EXPLORATION OF UHPC APPLICATIONS FOR MONTANA BRIDGES

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1 Problem Statement

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. However, using UHPC in concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing approximately 30 times more than conventional concrete. Previous research conducted at Montana State University (MSU) has focused on the development and evaluation of non-proprietary UHPC mixes made with materials readily available in Montana. These mixes are significantly less expensive than commercially available UHPC mixes, thus opening the door for their use in construction projects in the state. Building on the success of this previous research, the focus of the proposed project is to investigate further uses of this novel material in MDT bridge projects, and to start addressing some implementation questions that will need to be answered prior to its use in these applications.

Bridge deterioration (including decks and other members) is a problem across Montana, and UHPC overlays and patching/repairing may be a viable alternative to bridge/element replacement. Specifically, the research proposed herein will focus on exploring the following two applications: 1) thin-bonded overlays for bridge decks, and 2) patching and repairing deteriorating members. While this research will not be limited to one UHPC source, it will primarily focus on using the Montana UHPC (MT-UHPC) developed in the previous research at Montana State University. This project is a required step to fully understand and capitalize on the benefits of using MT-UHPC, and to ultimately increase the lifespan of Montana’s existing concrete infrastructure.

2 Background

UHPC became commercially available in the U.S. in 2000, and since then has been actively promoted by the Federal Highway Administration [1-6]. UHPC has been used in the U.S. for various applications, including: field cast connections of prefabricated bridge components, precast/prestressed girders, precast piles, and thin-bonded overlays for bridge decks. UHPC is generally understood to be a concrete with compressive strength of at least 20 ksi, post-cracking tensile strength of at least 0.72 ksi, and a discontinuous pore structure that improves durability by limiting permeability. These properties are achieved with: (1) low water-to-cement ratios, (2) aggregate gradations optimized for high particle packing density, (3) high quality aggregates and cements, (4) supplemental cementitious materials, (5) high particle dispersion during mixing, and (6) the incorporation of steel fiber reinforcement. Although the initial cost of UHPC far exceeds conventional concrete mixes, the use of UHPC has been shown to reduce the life-cycle costs [7], as the increased durability of UHPC results in a longer service life and decreased maintenance costs. Further, the use of UHPC results in smaller/lighter structural elements.

Previous research conducted at MSU [8, 9] has included (1) the development of nonproprietary UHPC mixes that are significantly less expensive than commercially available mixes and are made with materials readily available in Montana, (2) an investigation into several items related to the field batching of these mixes, (3) an exploration into the potential variability in performance related to differences in constituent materials, and (4) the investigation of rebar bond strength and the subsequent effect this has on development length. This previous research has been successful and has clearly demonstrated the feasibility of using MT-UHPC in Montana bridge projects. That being said, more research is needed to demonstrate the feasibility of using this material on an actual bridge project. This is currently the focus of an additional MSU project recently funded by MDT. In this funded project, MT-UHPC will be used in closure pours on two bridges spanning Trail Creek on Highway 43, west of Wisdom, MT. On these bridges, MT-UHPC is proposed to be used in precast pile cap joints and shear keys between precast deck elements.

There is significant potential for the use of MT-UHPC in other applications that will improve the performance of Montana bridges; however, before it can be used in other field applications, further research must be conducted to ensure proper performance in the desired application(s), the focus of the proposed project. For example, UHPC has been explored in a range of applications in the U.S., including bridge pier seismic strengthening [10], 100% UHPC structural elements such as girders [11], bridge member repairs, rehabilitation, and structural patching [12-16], composite slabs [17], and even precast applications [18]. One of the more promising applications of UHPC is its use in thin-bonded overlays for bridge deck rehabilitation [19-22]. In this application, UHPC not only provides enhanced structural performance, it also provides protection from chloride penetration and water ingression [20].

3 Objective

Now that the groundwork has been laid for MT-UHPC through previously funded MDT projects, a logical next step is to conduct a screening of potential new applications that can benefit future MDT Bridge Bureau projects. The primary objective of the proposed project is to explore applications of MT-UHPC in Montana Bridges. Specifically, this project will primarily focus on the use of MT-UHPC in thin-bonded deck overlays and will explore its use in the rehabilitation of deteriorating structural elements. Although the focus of the proposed research is on the experimental exploration of these potential new applications using MT-UHPC, it is important to note that the research will answer questions about UHPC in general and that any source of UHPC could be explored in the proposed applications.

