Blast and Fire Resistant Material

B A M

EXCELLENCE/0421/0137

DELIVERABLE D1.1

12 MONTHS PROGRESS REPORT

Co-funded by the European Union
Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION

Το έργο υλοποιείται στο πλαίσιο του Προγράμματος Πολιτικής Συνοχής «ΘΑλΕΙΑ 2021-2027» με τη συγχρηματοδότηση της ΕΕ

PROGRESS REPORT

RESTART 2016-2020 Programme for Research, Technological Development, and Innovation

RESEARCH AND INNOVATION FOUNDATION

Ευρωπαϊκή Ένωση
Ευρωπαϊκό Ταμείο Περιφερειακής Ανάπτυξης

Κυπριακή Δημοκρατία

Διαρθρωτικά Ταμεία της Ευρωπαϊκής Ένωσης στην Κύπρο

A.1. GENERAL PROJECT INFORMATION	
Project Protocol Number:	EXCELLENCE/0421/0137
ESIF Number:	
Project Title:	Blast and Fire Resistant Material
Project Title in Greek:	Υλικό Ανθεκτικό σε Έκρηξη και Πυρκαγιά
Host Organisation:	Frederick Research Center (FRC)

A.2. DESCRIPTION OF THE WORK CARRIED OUT BY ALL BENEFICIARIES DURING THIS REPORTING PERIOD. *(Maximum Recommended 3 pages)*

Please provide an overview of the progress towards the project objectives, justifying the differences between work described under Annex I of the Contract and work actually performed, if any.

The **General Objective (GO)** of the BAM project is to design, develop and validate at a laboratory scale two innovative smart materials, which will be fire and blast and impact resistant, and each of these materials will be manufactured with two different methods: i) with the conventional casting method and ii) with 3D-printing manufacturing. The two designed and developed materials with both production methods will be evaluated in terms of their thermal, mechanical, impact and blast properties.

Therefore, the 2 main **Scientific Objectives (SO)** of the BAM project are:

SO-1: Design and Development of a **Hybrid Laminated Material (HLM)** with combined resistance to blast, impact, and fire.

SO-2: Design and Development of a **Smart Composite Geopolymeric Concrete (SCGC)** with simultaneous resistance to blast, impact, and fire.

Specifically, both materials will be resistant to fire withstanding temperatures which are met in building applications, i.e., up to 1050 °C shown in ISO-834 fire curve. In addition, the materials will be resistant to explosive load equal to 3.5 kg, which simulates a typical building explosion and impact loads, validated through drop hammer tests (i.e., 20 kg hammer from 4 m drop-height).

Based on the abovementioned SO, the project's **Technological Objectives (TO)** are:

TO-1: Validation of the produced materials at a laboratory scale, in terms of mechanical and durability properties and by applying existing standard tests for fire resistance.

TO-2: Validation of the produced materials against blast and impact resistance with 3 methods: a) By testing materials' specimens against impact loading (e.g., by conducting Drop Hammer tests in the lab). Drop hammer tests will also serve as an indirect indicator for the resistance of materials against blast loads. b) Achievement of specific mechanical properties that are considered as essential for satisfactory blast and impact response of materials and c) Finite Element Analysis (FEA) of the materials' blast resistance.

TO-3: Validate the produced materials in technoeconomic and cost-benefit analysis terms, by setting a benchmark with commercially available ones.

The BAM project work plan consists of **five (5) distinct Work Packages**, implementing activities like material design and development, production, and validation in laboratory environment and through an analytical method, management, exploitation and dissemination, and techno-economic analysis. The successful completion of all the WPs will result in the achievement of all the project objectives.

The overall project's progress for the first reporting period is considered very satisfactory. A detailed report regarding the implementation of each WP is provided in section "A.3. EXPLANATION OF THE WORK CARRIED OUT PER WORK PACKAGE (WP)". Briefly, the progress of each separate WP towards the accomplishment of the project objectives is presented below:

- WP1 is accountable for managing and coordinating all project activities, including addressing administrative matters within the Consortium and Steering Committee. The research team monitored the progress of WP1 carefully and worked diligently to resolve any issues that might impede the project's smooth implementation. This ensured the successful preparation of the Midterm Progress Report, which was a specific output related to WP1 for the first reporting period. The deliverable was completed promptly and reviewed by internal peer-reviewers assigned as per the project's quality assurance plan.
- WP2 is dedicated to "Dissemination and Exploitation Activities" and focuses on preparing outputs such as the Dissemination Plan, Project Website, and Social Media Accounts. These outputs were completed on time and reviewed by assigned internal peer-reviewers. Moreover, in addition to these official deliverables, WP2 also carried out several activities aimed at disseminating and exploiting the project's results to a broader audience. For instance, seminars were organized for university students related to the activities of the BAM project, and interactive presentations were given to high-school students regarding the manufacturing of new materials using casting and 3D-printing. These activities were designed to maximize the dissemination and exploitation of the project's outcomes.
- WP3 aimed to design two new materials, namely HLM and SCGC, which were intended to withstand fire scenarios of ISO-834 used in building structures and urban tunnels, as well as blast and impact loads according to the validation methods proposed in the project. At the time of submitting this interim progress report, the design and development of the Hybrid Laminated Material (HLM) had been completed successfully. Additionally, satisfactory progress had been made towards the design and development of the Smart Composite Geopolymeric Concrete (SCGC). Both materials were designed to meet the project's specifications and were progressing well towards achieving their intended objectives.
- WP4 was dedicated to manufacturing the two materials using both conventional casting and 3D-printing methods, including appropriate modifications of syntheses to achieve optimal production results, as well as validating the materials' properties through laboratory testing and analytical methods. At the time of submitting this report, the precast manufacturing of HLM had been successfully optimized, while the precast manufacturing of SCGC had made very satisfactory progress. However, there are still some challenges to be addressed regarding the 3D-printing manufacturing of the two materials due to the presence of fibres in the mixtures. Moreover, work related to Finite Element Analysis (FEA) of the materials' blast resistance had also shown good progress with interesting results. Overall, WP4 is progressing well towards meeting its objectives.
- WP5 aimed to evaluate the developed materials using both production methods in terms of cost, efficiency, and environmental impact through techno-economic and cost-benefit analyses. WP5 has been continuously receiving results such as updated materials' recipes and cost of raw materials from the technical WPs (3 and 4). Draft versions of both D5.1: Technoeconomic Evaluation and D5.2: Cost-Benefit Analysis (CBA) have been produced based on these results. The objective of WP5 is to assess the feasibility of producing the new materials on a commercial scale, as well as to evaluate the economic and environmental impact of the manufacturing processes. Ongoing progress in WP5 is expected to provide valuable insights into the overall viability of the project's objectives.

A.3. EXPLANATION OF THE WORK CARRIED OUT PER WORK PACKAGE (WP). *(Maximum Recommended 3 pages per WP)*					
Work Package Number:	**1**	**Start Month:**	**1**	**End Month:**	**24**
Work Package Title	**Project Management**				
Work Package Leader	**Frederick Research Center**				
Partner Role	**FRC**	**UCY**	**RECS**		
Person Months	**2**	**2**	**1**		

Work Package Objectives as described in Annex I of the Contract.

Briefly describe the objectives of the WP and the work carried out during the reporting period towards the achievement of each listed objective.

WP1 is responsible for the overall project management, including monitoring, coordinating, and addressing all management issues. This work package supports all other work packages of the project and has the following objectives: 1) to maintain the consortium agreement among partners and organize meetings, 2) to act as an interface to the Research and Innovation Foundation (RIF) management team, 3) to monitor the project's progress, 4) to execute the dissemination strategy and track the deliverables and milestones closely, while also identifying and mitigating potential risks. Furthermore, it ensures that: (i) all project objectives are achieved within the stipulated time, quality, and cost; (ii) specific scientific and technical objectives for each work package are achieved; and (iii) innovation and intellectual property rights are managed.

Work Description and Key Results

Describe the activities undertaken relating to project management (e.g. preparation of Progress Reports, coordination meetings, decision making procedures etc.) and networking (i.e. exchange of visits between partners including timeframe and purpose of each visit). Where possible, provide quantitative information on activities and results.
Where appropriate, give details of the work carried out per task by each beneficiary involved, indicating the lead partner.

WP1 is led by the Host Organization, which is the Frederick Research Center (FRC), with the support and active involvement of all the consortium partners. Dr. Demetris Nicolaides, the Project Coordinator, has overall responsibility for the smooth implementation of all legal and contractual issues, financial and administrative management, intellectual property management, and technical and scientific issues of the project. To achieve this crucial objective, Dr. Nicolaides is supported by the BAM project's committees, the HO's administrative mechanisms, the WP and Task leaders, and all other consortium partners.

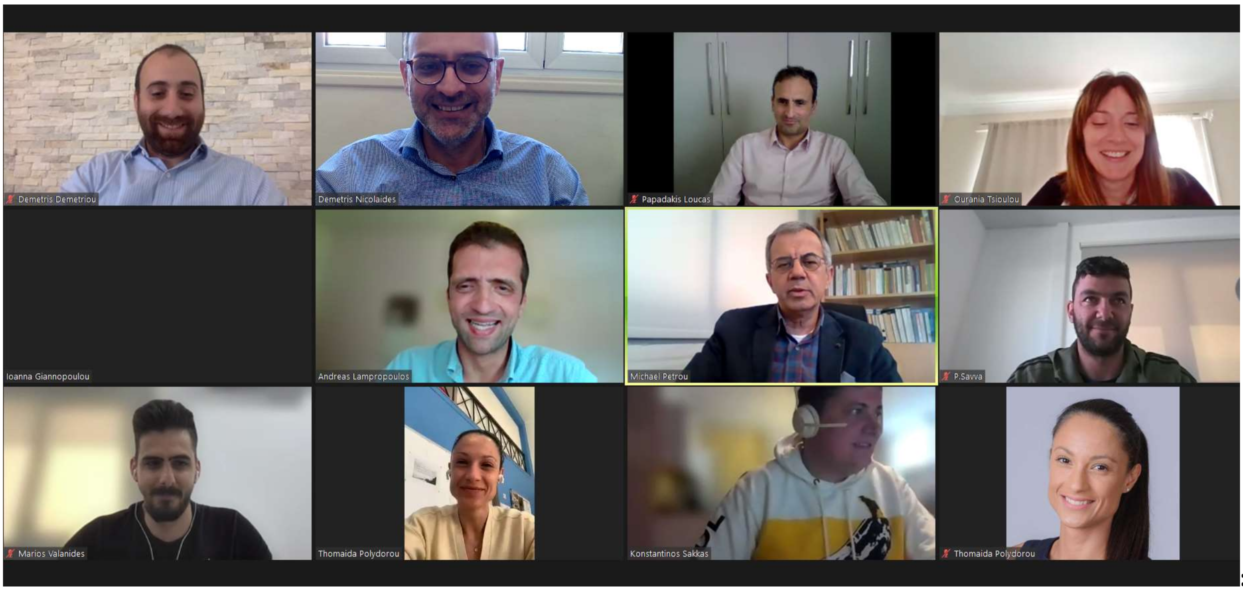
Within the framework of WP1, the research team aimed to fulfill the requirements and obligations of the following two tasks:

- Task 1.1: General Project Management (including (a) Legal and Contractual Management, (b) Financial and Administrative Management and (c) Scientific Management and Technical Project Coordination)
- Task 1.2: IP Management

Below is a summary of the activities carried out in WP1 during the first half of the project.

At the project's kick-off meeting, the coordinator presented the BAM Project Management framework, which aimed to achieve the best possible implementation of all technical and scientific tasks, compliance with the provisions of the Grant Agreement and any other applicable provisions of RIF, handling of legal issues, maintenance of the Consortium Agreement, and proper financial and administrative management. To ensure the successful implementation of these crucial objectives, specific actions were proposed, and decisions were made:

- Formation of a Steering Committee composed by the Project Coordinator (i.e., Dr Demetris Nicolaides, FRC), the Technical Manager (i.e., Dr Konstantinos Sakkas, RECS), the Quality Manager (i.e., Professor Michael Petrou, UCY) and the Dissemination Manager (i.e., Dr Pericles Savva, RECS).
- Assignment of Work Packages and Tasks Leaders, based on each organisations and individual researcher’s background and expertise.
- The project has adopted a Quality Assurance Plan for its deliverables. Each deliverable has been assigned a "Responsible Researcher" from the consortium who will coordinate the team and ensure the deliverable is completed on time, within budget, and meets technical requirements. Additionally, to maintain high quality, a peer review system has been established. The Responsible Researcher will submit the deliverable to the Peer Reviewer(s) before the official completion deadline, allowing sufficient time for review. A table summarizing Project Deliverables, Responsible Researchers, Peer Reviewers, and Delivery Completion Month has been distributed to the consortium. The Quality Manager of BAM will closely monitor and supervise this process.
- During the meeting, the participants were presented with templates for creating project deliverables, presentations, and reports. In addition, the project logo, and the necessary text for acknowledging the funding agency were also distributed.
- A tentative plan for consortium meetings (either as a whole or in smaller groups) was presented and discussed. Specifically, the coordinator discussed meetings of the General Assembly, Steering Committee, WP Leaders, Task Leaders, and others.
- Finally, Mr. Alexis Onoufriou, the director of the FRC Research Office (i.e., the Host Organisation), delivered detailed presentations to the participants regarding the financial management of the project and the applicable RIF regulations.



