductile composition and moderate strength of AL1 than AL2.

It can also be deduced from the BFS bar chart that the Composite Sandwich Panel filled with a grout having 1.5% Polyvinyl fiber (F) and grout with 15% Rubber / Tire Dust (T) produced relatively higher BFS than the Composite Sandwich Panels filled with a mortar mixture of Grout (only), grout with 25% Glass (G) powder and grout with 20% Iron powder (I). The above results are summarized in **Table 4.3** for better understanding.

Table 4.3: Summarizing BFS Results

Bullets	**Impact**	**Results**	**Remarks**
9×19mm	640 J	No BFS indentation	No noticeable indentation was observed in any sample.
5.56×45mm	1800 J	BFS indentation varied between 5 mm and 14 mm	Well within the max. average BFS limit of 25 mm.
7.62×51mm	3270 J	Perforation	Failed

CHAPTER 5

CONCLUSION

The proposed composite sandwich structures were prepared and then tested against compression and toughness. All the composite panels showed a great amount of resistance and the panels resisted multiple impacts successfully for 9 mm and 45 mm shots i.e., 640 J and 1800 J impact energy. The BFS was significantly less than the standard required BFS for Body Armor Standard HOBDS-2017 [33] i.e. 25 mm, meaning a larger amount of impact energy dissipated with relatively lower BFS than the permissible limit. Further, only a single cell of AHC was damaged against the 51 mm bore shot, thus, the overall structural integrity remained intact as anticipated.

It is time to work on modified composite materials to resist multiple impacts as well as resist BFS to a greater extent. Modern computational techniques can also be utilized for modeling & better results. Such developments/ innovations of composite structure are useful in resisting the impact/blast loading up to a great extent (if not completely) which can later be modified and used in the construction or manufacturing of mobile or immobile bunkers, armor manufacturing, tank, and anti-tank manufacturing, ballistic proofing/testing at any stage (internal, external, or terminal), etc. These composite sandwich panels can further be improvised and used as Add-on armor (additional or appliqué armor); an armor system that can be easily installed or removed from a vehicle without adversely affecting its structural integrity or operation. It usually covers vulnerable areas [41].

AHC which we used in our research was imported from China. The material itself was very cheap but the freight charges to import here in Pakistan mounted the overall price to a great extent. While the material can be locally manufactured as well. **Acknowledgement:** The authors acknowledges the cooperation and contribution of Sika Pakistan and X Caliber Pakistan in conducting this research work.

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