4 Business Case

Aging infrastructure and limited budgets require robust and proven bridge construction, rehabilitation and replacement strategies that are cost-effective and efficient. The non-proprietary fiber-reinforced MT-UHPC mixes developed in the Phase I/II research are significantly less expensive than proprietary mixes, costing $1000 per cubic yard, compared to $2500-3500 per cubic yard from commercial suppliers. If these mixes are found to be viable for other applications, Montana can take advantage of the cost savings of the non-proprietary mixes and ultimately improve the performance and durability of our bridges. If successful, using MT-UHPC for not only field cast joints, but also as a deck overlay solution and other applications could potentially turn a costly bridge replacement into a simple rehabilitation.

5 Research Plan

The research proposed herein will build on the recently completed research at MSU and investigate the use of the MT-UHPC mixes in additional applications. Specifically, the proposed project will include the following tasks:

Task 0 – Project Management

The Principal Investigator for this project will manage the project with respect to contractual compliance, budget and schedule, administrative tasks, and communications with the Technical Panel at MDT. Dr. Kirsten Matteson of the Civil Engineering Department at Montana State University will serve as the Principal Investigator. She will be the primary contact and assume the majority of the project management responsibilities. Management will generally be achieved through regular communication between the Principal Investigator, co-PI Dr. Michael Berry, the MDT project manager and Technical Panel, and other research team members.

Task 1 – Literature Review

As this research moves ahead, it is essential to be aware and take advantage of any work completed to date by other investigators/organizations. A comprehensive literature review will be conducted to evaluate the state-of-the-practice for and recent advances in UHPC, and in particular, this review will focus on the use of UHPC in actual bridge applications, including its use in overlays and as a repair material. Material properties and specifications documented by other researchers and state agencies will also be investigated. In general, the topics will include standard practices of other states that have successfully implemented UHPC for overlays and repairing, including required equipment, typical application methods, batch sizing for larger volumes of UHPC, etc. Specific topics that will be investigated during Task 1 are summarized as follows:

- Standard overlay thicknesses
- Underlying concrete surface preparation methods for overlays
- UHPC bond potential with weak/deteriorating underlying concrete
- The effects that chlorides and pH may have on the bond strength between deteriorating concrete and UHPC
- Cracking potential for overlays (crack propagation from the underlying concrete)

This task will also include a review of previous research on the cost/benefit of using UHPC in transportation applications. Specifically, this review will focus on UHPC mixes used in other states and outline the economic benefits reported for both overlay and repairing applications. In previous studies, UHPC overlays have been shown to be a viable option (75-year solution in some cases) for high profile bridges, but an evaluation of the cost/benefit for smaller scale applications is of particular interest for this project.

Information gathered for Task 1 will be helpful in guiding the future directions of this research. This literature will be revisited throughout the research and will be updated before submittal of the final report. A Task 1 report will be submitted by the end of the month following the completion of this task.

Task 2 – Material-Level Evaluation

Confidence in the use of MT-UHPC as a strengthening material will require the exploration of surface preparation/treatments and bonding between the UHPC and standard concrete. Material level testing/evaluation will be performed to further define MT-UHPC. The preliminary tests planned are listed below and additional material property tests may be warranted based on the literature review findings.

Specifically, the following tests focused on bond strength and flexural strength will be performed:

- Direct Tension Testing – ASTM C1583/Equivalent AASHTO Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)

  This testing will determine the tensile bond strength between standard concrete and a MT-UHPC overlay, dependent on concrete surface treatment. Specifically, the concrete surface will be treated such that at least a roughness of ¼” is produced through mechanical roughening (grinding and/or milling). A surface roughness of ¼” will yield conservative results, as surface treatments done in the field are typically at least this rough, if not much more, and these results are meant to establish a conservative baseline. The testing will determine both the failure loads and the failure modes. An example of a direct tension core specimen after testing is shown in Figure 1 [10]. For this example, the failure mode was failure in the substrate concrete showing a well bonded and strong UHPC overlay.