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Project’s Kick-Off Meeting

The points mentioned above were thoroughly discussed during various meetings, including the 1st and 2nd Steering Committee meetings, General Assembly meetings, and ad-hoc meetings with project partners. Moreover, during the visit of researchers from the University of Brighton to Cyprus in October 2022, the consortium had the opportunity to discuss technical and managerial issues related to the project in detail.

Apart from the scheduled formal consortium meetings (such as kick-off and Steering Committee meetings), the Project Coordinator also organized numerous informal meetings. These meetings included weekly separate meetings with the Technical Manager and Quality Manager of the project to discuss research progress, management of potential delays, evaluation of results, resolution of problems, Covid-19 complications, quality of results and deliverables, and other related issues. Additionally, regular meetings were held between the Project Coordinator and various WP and Task Leaders.

An important number of other activities related to the management of the BAM project were also conducted during the project's first 12 months. A sample of such activities is provided below:

- Establish an agreement and sign the pertinent contract with the Foreign Research Organisation (FRO) of the project, i.e., the University of Brighton.
- Hire new researchers for the needs of the project.
- Conduct formal and informal communication with RIF officer related to project's issues.

The management of intellectual property was overseen by the project's host organization (FRC), which has significant experience in this area. At the beginning of the project, a consortium agreement was prepared and signed by all partners, which governs the rules and procedures for IP management. The agreement defines decision-making rules, conflict resolution procedures, and confidentiality-related aspects. It also addresses rules regarding knowledge generated during the project, including results and confidentiality-related issues. Based on the analysis of end-user requirements and potential markets, the agreement specifies the results to be disseminated or exploited.

All the deliverables related to WP1 were completed on time and reviewed by internal peer-reviewers according to the quality assurance plan. The following section summarizes the deliverables completed under WP1 during the first 12 months of BAM. The remaining deliverables for WP1 during the second half of the project are:

D1.2: Minutes of Meetings (M24)

D1.3: Final Report (M24)

Future Work in WP1

In Work Package 1 (WP1), all management and coordination activities that aim to ensure the successful implementation of the project and the timely submission of its deliverables will continue in the upcoming reporting period.

Deliverables

List and describe the Deliverables of this WP for the reporting period.

D1.1: Mid-Term Report (M 12)

Work Package Number:	2	Start Month:	1	End Month:	24
Work Package Title	Dissemination Activities				
Work Package Leader	Frederick Research Center				
Partner Role	FRC	UCY	RECS		
Person Months	2	2	2		

Work Package Objectives as described in Annex I of the Contract.

Briefly describe the objectives of the WP and the work carried out during the reporting period towards the achievement of each listed objective.

WP2 aims to define strategies for the exploitation and dissemination of the project's results, including dissemination activities and communication measures, targeting to the widest possible promotion of the project results across Cyprus, EU and worldwide.

Work Description and Expected Key Results

Describe the activities regarding the dissemination of research results (e.g. Publications, Scientific Information Days, Conference Presentations etc.). Where possible, provide quantitative information on activities and results.
Where appropriate, give details of the work carried out per task by each beneficiary involved, indicating the lead partner.
Describe any problems encountered and how they were resolved. Include explanations for tasks not fully implemented, critical objectives not fully achieved and/or not being on schedule.

WP2 is managed by Frederick Research Center (FRC), with active involvement and support from the Dissemination Manager (Dr. Pericles Savva, RECS) and all consortium partners. Dr. Nicolaides (Project Coordinator) and Dr. Savva are responsible for ensuring smooth implementation of all dissemination, communication, and exploitation activities, with the support of BAM project committees, HO administrative mechanisms, WP and Task leaders, and other consortium partners. Within WP2, the research team aims to meet the requirements and obligations of Task 2.1: Dissemination and Communication of Project Results.

Below is a summary of the activities implemented in WP2 during the first half of the project.

Prior to the official start of the project, several meetings were held to organize WP2 activities. WP2 leaders held regular meetings with consortium members to provide project updates and worked closely with all partners to prepare WP2 deliverables. During the first half of the project, the research group prepared the following documents:

- D2.1: Dissemination Plan, that provides a full description of the key elements that formulate the BAM dissemination strategy, namely:
  - the objectives of dissemination (why, mission & vision)
  - the subjects of dissemination (what will be disseminated)
  - the target audience (to whom it will be disseminated)
  - the methods, tools, and channels (how to reach the target audience)
  - the timing (when the dissemination will take place)
  - the responsibilities for dissemination (who will perform the dissemination actions)
  - the rules for performing the dissemination activities, and

- the way to evaluate and assess the impact of the dissemination activities.

Deliverable D2.1 also includes a description of the dissemination and communication actions planned throughout the project (month 1- month 24), explaining in more detail the activities that have already been carried out, mainly the BAM visual identity, dissemination material, website, and social networks.

- “BAM Contact List”: A document including the names and contact details of stakeholders and other beneficiaries with potential interest in the project results. The filled “BAM Contact List” was used for the widest possible dissemination and communication of the project results.
- “BAM Project Team Directory”: A document including the names and contact details of all the members of the research team. The filled “BAM Project Team Directory” was used for the best possible communication amongst the consortium members.

During the first half of the project, the BAM team launched the BAM website (Deliverable D2.2) to increase project visibility among stakeholders and the public. The website aims to serve as a reference point for updates during and after the project period and to reduce the use of paper for dissemination. It provides information on the project's objectives, background on the technology utilized, conducted work, and expected outcomes. The website will be updated regularly, and the address (https://bam.frederick.ac.cy/) was advertised to attract potential end-users.

Additionally, the team developed social media accounts for BAM (Deliverable D2.3) to engage the public and promote project results. The accounts on LinkedIn, Instagram, and Facebook aim to attract a wider audience, initiate discussions on geopolymerization technology, and increase project visibility. The social media accounts are accessible through the project's website, and the links are provided below:

- LinkedIn: https://www.linkedin.com/showcase/bam-project/
- Facebook: https://www.facebook.com/profile.php?id=100087962876086
- Instagram: https://www.instagram.com/bam.frc/

The research team has authored and submitted three papers to the fib Symposium 2023, all of which have successfully passed the peer-review process and been accepted for oral presentation. Consequently, consortium members are currently making arrangements to attend and present these papers at the upcoming fib Symposium 2023, scheduled to be held in Istanbul in June 2023.

1. Giannopoulou, I., Ponsian, R., Polydorou, T., Demetriou, D., Tsioulou, O., Lampropoulos, A., Petrou, M. and Nicolaides, D. Novel blast and fire resistant composite materials: design and preliminary results. To be Included in the Proceedings of fib Symposium 2023, Building for the future: Durable, Sustainable, Resilient, Istanbul, Turkey, 05-07 June 2023.
2. Demetriou, D., Polydorou, T., Oikonomopoulou, K., Savva, P., Giannopoulou, I., Robert, P., Tsioulou, O., Lampropoulos, A., Nicolaides, D. and Petrou, M. Optimising Ultra High-Performance Fibre-Reinforced Concrete for Impact Resistance. To be Included in the Proceedings of fib Symposium 2023, Building for the future: Durable, Sustainable, Resilient, Istanbul, Turkey, 05-07 June 2023.
3. Lampropoulos, A., Tsioulou, O., Nicolaides, D. and Petrou, M. Strengthening of existing structures with UHPFRC: Concrete-to-UHPFRC interfaces. To be Included in the Proceedings of fib Symposium 2023, Building for the future: Durable, Sustainable, Resilient, Istanbul, Turkey, 05-07 June 2023.

Most of the BAM project’s publications are expected to be produced during the project’s second half.

The consortium members took part in various public events to present the idea and objectives of BAM, as well as its potential impact on the daily lives of citizens. These events are listed below:

- European Researchers' Night, September 30th, 2022
- Presentations in the frame of MSc Seminar Series, Frederick University (Fall Semester: December 06th, 2022 and Spring Semester: February 20th, 2023 – Different student audiences)
- Demonstration of BAM materials preparation with 3D-Printing and casting, to a group of high school students (February 8th, 2023)

The research team members will also take part in the 2023 European Researchers' Night, which will be held in Nicosia on September 29th, to present the BAM project.

Additionally, the BAM project aims to establish connections with other research consortia to organize joint events in the future. The following research projects are relevant and have been identified:

- “DEFEAT: Development of an Innovative Insulation Fire Resistant Façade from the Construction and Demolition Waste”, 2020-2023
- “Invalor101: A network for joint valorization of material flows in tourist areas”, 2017-2022

The deliverables associated with WP2 were completed on schedule and reviewed by assigned internal peer-reviewers in accordance with the established quality assurance plan. The list of deliverables produced under WP2 during the reporting period is outlined below. The remaining deliverables for WP2 in the latter half of the project are itemized below:

D2.4: Dissemination Event with Local Stakeholders (M 24)

Future Work in WP2

During the next reporting period, Work Package 2 (WP2) will involve the preparation of two open access publications in peer-reviewed journals. Additionally, a specific event will be organized to disseminate the project results to local stakeholders and authorities associated with the project activities. The deliverable "D2.4-Dissemination event with local stakeholders" will be prepared and submitted in the upcoming reporting period.

Deliverables

List and describe the Deliverables of this WP for the reporting period.
Provide information regarding the publications submitted to open access journals and deposited in relevant repositories.

D2.1: Dissemination Plan (M 3)

D2.2: Project Website (M 3)

D2.3: Creation of Project Accounts in Social Media (M 3)

Work Package Number:	3	Start Month:	1	End Month:	16
Work Package Title	Design of Materials				
Work Package Leader	Frederick Research Center / RECS Engineering				
Partner Role	FRC	UCY	RECS		
Person Months	12	5.5	12.5		

Work Package Objectives as described in Annex I of the Contract.

WP3 targets the design of the 2 new materials, i.e., HLM and SCGC. Both materials are designed in order: i) to resist under the fire scenario of ISO-834 which is used in all building structures, as well as in urban tunnels, ii) to resist under blast and impact loads, as per the validation methods described below.

Work Description and Expected Key Results

WP3 is dedicated to the development of two new materials, namely the Hybrid Laminated Material (HLM) and the Smart Composite Geopolymeric Concrete (SCGC). HLM is comprised of a superficial layer of fire-resistant geopolymeric concrete and an impact/blast resistant Ultra High Strength Concrete (UHSC) layer. The SCGC is a dual fire and blast/impact-resistant material.

After detailed analytical and experimental work, the two different materials that will eventually compose the HLM (i.e., the fire-resistant geopolymeric concrete and the UHSC) are optimized for production with conventional casting method.

The fire-resistant geopolymeric concrete was developed using Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and NaOH (7M) as an activator. The achieved compressive strength of this material exceeded 25 MPa (i.e., 25.4 MPa). Details regarding the synthesis and curing conditions of the optimized material (material code: FA90-BFS10-SF0-N7) are summarized in Table 1 below.

Table 1: Details regarding the synthesis and curing conditions of the optimized fire-resistant geopolymeric concrete.

FA90-BFS10-SF0-N7 (optimum)	
Conditions of Synthesis	
Mass of FA (g)	360
Mass of GGBFS (g)	40
Mass of SF (g)	0
Volume of 7 M NaOH (mL)	72.4
Molarity of NaOH solution (M)	7
Volume of Na-Silicate solution (mL)	32.6
Ratios	
[NaOH] in activator	5.9
S/L (g/mL)	3.8
SS:SH (v/v)	0.45
SiO_2/Na_2O (Ms)	0.637
Curing Conditions	
Temperature (°C)	30
Time (days)	7

A preliminary report regarding the experimental work on fire-resistant geopolymeric concrete is provided as Appendix 1, at the end of this interim progress report. A more detailed report on the designed and developed HLM will be included in Deliverable D3.1.

The UHSC layer of the HML material was developed based on a reference UHPFRC mixture studied in a paper titled "Mix design and mechanical properties of Ultra-High-Performance Fibre Reinforced Cementitious Composites (UHPFRCCs)" by Nicolaides D et al. (2013). Prior to the quantitative modification of the reference mixture, the consortium investigated the effects of varying water to binder (w/b) ratio, fibre content and type (steel only and steel/PVA combinations), steel fibre lengths, sand type, superplasticizer type and content, mixing speed and time, volume of mixture and method of fibre placement in a systematic manner, to generate consistent results. This investigation yielded significant information regarding the abovementioned aspects.

As a first modification of the reference mixture, the possibility of substituting the local sand with standard silica sand was explored. Various tests on mixtures containing different type and contents and denominations of fibres, and w/b ratios, showed that standard sand produced favorable results compared to the local sand, thus the team adopted its use throughout the second phase of experimental development. During this phase, the team has performed a series of optimization attempts to identify the minimum amount of fibres necessary to capture the benchmark requirements of 150 MPa compressive and 20 MPa flexural strength set for the UHSC layer of the BAM HML.