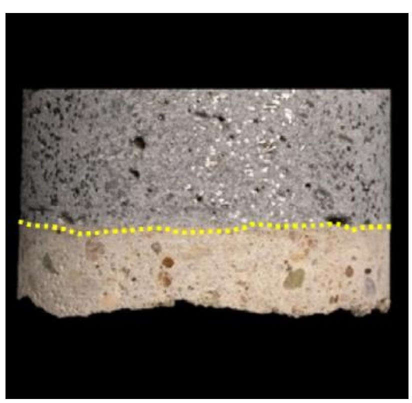


Figure 1: Example direct tension bond strength core specimen [10]

- Slant Shear Testing – Similar process to ASTM C882 Standard Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear, but for UHPC

  This testing will determine the shear bond strength between standard concrete and MT-UHPC, again dependent on concrete surface treatment. The same surface treatment discussed above will be investigated for this test. Shear bond strength is a critical parameter needed to fully assess the bonding of MT-UHPC to standard concrete for a range of potential applications. An example test setup is shown in Figure 2.

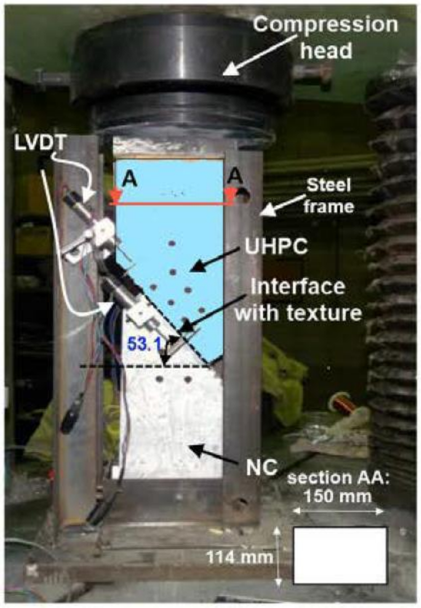


Figure 2: Example slant shear test setup [12]

- Flexural Testing – ASTM C78/Equivalent AASHTO Standard Test Method for Flexural Strength of Concrete

  Flexural tests were performed on earlier MT-UHPC mix designs during Phase I of the UHPC research (shown below in Figure 3) but have not been conducted on mixes with the new steel fibers. This testing will evaluate the flexural performance of the mix and yield a measurement of the rupture modulus for MT-UHPC with the new fibers.

Figure 3: Example flexural test performed on an earlier MT-UHPC mix at MSU

The tests described here will yield a baseline for bond strengths between standard concrete and MT-UHPC and assess the rupture modulus of the current mix. These properties are key information for assessing the potential use of MT-UHPC for thin-bonded overlays for bridge decks and repairing deteriorating members.

It is important to note that chloride permeability testing was performed on previous batches of MT-UHPC during Phase I per ASTM C1202/AASHTO T277 – Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. This testing assessed the chloride permeability of MT-UHPC by measuring the coulombs passed through a vacuum saturated 4 in. diameter by 2 in. thick cylinder exposed to a current for 6 hours. MT-UHPC was found to not be susceptible to chloride ion penetration, with an average of 70 coulombs passed and a rating of Negligible. For reference, a concrete determined to have a low susceptibility to chloride ion penetration would be in the range of 1,000-2,000 coulombs. Depending on possible changes to the mix and/or new geometries investigated during this new phase of research, e.g. steel fiber source and overlay thickness, the research team and Technical Panel may deem another round of chloride permeability testing necessary. Overall, the chloride permeability is critical information for determining the potential chloride profile through a bridge deck with a MT-UHPC thin-bonded overlay.

A Task 2 report will be submitted by the end of the month following the completion of Task 2.

Intermediate Technical Panel Meeting Task

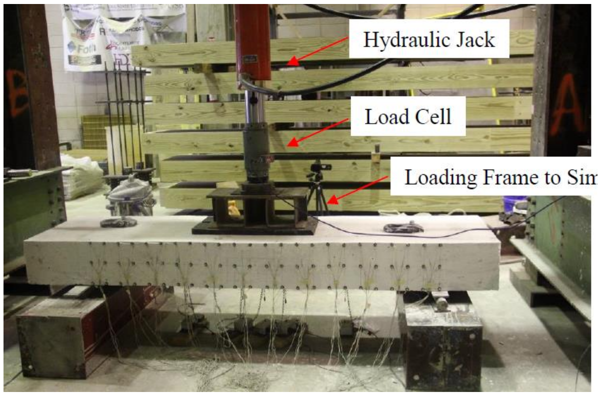
The MSU research team will meet with the MDT Technical Panel upon completion of these first two tasks to present their findings, and to discuss the focus and direction of the structural testing portion of this research, Tasks 3 and 4. The review of cost/benefit analyses will be a key point of this meeting. The goal of this meeting will be to gather input from the Technical Panel required to guide key aspects of the remaining research for successful future implementation projects.

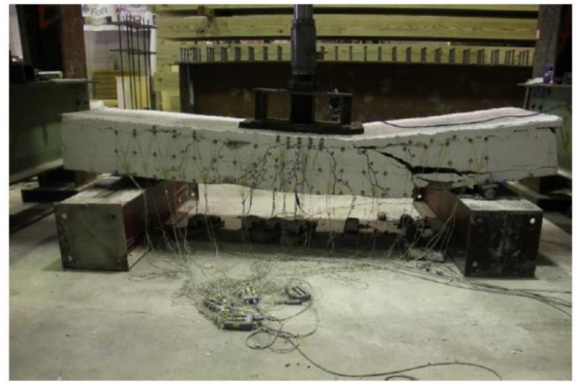
Task 3 – Experimental Design of Structural Testing

As mentioned above, the specifics of this task will be determined based on the results of the first two tasks of this research and during the intermediate Technical Panel meeting. That being said, this task will most likely focus on testing the structural performance of scaled slab elements rehabilitated with MT-UHPC overlays, and the testing of deteriorated/damaged structural elements repaired with MT-UHPC.

The use of MT-UHPC as a thin-bonded overlay on bridge decks may involve flexural tests of scaled slab elements rehabilitated with thin-bonded overlays, similar to what has been conducted by other researchers [22]. In this previous research, slab elements with UHPC overlays were tested under 3 point bending until failure. Figure 4 shows (a) the typical load setup used in this testing and (b) the observed shear failure mechanism followed by partial UHPC debonding. In addition to the flexural testing, this evaluation may include investigating the punching-shear capacity of the deck and the bond characteristics between the overlay and the conventional concrete deck, including the potential effects that temperature gradients may have on this bond. This research will also address several implementation/preparation issues that may arise during construction, which could hinder the use of MT-UHPC as an overlay. For example, this research could investigate formwork methods and varying concrete flows for dealing with large deck grades, and could investigate finishing/consolidation techniques that could vary based on overlay thickness/construction techniques. After slab specimen construction and testing, cross-section cores could possibly be drilled to check for consolidation issues/entrapped air, and other possible issues.

The thickness(es) of the overlays explored for this research will be dependent on the findings from Task 1 and the intermediate Technical Panel meeting discussion. However, most state DOTs recommend 1.5-2 inches for UHPC overlays. The use of thinner overlays (perhaps at 1 inch thick) may be investigated in this research, as this could significantly reduce material costs.





a) Test setup b) Partial overlay debonding following shear failure

Figure 4: Example testing of a concrete deck with UHPC overlay [22]

The researchers foresee the thin-bonded overlay for bridge deck rehabilitation application being the primary focus of this task; however, as discussed earlier, other applications of interest to the Technical Panel could potentially be investigated in this task, depending on importance, funds, and timing. In particular, the testing of deteriorated/damaged structural elements retrofitted with MT-UHPC will also be explored. This has been the subject of numerous recent research projects. For example, UHPC has been investigated as a repair method to rehabilitate damaged flexural members [15], steel girders [12], and columns [16], and used to strengthen reinforced concrete frames [14]. One example that may be of particular interest to the Technical Panel is the previous research conducted on repairing steel girder ends [12]. The repairs involve the application of shear studs to aid in the bonding between the existing member and the UHPC repair. An example steel girder repair is shown in Figure 5 [12].

b) Installation of shear studs for UHPC repair

a) Typical end corrosion of bridge girders c) Example finished repair

Figure 5: Example Steel Girder Repair with UHPC [12]

Although not all questions can be answered during this phase of research, gathering this preliminary data will shed light on directions for future research projects, with an overall goal of gathering the required information to prepare a contractor to successfully implement thin-bonded bridge deck overlays and/or repairs using UHPC for bridge projects in Montana.

A Task 3 report will be submitted by the end of the month following the completion of Task 3.

Task 4 – Structural Testing

This task will involve the carrying out the test series determined in Task 3. While the specifics of this task will not be determined until Task 3 is complete, this task will include the construction of the test specimens and load frame(s), instrumentation of specimen, data acquisition setup, and ultimately testing.

A Task 4 report will be submitted by the end of the month following the completion of Task 4.

Task 5 – Analysis of Results and Reporting

The results from this work will be thoroughly analyzed in this task.