After iterative mix development and property evaluation trials, the research team successfully met the project's minimum compressive strength requirement of 150 MPa, with a mixture containing 2% steel fibres and 1% polyvinyl alcohol (PVA) fibres and a w/b ratio of 0.16. From an in-depth optimization effort, the mixture with 2% steel fibres (of 6mm and 12mm lengths at 1:1 ratio) and 1% PVA fibres demonstrated the highest flexural strength value of 22.7 MPa, surpassing the required target of 20 MPa. The mix-design of the current mixture is presented below:

Table 2: Optimal mixture achieving the benchmark of 150 MPa compressive and 20 MPa flexural strengths.

Constituent	Steel Fibres 2% & PVA 1%
	Content (kg/m^3)
Cement	880
Microsilica	220
Reference Sand	833
Water	172
Superplasticizer	67
Steel fibres 6mm	80
Steel fibres 13mm	80
PVA fibres	13
Water/Binder	*0.16*

As with the report on the development of fire-resistant geopolymeric concrete, a preliminary report on the development of UHSC is also included as Appendix 2 at the end of this interim progress report. An updated version of this report will also be included in D3.1: Designed and Developed Hybrid Laminated Material (HLM).

As of submitting this interim progress report, the design and development of the Smart Composite Geopolymeric Concrete (SCGC) had also made satisfactory progress. Initial investigations suggest that the development of SCGC will be based on the use of FA, GGBFS, SF, K_2SiO_3-based alkaline activator, sand, and steel fibres. Two preliminary mix designs of the investigations are summarized in Table 3 below, and detailed reporting will be provided as a project deliverable at a later stage of the project.

Table 3: Preliminary mix designs of Smart Composite Geopolymeric Concrete (SCGC).

Material	**Mix Proportions (kg/m³)**	
	SFRGC	**PVAFRGC**
Fly Ash	388	388
Slag	310	310
Silica Fume	78	78
Cement	-	-
Alkaline Activator	93	93
Water	194	194
Sand	1052	1052
Gravel	-	-
Steel Fibre	234	-
PVA Fibre	-	26
Curing Condition	Room Temperature	

The team is currently conducting research to evaluate the rheological properties and setting time of the materials. A comprehensive report on this aspect of the work will be included in the final versions of D3.1: Designed and Developed Hybrid Laminated Material (HLM) and D3.2: Designed and Developed Smart Composite Geopolymeric Concrete (SCGC).

Furthermore, publishing papers in the proceedings of the fib Symposium, slated for June 2023, will meet the WP's need for a conference publication, as stated in D3.4: Publication in Conference.

Future Work in WP3

During the upcoming reporting period of the project, Work Package 3 (WP3) will involve completing the experimental activities for the development and optimization of the HLM and SGSC. Furthermore, all the deliverables of Work Package 3 (WP3) will be prepared and submitted in the same reporting period.

Deliverables

Deliverables of WP3 are scheduled to be prepared and submitted at a subsequent stage of the project (i.e., Months 15-16).

Work Package Number:	4	Start Month:	6	End Month:	24
Work Package Title	Manufacturing and Validation of the Designed Materials				
Work Package Leader	University of Cyprus / RECS Engineering				
Partner Role	FRC	UCY	RECS		
Person Months	8	5	14		

Work Package Objectives as described in Annex I of the Contract.

Briefly describe the objectives of the WP and the work carried out during the reporting period towards the achievement of each listed objective.

WP4 aims to manufacture both materials using both casting and 3D printing methods, as well as validating them in the laboratory and through analytical methods.

Work Description and Expected Key Results

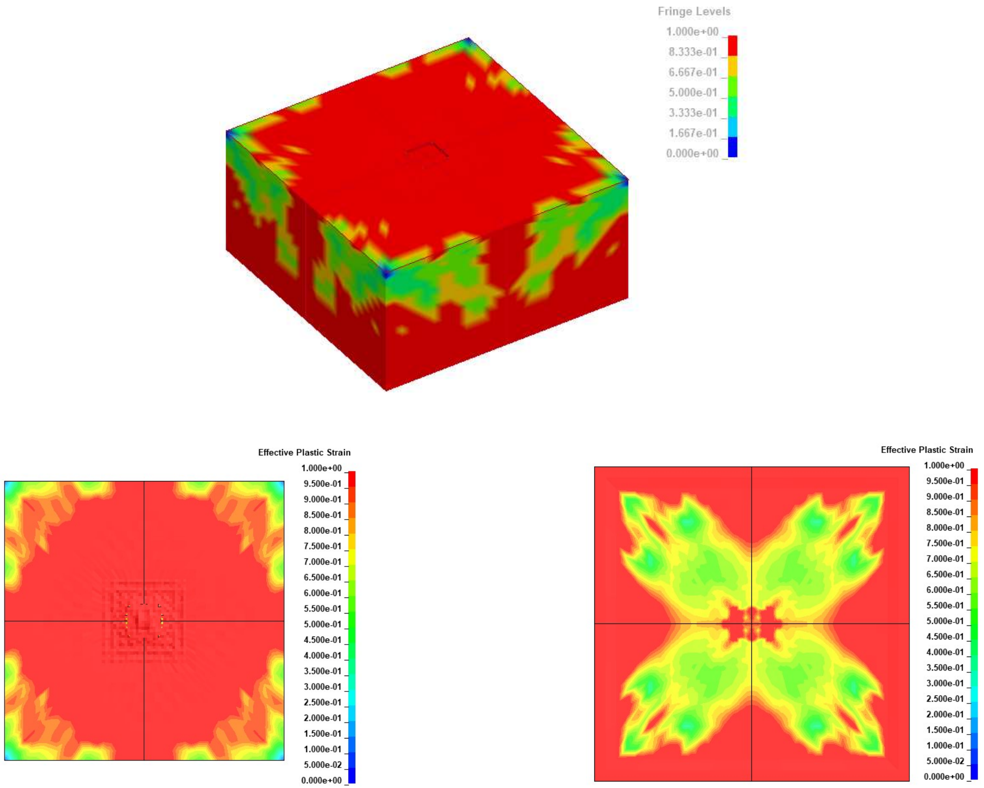
Describe the activities implemented in the frame of this specific WP. Where possible, provide quantitative information on activities and results.
Where appropriate, give details of the work carried out per task by each beneficiary involved, indicating the lead partner (including Foreign Research Organisations).
Describe any problems encountered and how they were resolved. Include explanations for tasks not fully implemented, critical objectives not fully achieved and/or not being on schedule.

WP4 is dedicated to manufacturing the two materials using both conventional casting and 3D-printing methods, including appropriate modifications of syntheses to achieve optimal production results, as well as validating the materials' properties through laboratory testing and analytical methods.

As of the submission of this report, the optimization of precast manufacturing for HLM has been successfully achieved, and the precast manufacturing of SCGC has made considerable progress. However, challenges remain with the 3D-printing manufacturing of both materials due to the presence of fibres in the mixtures. The WP4 project will continue until the end of the BAM project, and the research team is confident that they will overcome this challenging task. The consortium will leverage their previous experiences with 3D-printing geopolymeric and cement-based materials. For the 3D-printing of the BAM materials the 3DWASP printer available at the premises of FRC is utilised.

The validation of the materials' performance against fire, impact and blast loading will be conducted on the optimised materials that will be eventually developed in the frame of this project. However, in May 2023, the research team sent specimens for preliminary testing against impact at the "Demokritos" National Centre of Scientific Research (NCSR), Greece's leading research centre. The team chose to work with NCSR due to its state-of-the-art facilities and expertise in the field of materials science. The preliminary testing was an essential step towards further optimization of the developed materials, aiming to provide valuable insights into the material's properties. The team is expecting the test results to refine their research approach and explore further possibilities for the project.

Furthermore, progress has been made in Finite Element Analysis (FEA) related to the blast resistance of the materials, yielding interesting results. A preliminary report on the numerical analysis of HLM material's blast resistance is included as Appendix 3 at the end of this interim progress report. The report investigates the behaviour of UHPFRC material under impact loads using LS-DYNA software, which indirectly validates the effectiveness of the finite element model for structures under blast loading. Then, the behaviour of UHPFRC is further studied under the influence of blast loading using the Multi-Material Arbitrary Lagrangian Eulerian (MM_ALE) approach. This explicit modelling of the explosive, air, and structure gives more accurate results than other methods such as Conwep and empirical formulations, where the blast load is idealized as an exponential function of time. Finally, initial finite element models are proposed for composite structures that include a UHPFRC layer, an adhesive layer, and a thermal protective layer under both impact and blast loads, using material data from experimental analyses performed in the BAM project as well as from literature. The results demonstrate that LS-DYNA software has adequate capabilities and efficiency to capture the behaviour of these composites (Figure 1).



Front side to the blast load   Rear side to the blast load

Figure 1: Blast load effect on UHPC.

The research team is currently exploring suitable laboratory options to experimentally validate the materials against impact loading by using a drop hammer or similar testing apparatus, such as the split Hopkinson machine. Discussions have already taken place with specialized laboratories, such as the Joint Research Center (JRC) in Ispra.

Last, publishing papers in the proceedings of the fib Symposium, slated for June 2023, will meet the WP's need for a conference publication, as stated in D4.5: Publication in Conference.

Future Work in WP4

During the next reporting period, Work Package 4 (WP4) will involve the implementation of the manufacturing process for the optimized materials on a larger scale, using both the casting and 3D-printing methods. Additionally, the physical, mechanical, and durability properties of the prepared materials will

be evaluated and compared. The performance of the optimized materials against fire and impact/blast will also be validated through relevant standard tests. Moreover, the Finite Element Analysis (FEA) related to the blast resistance of the materials will be completed. All the deliverables of WP4 will be prepared and submitted during the same reporting period.
Deliverables
List and describe the Deliverables of this WP for the reporting period. Deliverables of WP4 are scheduled to be prepared and submitted at a subsequent stage of the project (i.e., Months 20-24).

Work Package Number:	5	Start Month:	6	End Month:	24
Work Package Title	Technoeconomic Evaluation and Cost-Benefit Analysis				
Work Package Leader	RECS Engineering				
Partner Role	FRC	UCY	RECS		
Person Months	2	2	6		

Work Package Objectives as described in Annex I of the Contract.

Briefly describe the objectives of the WP and the work carried out during the reporting period towards the achievement of each listed objective.

WP5 aims at: (i) performing the techno-economic evaluation of the developed materials and the corresponding manufacturing methods; (ii) performing a cost-benefit analysis (CBA).

Work Description and Expected Key Results

Describe the activities implemented in the frame of this specific WP. Where possible, provide quantitative information on activities and results.
Where appropriate, give details of the work carried out per task by each beneficiary involved, indicating the lead partner (including Foreign Research Organisations).
Describe any problems encountered and how they were resolved. Include explanations for tasks not fully implemented, critical objectives not fully achieved and/or not being on schedule.

WP5 aims to evaluate the developed materials using both production methods in terms of cost, efficiency, and environmental impact through techno-economic and cost-benefit analyses. The objective of WP5 is to assess the feasibility of producing the new materials on a commercial scale, as well as to evaluate the economic and environmental impact of the manufacturing processes. Ongoing progress in WP5 is expected to provide valuable insights into the overall viability of the project's objectives.

WP5 has been continuously receiving results such as updated materials' recipes and cost of raw materials from the technical WPs (3 and 4). Draft versions of both D5.1: Technoeconomic Evaluation and D5.2: Cost-Benefit Analysis (CBA) have been produced based on these results. The final versions of D5.1 and D5.2 will be produced after the materials (i.e., HLM and SCGC) have been optimized.

Future Work in WP5

During the upcoming reporting period, Work Package 5 (WP5) will involve performing most of the work reported in this WP. Specifically, the techno-economic analysis of the developed and optimized HLM and SGSC materials will be completed, and a Cost Benefit Analysis will be performed at the EU level market, including environmental and health & safety impacts. The two deliverables of WP5 will be prepared and submitted during the same reporting period.

Deliverables

List and describe the Deliverables of this WP for the reporting period.

Deliverables of WP5 are scheduled to be prepared and submitted at a subsequent stage of the project (i.e., Month 24).

A.4. TABLE OF WORK PACKAGES					
		Contract		Actual Implementation	
Work Package	Work Package Title	Start Month	End Month	Start Month	End Month
WP1	**Project Management**	**1**	**24**	**1**	**24**
WP2	**Dissemination and Exploitation Activities**	**1**	**24**	**1**	**24**
WP3	**Design of Materials**	**1**	**16**	**1**	**16**
WP4	**Manufacturing and Validation of the Designed Materials**	**6**	**24**	**6**	**24**
WP5	**Technoeconomic Evaluation and CBA**	**6**	**24**	**6**	**24**

B.1. ADDITIONAL INFORMATION (OPTIONAL)
Provide, where deemed necessary, any additional information regarding the Project. Include explanations on deviations of the use of resources between actual and planned use of resources based on the project contract (if applicable). Include explanations on transfer of costs between categories (if applicable).

Notes:

Collection and processing of personal data is carried out according to the RIF's Policy for the Protection of Personal Data. The RIF's Policy is posted on IRIS.

Appendix 1: Preliminary Report on Experiments for the Development of Fire-Resistant Geopolymeric Concrete for Hybrid Laminate Material (HLM)

The initial experimental series focuses on the geopolymerization of fly ash (FA), which comprises 24 experiments. These experiments aim to optimize the following parameters for the synthesis of geopolymers in terms of stability and compressive strength:

(1) Replacement of FA with GGBFS

(2) Addition of SF

(3) Ratio S/L (weight per volume)

(4) Type of Alkali and Concentration of alkali hydroxide solution

(5) Content of alkali silicate solution in the activator (volumetric ratio of solutions in the activator)

(6) Curing time

1. Replacement of FA with GGBFS (wt. %)

Four values were tested: *0, 10, 30 and 50%*

Curing: 70^{o}C for 3 d (the specimens were left for 7 days for hardening, before CS testing)

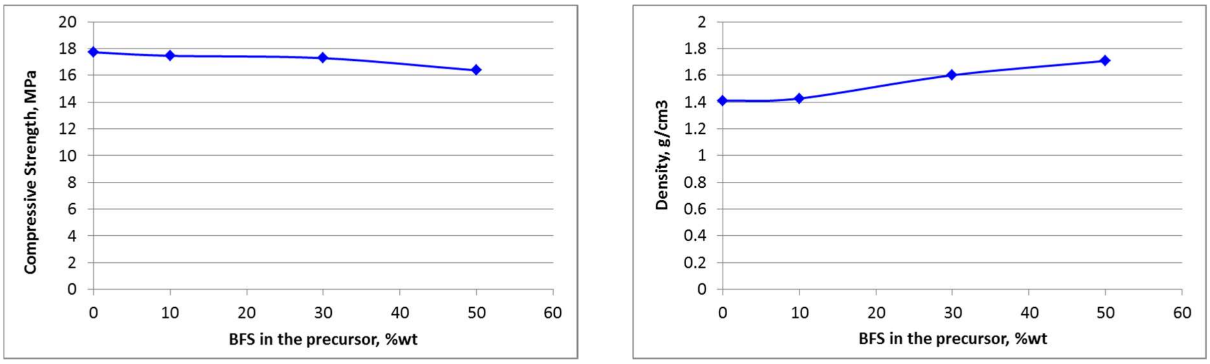


Fig. 1

Based on the results, there were no significant differences in the compressive strength of the geopolymers. Geopolymers made with 100% FA (0% GGBFS) had a compressive strength of 17.73 MPa, while those made with 50% FA and 50% GGBFS had a compressive strength of 16.83 MPa. However, the compressive strength values may not reflect the true strength of the materials since an increase in GGBFS in the precursor resulted in materials that were more plastic and prone to deformation under loads without breaking (i.e., disruption of cohesion).

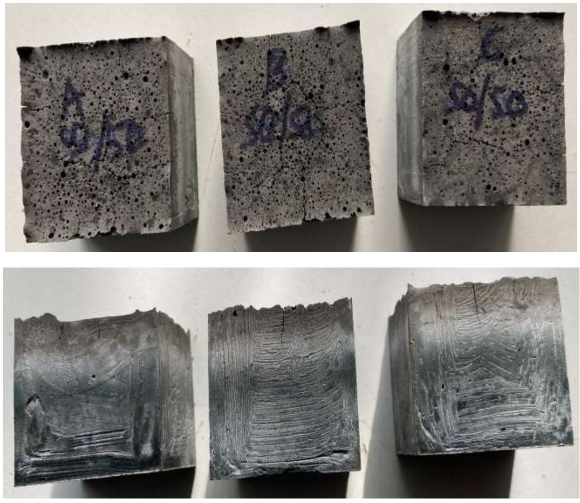
As shown in Figure 2(a) below, increasing the GGBFS content in the precursor led to materials with extensive surface cracking and increased shrinkage (which is linked to water evaporation).

(a)

(b) FA100 – BFS0

(c) FA90 – BFS10

(d) FA70 – BFS30



(e) FA50 – BFS50

Fig. 2

As illustrated in Figure 3, the specimens with an FA:GGBFS ratio of 50:50 (a) exhibited plastic behaviour during the CS testing, in contrast to those with an FA:GGBFS ratio of 90:10 (b), which displayed the typical conchoidal fracture.

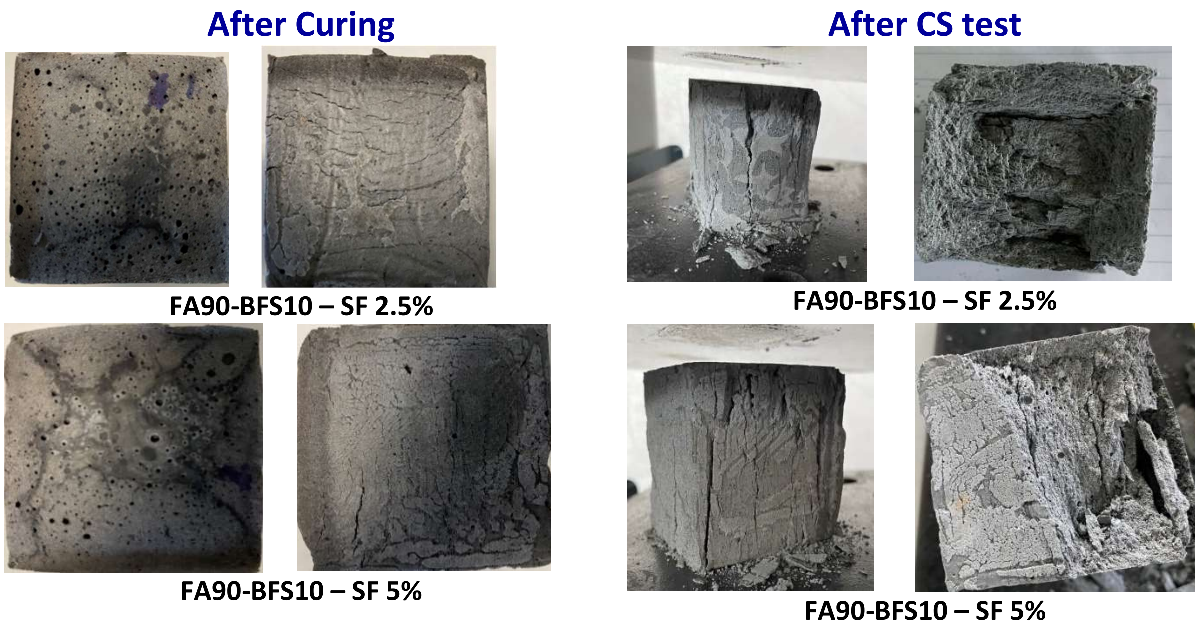
(a) (b)

Fig. 3

Based on the above, it can be concluded that the optimal ratio of FA to GGBFS in the precursor is 90:10.

2. **Addition of SF**

Initially, four experiments were conducted with SF addition, where the weight percentages of 2.5%, 5%, 10%, and 15% were used. The curing was carried out at 70°C for 3 days, followed by a 7-day hardening period before conducting the CS test. However, the specimens developed swelling and extensive surface cracking after curing, which adversely affected their compressive strength. Nonetheless, the compressive strength of these materials ranged between 11 and 14.6 MPa. The photos of the specimens after curing and the CS testing are displayed below.



FA90-BFS10 – SF 10%

FA90-BFS10 – SF 10%

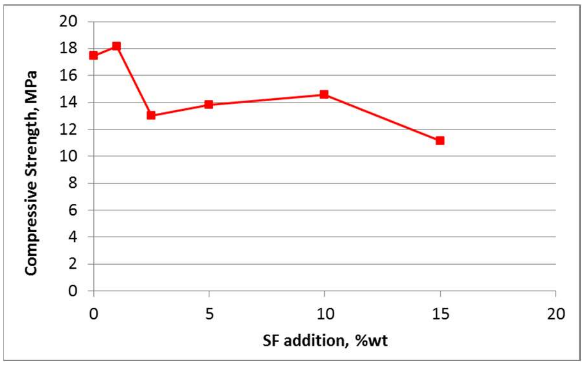
FA90-BFS10 – SF 15%

FA90-BFS10 – SF 15%

Fig. 4

Subsequently, we chose to decrease the SF addition and conducted an experiment with 1% SF addition (per weight). The geopolymer was cured at 30°C for 7 days to simulate ambient temperature curing, and the CS test was conducted immediately after curing was completed.

The compressive strength test results and material density measurements are provided below.



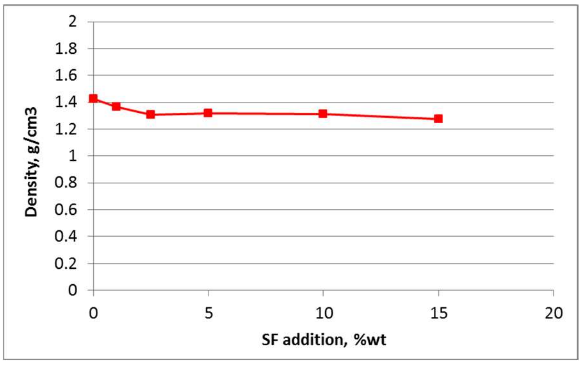


Fig. 5

Based on the results, it can be concluded that the addition of 1% SF resulted in the highest CS (18.14 MPa), and the density of the materials did not change significantly (ranging from 1.43 to 1.28 g/cm3). As a result, it can be inferred that the optimal amount of SF for FA geopolymers is 1%.

3. Solid to Liquid Ratio

During the investigation of the previous two parameters, it was observed that the resulting geopolymer paste had a higher water content than necessary, as evidenced by the photos presented in Fig. 4. Therefore, we decided to decrease the liquid content in the materials synthesis by increasing the S/L ratio. Two values of S/L, 2.8 and 3.8 g/mL, were tested for the synthesis of the geopolymer with precursor FA90-BFS10-SF1 and Na-based activator.

The geopolymer with an S/L ratio of 2.8 g/mL was cured at 70°C for 3 days, followed by 7 days of hardening before the CS test. The geopolymer with an S/L ratio of 3.8 g/mL was cured at 30°C for 7 days, and its CS test was performed immediately after the curing was completed.

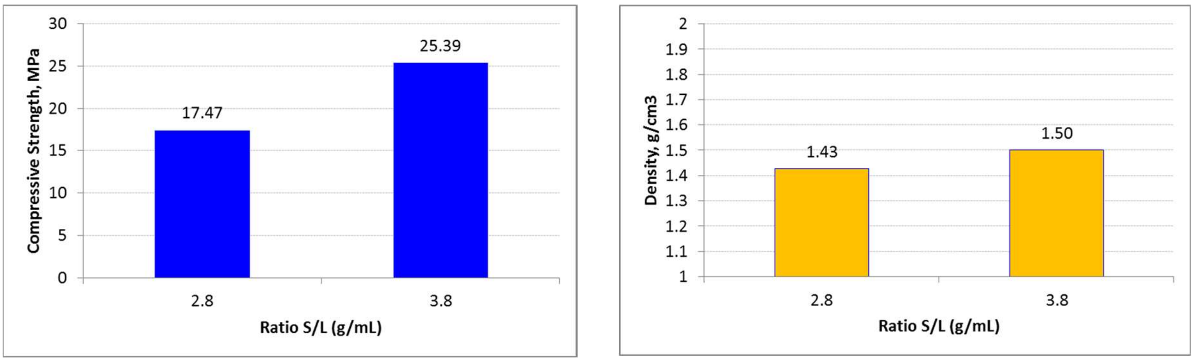


Fig. 6

Based on the results, the compressive strength showed an upward trend as the S/L ratio was increased, while the density remained almost constant.

4. Type of Alkali and Concentration of the Alkali Hydroxide Solution

The study investigated the effects of Na and K alkalis, combined with solutions of Na_2OSiO_2 and K_2OSiO_2 respectively, in the geopolymer activator. The concentration of the alkali hydroxide (NaOH or KOH) solution was tested at five values: 4, 5, 7, 8, and 10 mole/L (M), using the geopolymer precursor FA90BFS10SF1 and S/L ratio of 3.8 g/mL. All specimens were cured at 30°C for 7 days, with some specimens cured for 28 days at the same temperature for selected concentrations of alkali hydroxide solution and tested for compressive strength.

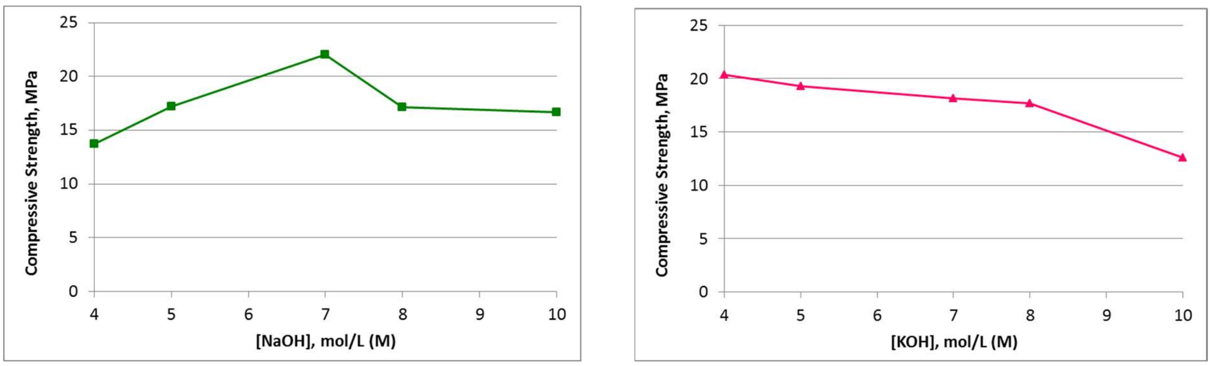


Fig. 7

Based on the results, it was found that the Na-based geopolymer system was optimized with [NaOH] = 7M, resulting in a compressive strength of 22 MPa, while the K-based system was optimized with [KOH] = 4M, resulting in a strength of 20 MPa. Generally, both Na-based and K-based geopolymers exhibited similar strength regardless of the type of alkali used.

Regarding the effect of curing time, the Na-based geopolymers developed similar strength (around 20 MPa) after 28 days of curing at 30oC, regardless of the concentration of NaOH solution. This strength was higher than that of the geopolymers cured for 7 days when [NaOH] ≥ 8 M and lower, when [NaOH] < 8M. For the K-based geopolymers, those cured for 28 days exhibited similar compressive strength to those cured for 7 days when [KOH] was 7 or 10 M, but lower when [KOH] was 8 M.

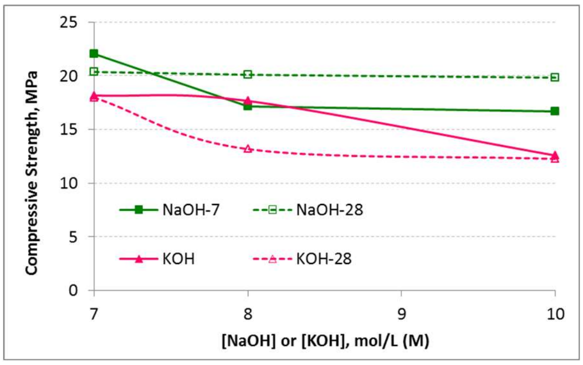


Fig. 8

The main conclusion that can be drawn from these experiments is a well-established one for geopolymers: they exhibit high compressive strength at early stages. However, the increase in compressive strength from 7 days to 28 days of curing time was found to be minimal.

5. Increase of the Silicate Solution in the Activator

The aim of this study was to optimize the content of silicate solution in the alkali activator of geopolymers. To achieve this, five different concentrations of the silicate solution were investigated. The concentrations were expressed as volumetric ratios of the alkali silicate solution (SS) to the alkali hydroxide solution (HS) in the activator. The investigated SS:HS ratios (v/v) were 0.31, 0.45, 0.6, 0.8, and 0.99. In all experiments, the geopolymer precursor FA90BFS10SF1 was used, the S/L ratio was 3.8 g/mL, and the Na-based activator was selected due to its higher compressive strength ([NaOH] = 7M). The goal was to determine the optimum ratio of SS:HS for maximum strength development in the geopolymers.

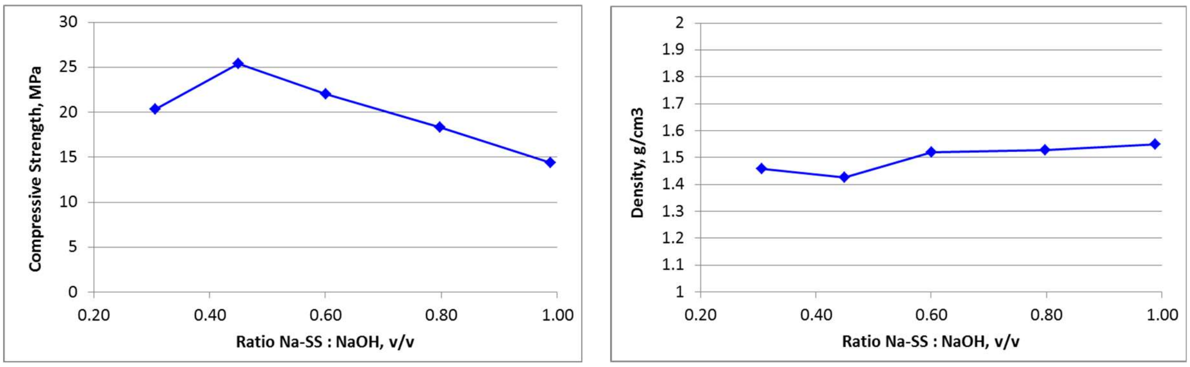
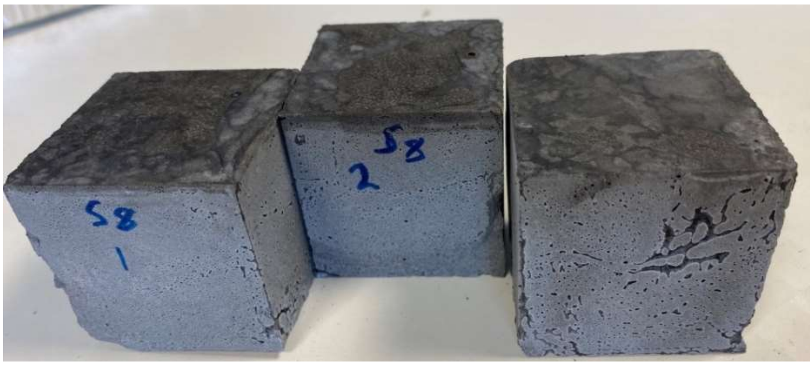


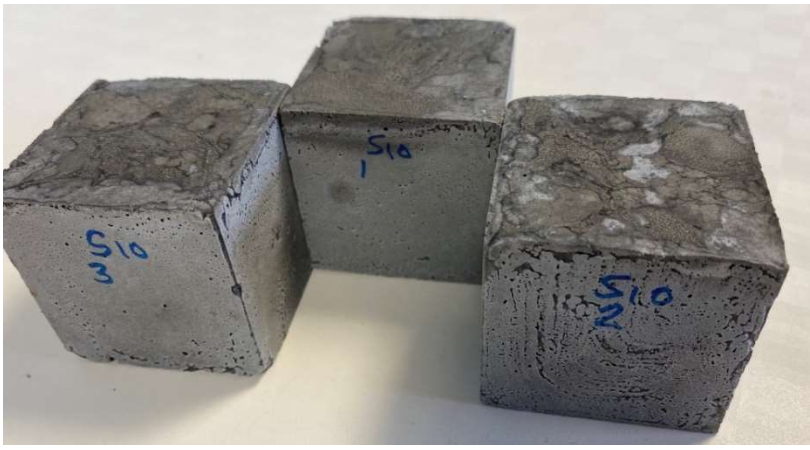
Fig. 9

Based on the results, the optimal ratio of the alkali silicate solution (SS) to the alkali hydroxide solution (HS) in the activator of geopolymers is 0.45 (v/v). However, an increase in the soluble silicate content in the activator and geopolymer paste resulted in decreased workability and difficulties during casting. This issue is apparent in the accompanying photos, where specimens S8 and S10 exhibit deficiencies and irregularities. The stiff geopolymeric paste impeded the formation of well-formed cubic specimens. In general, a higher concentration of soluble silicon in geopolymers results in pastes that are more difficult to handle and cast effectively. This difficulty in casting is evident in the accompanying photos, which depict voids and irregularities in the edges of the cubes. It is believed that this decrease in workability is the cause of the decrease in compressive strength observed.

Specimens of geopolymers with different SS:HS ratios



Specimens of the ratio SS:HS = 0.8



Specimens of the ratio SS:HS = 0.99

Fig. 10

6. Conclusions

Based on the results of the first experimental series on the geopolymerization of FA, the following conclusions can be drawn:

(i) The optimum ratio of FA to GGBFS in geopolymers for maximum compressive strength and stability is 90 to 10 (wt.%).

(ii) The NaOH solution concentration of 7 M is optimal for sodium-based geopolymers, while for K-based geopolymers, the optimal concentration is 4 M.

(iii) The sodium-based geopolymers exhibit higher strength compared to K-based geopolymers.

(iv) The optimum curing time for FA geopolymers is 7 days, during which they develop around 85-98% of their compressive strength after 28 days.

(v) The addition of amorphous silicon oxide in geopolymers was investigated in two different forms: solid (silica fume) and soluble (sodium silicate solution). *Unfortunately, the materials corresponding to case (i) contained both silica fume and sodium silicate solution*. The silica fume addition was optimized at a 1 wt.% level, and the addition of sodium silicate solution was optimized at a volumetric ratio of Silicate solution to Hydroxide solution of 0.45 (v/v).

(vi) The FA90BFS10SF0N7 (optimum) geopolymer, which exhibited the highest compressive strength (25.39 MPa), was based on Na with [NaOH] = 7M in the activator, did not contain silica fume, and was synthesized with ratios of FA:BFS = 90:10 (w/w), S/L = 3.8 g/mL, and SS:HS in the activator of 0.45. The synthesis and curing conditions of this geopolymer are presented below.

FA90-BFS10-SF0-N7 (optimum)	
Conditions of synthesis	
mass of FA (g)	360
mass of GGBFS (g)	40
mass of SF (g)	0
volume of 7 M NaOH (mL)	72.4
Molarity of NaOH solution (M)	7
volume of Na-silicate solution (mL)	32.6
Ratios	
[NaOH] in activator	5.9
S/L (g/mL)	3.8
SS : SH (v/v)	0.45
SiO_2/Na_2O (Ms)	0.637
Curing conditions	
Temperature (°C)	30
time (days)	7

(vii) Five geopolymers were synthesized that developed compressive strength higher than 20 MPa. The synthesis conditions of these geopolymers are listed below:

Table 1	FA90-BFS10-SF0-N7	FA90-BFS10-SF1-N7	FA90-BFS10-SF1-K4	FA90-BFS10-SF0-N7-S3	FA90-BFS10-SF0-N7-S6
Conditions of synthesis					
Mass of FA (g)	360	445.5	445.5	450	450
Mass of GGBFS (g)	40	49.5	49.5	50	50
Mass of SF (g)	0	5	5	0	0
Volume of 7 M NaOH (mL)	72.4	90.5	90.5	100.5	82
Molarity of NaOH solution (M)	7	7		7	7
Molarity of KOH solution (M)			4		
V of Na-silicate solution (mL)	32.6	40.75		30.75	49.25
V of K-silicate solution (mL)			40.75		
Ratios					
FA:GGBFS	90:10	90:10	90:10	90:10	90:10
Silica Fume (%wt)	0	1	1	0	0
[NaOH] in activator	5.91	5.91	3.84	6.17	5.68
S/L (g/mL)	3.8	3.8	3.8	3.8	3.8
SS:SH (v/v)	0.45	0.45	0.45	0.31	0.6
SiO_2/Na_2O (Ms)	0.637	0.637	0.98	0.611	1.801
Curing conditions					
Temperature (°C)	30	30	30	30	30
Time (days)	7	7	7	7	7
Compressive Strength (MPa)	**25.39**	**22.02**	**20.35**	**20.36**	**22.05**

7. Further Work to Complete this Experimental Series

(a) Repeat the experiments with the ratios of FA / GGBFS (the first three experiments with FA:BFS ratios equal to 90:10, 70:30 and 50:50) and curing time: 7 days at 30°C.

(b) Grinding of selected materials to perform different characterizations:

- FA100-BFS0 (No GGBFS, no silica fume), S/L = 2.8
- FA90-BFS10 (No silica fume), S/L = 2.8
- FA70-BFS30 (No silica fume), S/L = 2.8
- FA90-BFS10-SF1, S/L = 2.8
- FA90-BFS10-SF5, S/L = 2.8
- FA90-BFS10 (No silica fume), S/L = 3.8
- All the samples with the different KOH concentration (5 samples)
- All the samples with the different content of sodium silicate solution (4 samples)

(c) Study of selected materials on heating at elevated temperatures (two geopolymers: the first and the 3rd from Table 1 above):

- **FA90-BFS10-SF0-N7 (the optimum / it is a Na-based geopolymer)**
- **FA90-BFS10-SF1-K4 (the optimum among the K-based geopolymers)**

The materials will be heated at four different temperatures: 400, 600, 800 and 1050°C. We will use 2 specimens for each temperature (will be left for 2 h) and we will measure the dimensions, weight, and compressive strength. So, we need 8 specimens from each geopolymer that will be tested (thus, we will produce 9 specimens of each geopolymers selected for testing).

After curing (7 days at 30°C), the specimens will be left for about 1 month (4-5 weeks) at ambient conditions, before testing them at the selected temperatures.

Details for the heating tests will be discussed later.

The materials will undergo heating at four different temperatures: 400, 600, 800, and 1050°C. Two specimens will be used for each temperature, and they will be heated for two hours. The dimensions, weight, and compressive strength will be measured. Therefore, a total of 8 specimens will be needed for each geopolymer to be tested.
After curing for 7 days at 30°C, the specimens will be left to sit at ambient conditions for approximately 1 month before being tested at the chosen temperatures. Further details regarding the heating tests will be discussed at a later time.

Co-funded by the European Union

Republic of Cyprus

RESEARCH & INNOVATION FOUNDATION

Το έργο υλοποιείται στο πλαίσιο του Προγράμματος Πολιτικής Συνοχής «ΘΑλΕΙΑ 2021-2027» με τη συγχρηματοδότηση της ΕΕ

Appendix 2: Preliminary Report on Experiments for the Development of Ultra High Strength Concrete (UHSC) for Hybrid Laminate Material (HLM)

UCY was responsible for developing the UHSC layer of the HML material, using a reference UHPFRC mixture studied in the paper titled “Mix design and mechanical properties of ultra-high-performance fiber reinforced cementitious composites (UHPFRCCs)”, by Nicolaides D, Kanellopoulos A, Savva P, Mina A, Petrou M (2013) at the “Proceedings of the 1st International RILEM Conference on Rheology and Processing of Construction Materials”, (Paris, France). UHPFRC reference mixture contents are demonstrated in Table 1.

Table 1: Reference mixture of UHPFRC

Constituent	Content (kg/m^3)
Cement	880
Microsilica	220
Sand 125-250µm	475
Sand 250-500µm	358
Water	172
Superplasticizer	67
Steel fibres 6mm	401
Steel fibres 13mm	80
Water/Binder	*0.16*

The mentioned mixture required an optimum microsilica content of 20%, a water/binder ratio of 0.16, heat curing for 7 days at 90 °C and a steel fibre content of 6% with 3:1 fibre ratio (short to long), achieving compressive and flexural strengths exceeding 150 MPa and 20 MPa, respectively. However, the reference mixture relied on locally sourced sand, that needed to be sieved into two different grades (125-250 µm and 250-500 µm). This process was costly and most importantly time-consuming and thus caused significant delays. Therefore, the possibility of substituting the local sand with standard silica sand was explored. In addition, as observed in Figure 1, further reduction in the steel fibre content was successfully employed, without sacrificing achievement of the project’s required strength goals.

Consequently, two mixtures were investigated: one with a steel fibre content of 2% and a 1:1 short to long ratio, and another with 2% steel fibres, along with 1% polyvinyl alcohol (PVA) fibres. These mixtures were examined for their compressive strength (EN 12390-3) on the 14th and 28th day, as well as their flexural strength (EN 12390-5) on the 28th day. As depicted in Figure 2, modifying the steel fibre ratio from 3:1 to 1:1 enhanced the 28-day compressive strength, although it did not reach the target of 150 MPa. However, formulations containing 2% steel fibres and 1% PVA, along with the replacement of local sand with standard silica sand, met the project’s minimum compressive strength requirement of 150 MPa.

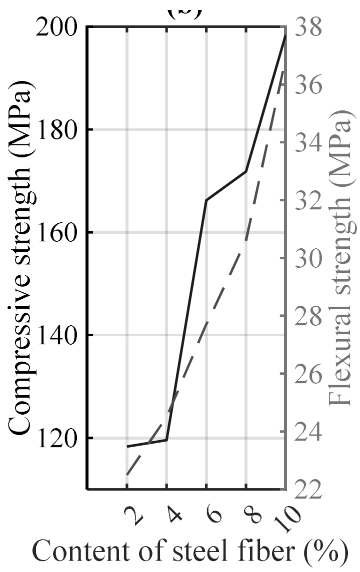


Figure 1: 28-day compressive and flexural strength at varied steel fibre contents (3:1 short to long).

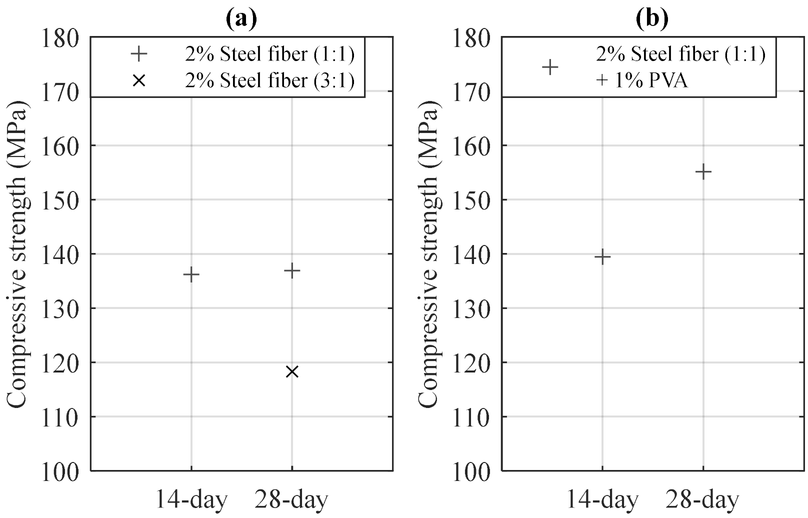


Figure 2: a) Compressive of mixture containing 2% steel fibres (1:1) and 2% steel fibres (3:1), b) mixtures containing 2% steel fibres (1:1) and 1% PVA.

Further optimization and examination of the flexural strength properties were conducted for various formulations containing steel and PVA fibres, with a step increment of 0.5% in each mixture. As anticipated and observed in Figure 3, increasing the fibre content resulted in higher flexural strength, with mixtures containing minimal fibre amounts exhibiting the lowest values. The mixture containing 2% steel fibres (1:1 ratio) and 1% PVA fibres demonstrated the highest flexural strength value of 22.64 MPa, surpassing the required target of 20 MPa.

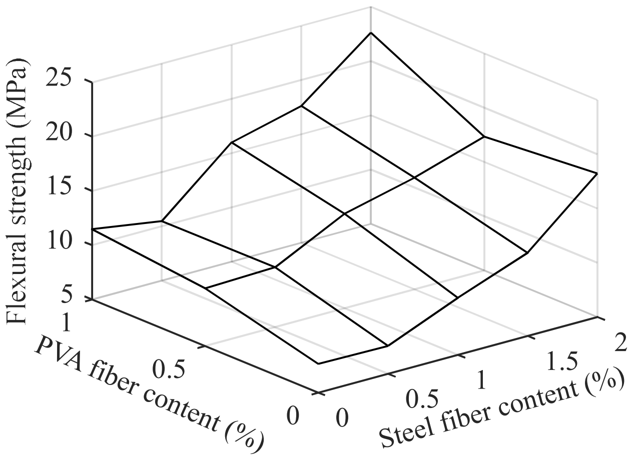


Figure 3: Combinations of PVA and steel fibre contents and their effect on flexural strength.

After successfully meeting the required project targets, further optimization was carried out to enhance workability. This involved increasing the water-to-binder (w/b) ratio to 0.21 and incorporating higher quantities of superplasticizer, to classify the mixture as a self-compacting UHPFRC. Both mixtures' design details can be found in Table 2.

Table 2: SCC Mixture Contents

Constituent	Steel Fibres 2%	Steel Fibres 2% & PVA 1%
	Content (kg/m^3)	Content (kg/m^3)
Cement	880	880
Microsilica	220	220
Reference Sand	833	833
Water	231	231
Superplasticizer	67	67
Steel fibres 6mm	80	80
Steel fibres 13mm	80	80
PVA fibres	-	13
Water/Binder	*0.21*	*0.21*

Results from compressive and flexural tests are illustrated in Figure 4 and Figure 5. It was observed that for formulations with 2% steel fibre content, alterations in the w/b ratio and compaction method did not have a significant impact on compressive and flexural strength results; however, a different behaviour was observed when PVA fibres were incorporated to the formulations. Specifically, the inclusion of PVA fibres led to a decrease of 16.51% and 18.43% in the compressive and flexural strength, respectively. These results are complemented by the stress-strain curves of Figure 6 and Figure 7 attained from compressive and direct tension tests.

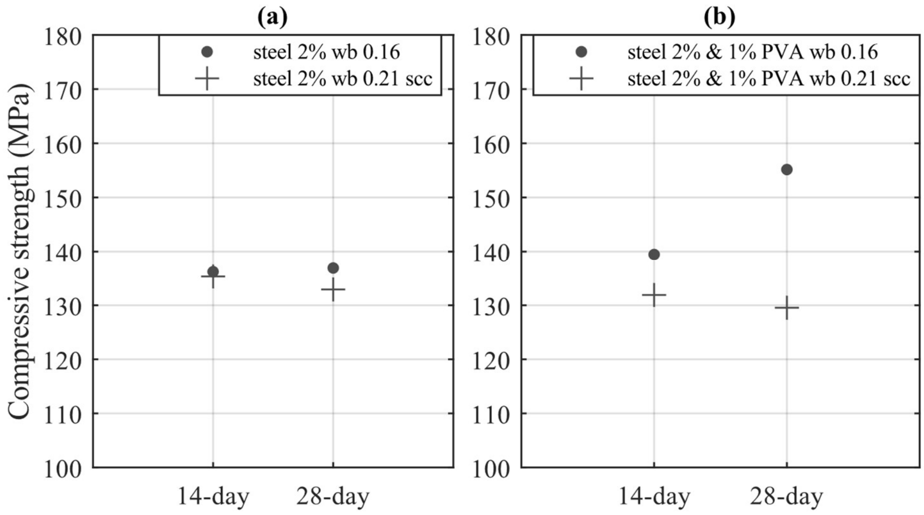


Figure 4: Compressive strength of mixture containing 2% steel fibres at W/B of 0.16 and SCC with 2% steel fibres at W/B of 0.21 and (b) and mixture containing 2% steel fibres (1:1) and 1% PVA at W/B of 0.16 and SCC with 2% steel fibres (1:1) and 1% PVA at W/B of 0.21.

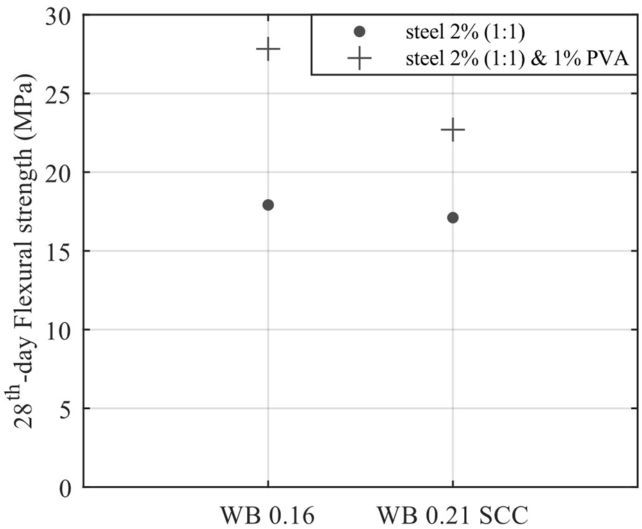


Figure 5: Flexural strength of mixture containing 2% steel fibres and mixture containing 2% steel fibres and 1% PVA at W/B of 0.16 and SCC W/B of 0.21.

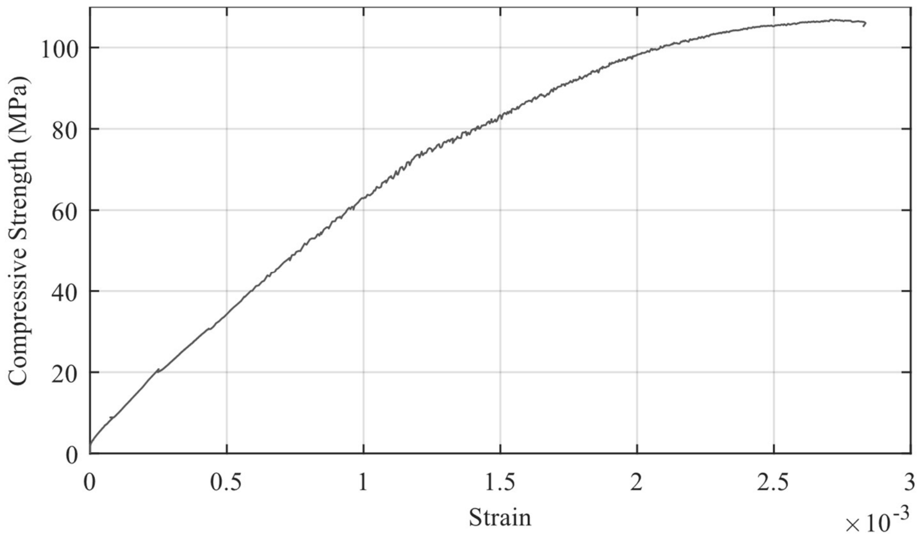


Figure 6: Stress-Strain relationship from compressive tests on cylinders.

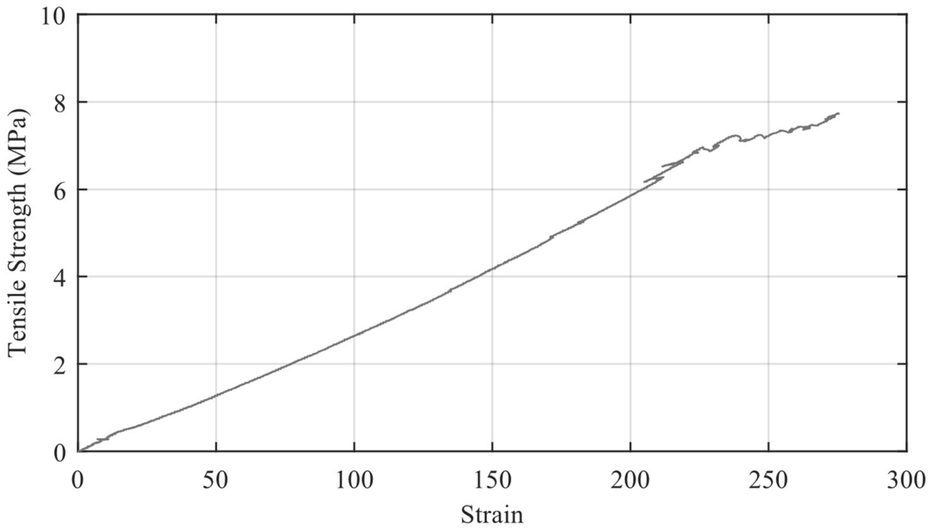


Figure 7: Stress-Strain relationship from tensile tests on beams.

Concluding Statement

The UHSC layer of the HLM was developed on the basis of an UHPFRC material design previously developed by members of the research team. Various mix differentiations were examined before concluding that formulations containing 2% steel and 1% PVA fibres, along with the replacement of local sand with standard silica sand, were selected as the most cost effective that met the project's minimum strength requirements. In addition, a self-compacting version of the 2% steel and 1% PVA UHSC was developed, which a exhibited a 16.51% decrease on compressive strength, and 18.43% decrease on flexural strength.

Importantly, when no PVA fibres were included, the 2% steel fibre USHC layer did not reach the BAM project strength requirements. The self-compacting version of this particular mix did not exhibit significant disparity in terms of strength, compared to its non-self-compacting equivalent.

Appendix 3: Preliminary Report on Numerical Analysis of Blast Effect

Introduction

In the last decades, the use of innovate materials for blast, impact, and fire resistant of structures have intensively increased in construction, which highlights the importance and need of appropriate simulation and design methods for these kind of structures under extreme dynamic loads. Concrete can be considered as an effective and widely material in the design of protective structures under impact and blast loading. Compressive strength of concrete is about 10 times of its tensile strength which indicates that concrete is weak in tension. To improve tensile strength of concrete, longitudinal reinforcement bars as well as fibres can be used to increase the tensile strength of concrete significantly. The use of fibres as an additive material to the normal concrete mixture which leads to an ultra-high performance fibre reinforced concrete (UHPFRC), in addition to increasing tensile strength, increases the failure strain and reduces tensile cracks. On the other hand, the current single-functional blast and impact resistant materials as UHPFRC suffering from non-fire resistance properties, since during their exposure at high temperatures occurring in a fire incident event are losing their structural integrity due to severe explosive spalling phenomena. In this regard, two different strategies can be considered to overcome this problem. One is proposing a new material to have enough strength against both structural and thermal loading and the second is using composite structures including different resistant layers of material against thermal and extreme loads. Therefore, first knowledge about the behaviour of composite structures under impact and blast loads are of interest, and thereafter improving the behaviour under thermal effect is the final objective. In this report, the behaviour of UHPFRC material under impact loads are investigated with the aid of LS-DYNA software, which is an indirect validation for the efficiency of finite element model for structure under blast loading. Then, the behaviour of UHPFRC will be further investigated under the effect of blast loading by using the Multi-Material Arbitrary Lagrangian Eulerian (MM_ALE) where the explosive, air and structure are explicitly modelled which gives more accurate results than other approaches of blast loading, i.e., Conwep and empirical formulations, where the blast load is idealized as an exponential function of time. Finally, initial finite element models are proposed for composite structures including UHPFRC layer, adhesive layer and thermal protective layer under both impact and blast loads based on material data from experimental analyses performed in the frame of the BAM project as well as from the literature. The results show that the finite element modelling by LS-DYNA software has sufficient capacities and efficiency to capture the behaviour of the aforementioned composites.

Material properties and model details

Due to superior mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC) (such as high strength, energy absorption capacity, and distinctive strain hardening / softening behaviour), this material has a promising future as a construction material for protective structures [1] under the effect of extreme dynamic loadings like as blast and impact. Several research studies can be found in the literature that have been dedicated to find the response of UHPC under blast and impact [2-5] as well as other types of loading as seismic [6, 7], environmental [8] and fire loading [9, 10]. Specifically in this research report, a special attention has been spent on the behaviour of adhesively bonded cement-based composites under blast and impact loadings. The composite structure considered consists of three different layers with different material properties. The first layer is made by UHPFRC material which works as a protective layer for composite structure. The second material used in the composite structure is Geopolymer concrete material (GPC) that only has a protective role against thermal conditions (i.e., fire loading) and has no resistance against extreme dynamic loads (i.e., blast and impact). Another layer of composite structure is the adhesive layer between the UHPFRC and GPC which works as an interface to tie and connect these layers together. As explained, knowing the behaviour of these materials under blast and impact loadings are important to find the response of entire composite structure.

To modelling the composite structure under impact and blast loads, a high-fidelity physics-based numerical model, which consists of a composite structure, a TNT explosive charge, drop weight or hammer (only in case of impact load) and a surrounding air domain (only in case of blast load), is developed in the nonlinear dynamic analysis program LS-DYNA. Eight-node constant stress solid elements are used to discrete the composite layers (i.e., concrete, cohesive layer and geopolymer material)). To model the explosive detonation (i.e., TNT), the blast wave propagation and its interaction with the composite structure, the multi-material Arbitrary Lagrange-Euler (MM-ALE) formulation is utilized in LS-DYNA. The TNT explosive charge and air domain are modelled by one-point MM-ALE solid elements. It should be noted that the blast load is transferred to the composite via the CONSTRAINED_LAGRANGE_IN_SOLID card which provides a penalty coupling mechanism for modelling the fluid-structure interaction (FSI) between the blast wave and the composite. The boundary conditions are idealized in such a way that they introduce a condition as same as the experiment. The non-reflecting boundaries conditions are applied to the four side surfaces and the top of the air domain to eliminate the blast wave reflection at the boundaries of the air domain. To reduce the computational efforts, according to the symmetry of the model, only one quarter of the structure is modelled, and appropriate symmetry conditions are assigned to the relevant boundaries. The outside pressure of the air domain is set to 0.1 MPa with the CONTROL_ALE command.

Material models for UHPC

In both civil and military applications, concrete is a frequently used construction material. Although there are practically infinite varieties of concrete, most of them can be described by a single characteristic called the uniaxial unconfined compressive strength, which is frequently written as fc' in the field of civil engineering. Even though at first glance this single parameter characterization seems to be similar to that of metals, where the yield strength can be used as a single parameter to characterize metals of a similar class, such as steels (say F_y). In the case of concrete, the unconfined compressive strength parameter describes both the elastic and the inelastic (plastic) responses, including the shear failure envelope, compressibility, and tensile failure. It is obvious that a single parameter cannot adequately describe every aspect of concrete material, however, engineers are frequently asked to conduct analyses involving concrete when no data is available to characterize the concrete beside from fc'. In this regard, the Karagozian & Case Concrete (K&C) model has been proposed in the literature [11, 12] in order to capture the behaviour of concrete under different types of loading. Originally, this material model was proposed and calibrated for a normal strength concrete with an unconfined compressive strength of 45.6 MPa and has the ability to generate model parameters solely based on the unconfined uniaxial compressive strength. On the other hand, the composition of UHPC differs significantly from that of normal strength concrete, hence, using this model material for UHPC without any modification leads to inaccurate results. In this regards, there are several research studies in the literature that have been dedicated to modify the K&C model material and calibrate it for UHPC under extreme dynamic loading as blast and impact [2, 3]. In this research project, the proposed formulations of Zhang et al. [3] are used for the UHPC material considering following:

- Failure surface parameters
- Strain rate effect

- Volumetric behaviour be means of the equation of state (EOS)
- Failure surface interpolation function

The reason for selecting this method is that the calibration of the model was performed based on several experimental tests of impact loadings, which in this study, is first used to show the accuracy of this model material for a UHPC specimen under drop weight, and after that, extending it for other type of impact loads. However, other material models can also be used, and the results can be compared to each another.

Material models for Geopolymer Concrete (GPC)

Moreover, in order to model the GPC material mat K&C has been also used which as mentioned before, it is a powerful material property that can be used for different type of concrete material by modifying the input parameters. In 2022, Chen et al. [13] discussed the suitability of different dynamic constitutive models for prediction of geopolymer concrete structural responses under blast and impact loading. They showed that the K&C model could best model the brittle failure behaviour of GPC after reaching its ultimate compressive strength. Furthermore, the K&C model with modified material input parameters could better predict GPC structure responses under impact and blast load when structural response is dominated by flexural response mode. In the literature, there are many dedicated studies proposing the K&C material under thermal effect to determine relationships of the input parameters as a function of the exposed temperature [20]. On the other hand, in this research project, the use of GPC layer is intended for fire protection of the composite structure, and thus, the used model material should have the possibility to take into consideration the effect of thermal load. In this regard, several research studies (e.g. [20]) can be found in the literature, which are dedicated in the calibration of the K&C material model for GPC under the effect of thermal load. In this task, a same approach is adopted according to [14] to model the behaviour of GPC under the effect of thermal, blast and impact loadings.

Modelling of the adhesion layer

To model the adhesive layer (i.e., the interface layer between composite layers) two different strategies can be used. The first strategy is modelling the adhesive layer using 3D finite element model and assigning the corresponding material properties of the adhesion layer. In this case, the behaviour of cohesive layer is defined using *MAT_COHESIVE_MIXED_MODE and relevant inputs are assigned to this card depending on the material used for paste layer. In the second method, composite layers are tied to each other via *CONTACT_TIEBREAK_SURFACE_TO_SURFACE in LS-DYNA. In this method, the values of NFLS (interface normal failure stress) and SFLS (shear failure stress) are the controlling parameters which are assigned to two different segment sets of the connected layers. This contact algorithm incorporates failure criteria that, when achieved, release the tied interface between the contacting faces, and the constraint is transformed to surface-to-surface contact that allows sliding between the faces while preventing the penetration of nodes between the parts in contact. Deboning occurs when the following equation is satisfied:

$$\left(\frac{\sigma}{NFLS}\right)^2 + \left(\frac{\tau}{SFLS}\right)^2 \geq 1$$

where σ and τ are the normal and shear stresses at the interface, SFLS and NFLS representing shear failure stress and interface normal failure stress were set to 2.0 MPa.

Modelling of impact and air blast loads

To model the impact load, the impactor component is modelled using 3D solid element and MAT_RIGID (MAT_020) is used to define its material behaviour. The reason for selecting this model material is firstly to minimise the computational time of the FE simulations and secondly because no significant deformation is expected on the hammer during impact. Also, an initial velocity or initial energy (an initial energy value of 20 J is considered for a hammer with mass 816 gr which is dropped from height of 2500 mm and reaches a velocity of around 7 mm/msec) can be assigned to the hammer using appropriate cards (e.g., *INITIAL_VELOCITY_GENERATION).

Furthermore, to model the air blast loading in LS-DYNA, instead of using empirical relationships to define the blast load parameters, both TNT and air are modelled using 3D finite element to increase the accuracy of blast load. In this regard, the air is modelled as an ideal gas by using the MAT_NULL material model and the linear polynomial equation of state (i.e., EOS_LINEAR_POLYNOMIAL) is assigned, which gives the air pressure related to the volume and internal energy as follows:

$$P = C_0 + C_1\mu_a + C_2\mu_a^2 + C_3\mu_a^3 + (C_4 + C_5\mu_a + C_6\mu_a^2)E_{0,Air}$$

where C_0, C_1, C_2, C_3, C_4, C_5 and C_6 are the linear polynomial equation coefficients; $\mu_a = \rho/\rho_0 - 1$, in which ρ and ρ_0 are the current and initial densities of air; and $E_{0,\mathrm{Air}}$ is the internal energy per unit volume.

In case of TNT modelling, the Mat_High_Explosive_Burn is used along with the Jones-Wilkins-Lee equation of state (i.e., EOS_JWL in LS-DYNA). The EOS_JWL defines denotation pressure as a function of the relative volume of the denotation product and an initial explosive internal energy, and it is expressed as follow:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_{0,TNT}}{V}$$

where V is the relative volume of the detonation products; A, B, $R1$, $R2$, and ω are parameters related to the explosive type; and $E_{0,\mathrm{TNT}}$ is the internal energy per unit volume. The input parameters used for the TNT and air are presented in Table 1. It should be noted that for other input parameters, the default values are adopted.

Table 1: EOS parameters and material properties of TNT and air.

Material	Material model and EOS	Input parameters	Value
Air	MAT_NULL	Initial density, $\rho 0$ (g.mm^{-3}) Pressure cut-off	1.29e-6 0
	EOS_LINEAR_POLYNOMIAL	$C0$, $C1$, $C2$, $C3$, $C6$ $C4$, $C5$ Internal energy, $E_{0,air}$ (N/mm^2)	0 0.4 0.25
TNT	MAT_HIGH_EXPLOSIVE_BURN	Initial density, $\rho 0$ (g.mm^{-3}) Detonation velocity, D (mm/msec) Chapman-Jouguet pressure, PCJ (MPa)	1.63e-3 6930 21000
	EOS_JWL	A (MPa) B (MPa) R_1 R_2 Ω Initial energy, $E0$, TNT (N/mm^2)	371200 3231 4.15 0.95 0.3 7000

Preliminary results

In this section, the preliminary results of finite element modelling for both impact and blast loaded structures are provided.

Impact loaded UHPC

In this case, a UHPC specimen is simulated under the hammer load in LS-DYNA software. The UHPC specimen has dimensions of 100*100*50 mm^3 and its compressive strength is about 175.6 MPa. The finite element model is shown in Figure 1. The hammer has mass of 816 gr and initial velocity of 7.0 mm/msec (this value is obtained by the kinetic energy of a hammer dropped from the height of 2500 mm).

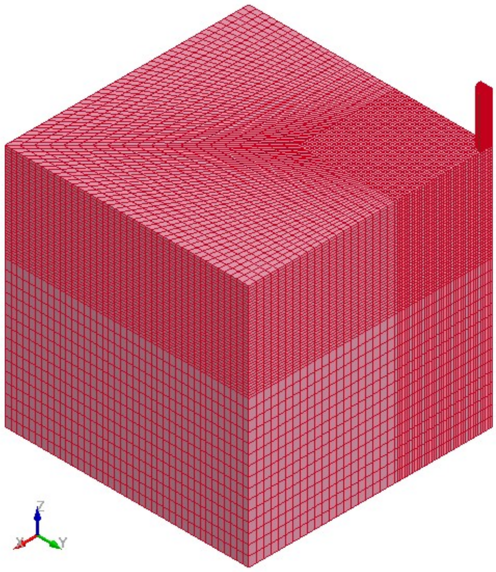


Figure 1: Finite element modelling of UHPC under hammer impact

As it can be seen in Figure 2, the UHPC sample is damaged under the effect of hammer load and the damaged elements are removed from the mesh. It should be noted that, the MAT_ADD_EROSION is used to eliminate eroded elements that reach a plastic strain of 0.2. Furthermore, the fringe levels shown on the figure indicate the amount of damage to the concrete, whereby the 0 value is for non-damage state and 1.0 represents a severe (complete) damage to the elements. Figure 2 also shows that the depth and radius of the damaged region are sensitive according to element size. Accordingly, the hole radius of damaged region is calculated as 10.1 mm by using element size of 1 mm, and reaches 12.04 mm with element size 2 mm. On the other hand, the radius of specimen with severe damage is equal to 40 mm for mesh size 1 mm, while it reached 70 mm for mesh size 2 mm. A sensitivity analysis showed that the best mesh dimension is about 0.5 mm for the mesh area adjacent to the effect of the dropped hammer.

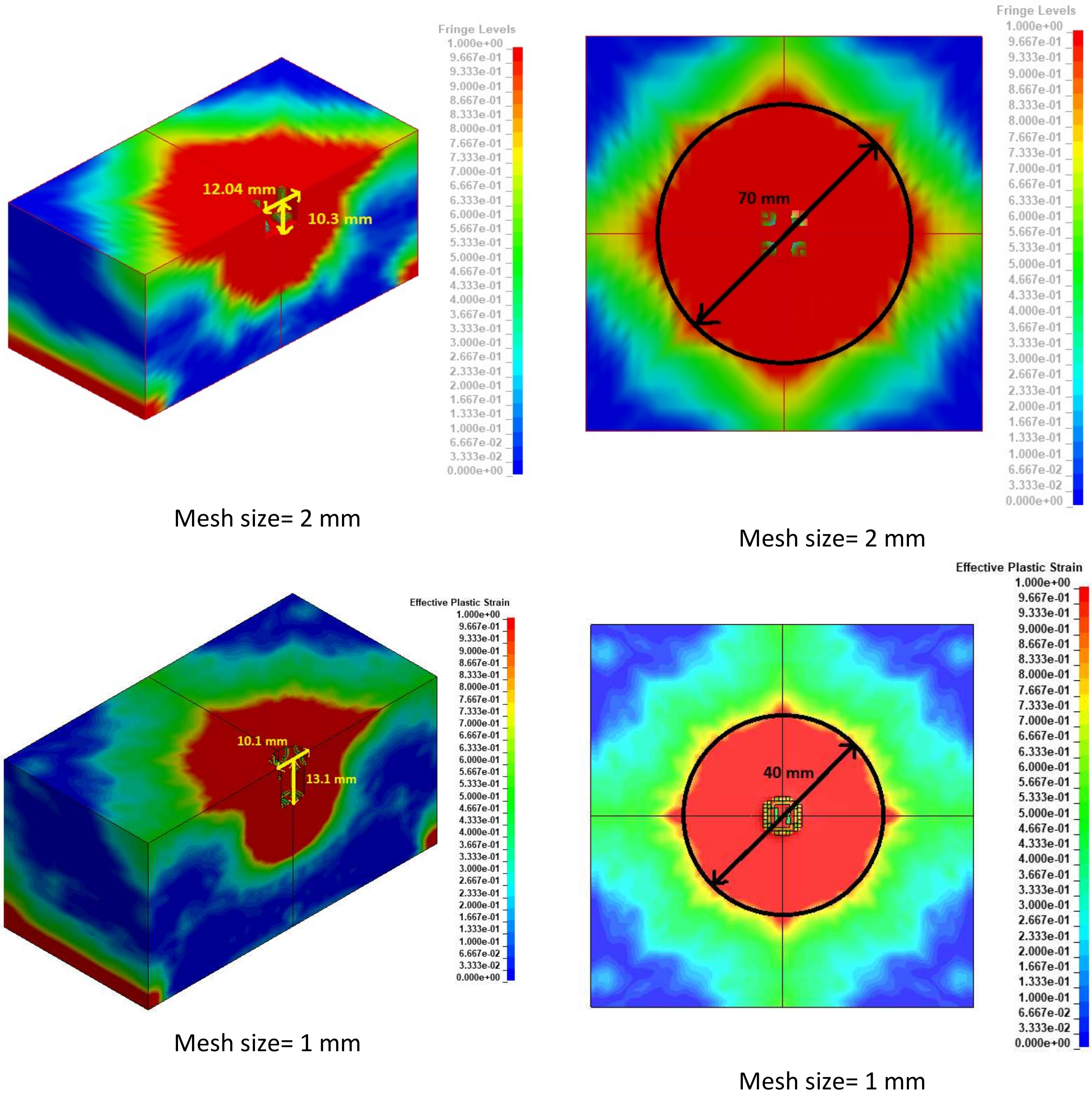


Figure 2: Effect of mesh dimension on the results of finite element.

Blast loaded UHPC:

In this section, the UHPC specimen (with similar properties as considered above) is subjected to a blast load with 7.7 gr TNT at stand-of-distance 46.7 mm. The finite element model is shown in Figure 3.

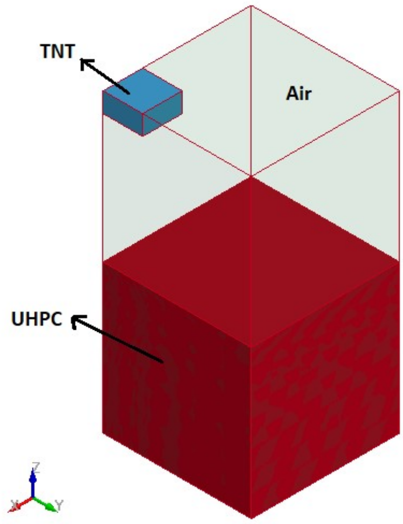
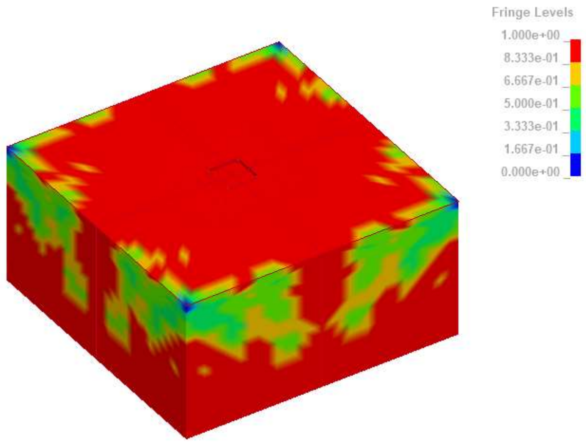
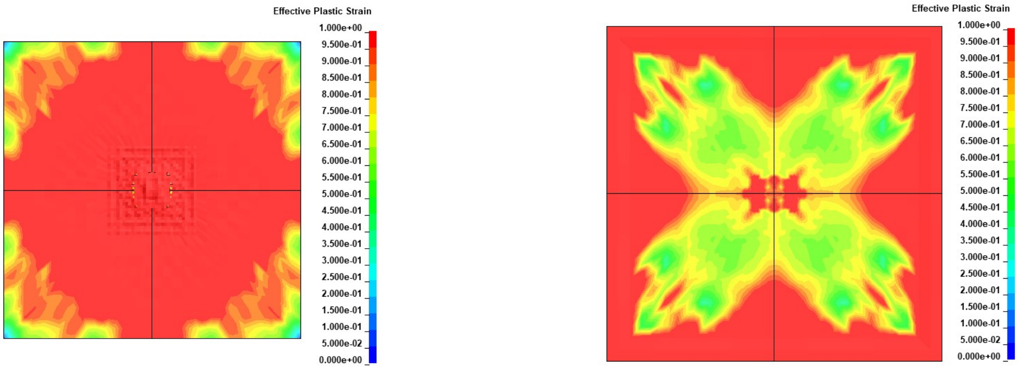


Figure 3: Finite element modelling of UHPC under blast load

As can be seen from Figure 4, the UHPC sample is damaged under the effect of blast load, and the damaged elements are removed from the model. The fringe levels shown in the figure indicate the amount of damage to the concrete, of which 0 value stands for non-damage state and 1.0 shows severe (complete) damage to the elements. Also, based on the figure, it can be noticed that the model for the explosion load follows a correct process because the elements that were closer to the explosion center suffered more damage, and less damage is noticeable in those elements far away from the explosion center. This can be seen also in Fig. 4 for the front and rear view of the UHPC. A verification based on experimental data is pending.



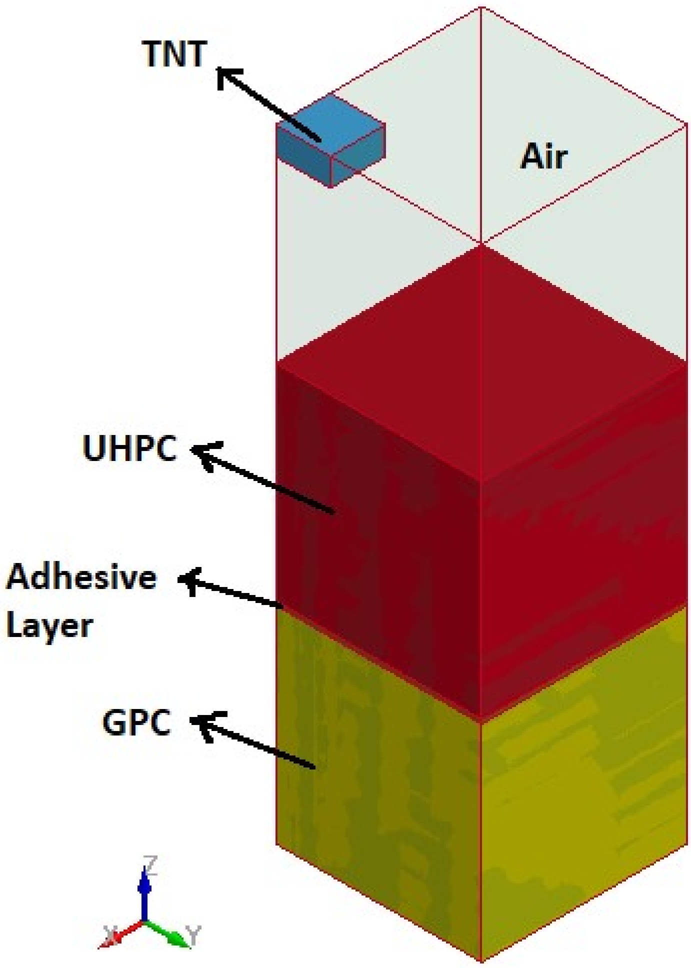


Front side to the blast load Rear side to the blast load

Figure 4: Blast load effect on UHPC

Blast loaded composite:

In this part, a composite structure is subjected to a similar blast load as described above. The composite layers are UHPC, adhesion layer and GPC layers. The finite element modelling in LS-DYNA is shown in Figure 5. It should be noted that two layers are connected together with two different approaches as cohesive layer and tied contact strategy. Experimental analyses are pending in order to use the appropriate parameters corresponding to each material model and adhesion layer for performing the simulation.



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