A comprehensive final report that documents the findings of this research, including the material evaluation, experimental design details, test results, analysis of results, and recommendations, will be prepared in conformance with MDT's standard research report format. A draft report will be sent to MDT to be distributed to the Technical Panel for review and comment. The results of the project will also be disseminated, as appropriate, to the professional community through presentations at various conferences and/or through journal papers. A Project Summary Report will be written and submitted to MDT near the end of the project to summarize the background, methodology, results, and recommendations of this research. This summary report will be edited, published, and distributed by MDT to be distributed to the Technical Panel for review and comment.

In addition to the final and project summary reports, four task reports will be written to summarize work associated with the following major activities:

- Task Report 1 – Literature review
- Task Report 2 – Material-Level Evaluation
- Task Report 3 – Experimental Design of Structural Testing
- Task Report 4 – Structural Testing

Quarterly progress reports will be submitted to provide updates on the administrative aspects of the project, such as progress regarding the deliverables, schedule, and budget.

6 MDT Involvement

In keeping with standard requirements, MDT will review and comment on all products, including but not limited to task reports, quarterly progress reports, the final report, and the project summary report. Also, as discussed above, feedback will be requested from the Technical Panel during the meeting scheduled at the conclusion of Task 2.

7 Products

The products to be delivered during this project include the following items.

- Kick-off meeting and subsequent notes.
- 7 quarterly progress reports.
- 4-task reports (Tasks 1-4).

- Draft final report and executive summary describing the research methodology, findings, conclusions, and recommendations, followed by a final report addressing comments and suggestions from the Technical Panel.
- Final presentation and webinar.
- Project summary report.
- Implementation report, meeting, and material specifications.
- Performance measures report.
- Project Poster.

8 Implementation

Another proposed project by the researchers aims to demonstrate the viability of non-proprietary MT-UHPC in field cast joints and focuses on an implementation project for two Montana bridges. Upon successful completion of that pilot project, MDT will have a new concrete available for use in bridge construction. There is significant potential for the use of MT-UHPC in other applications; however, further research must be conducted to ensure performance in the desired application(s) (i.e. the research proposed herein). If successful, a future field demonstration project could be pursued to further investigate possible construction issues that may hinder the use of MT-UHPC in the proposed applications (for example, thickness vs. finishing techniques and time involved for grinding an entire bridge deck surface). Then, other future implementation projects on other MT-UHPC applications for Montana bridges will be pursued.

9 Schedule

The estimated project schedule is depicted in Table 1. The total proposed duration of the project is 24 months, with an estimated start date of August 1, 2021, and an estimated completion date of July 31, 2023. In addition to the product deliverables shown in Table 1, quarterly progress reports (QPRs) will be submitted at the ends of Quarters 1-7.

Table 1: Project Schedule

Activities	Dates	Project Quarter							
		1 Aug 1 - Oct 31, 2021	2 Nov 1 - Jan 31, 2022	3 Feb 1 - Apr 30, 2022	4 May 1 - Jul 31, 2022	5 Aug 1 - Oct 31, 2022	6 Nov 1 - Jan 31, 2023	7 Feb 1 - Apr 30, 2023	8 May 1 - Jul 31, 2023
Kick-off Meeting	8/2/2021	X							
Task 0 - Project Management		X	X	X	X	X	X	X	X
Task 1 - Literature Review		X	X	X	X	X	X	X	X
Task 1 Report	1/31/2022		X						
Task 2 - Material Evaluation		X	X	X					
Task 2 Report	4/29/2022			X					
Intermediate Technical Panel Meeting	5/16/2022				X				
Task 3 - Application(s) Experimental Design					X	X	X		
Task 3 Report	1/6/2023						X		
Task 4 - Testing					X	X	X	X	
Task 4 Report	2/28/2023							X	
Task 5 - Analysis of Results and Reporting								X	X
Draft Final Report	3/31/2023							X	
Project Summary Report	5/15/2023								X
Performance Measures Report	5/15/2023								X
Project Poster	5/15/2023								X
Final Report	7/3/2023								X
Final Presentation and Webinar	7/17/2023								X
Implementation Meeting	7/17/2023								X
Implementation Report	7/31/2023								X

10 Budget

This proposal is requesting $161,015 in funding from MDT, as shown in the itemized budget presented in Table 2. A breakdown of expendable supplies and materials is provided in Table 3. The pay rates and benefit rates of the investigators is provided in

Table 4. Projected expenditures by task are shown in Table 5. Projected expenditures by state fiscal year are shown in Table 6.

Table 2: Project Budget by Item

Item	Total
Salaries	$84,457
Benefits	$16,955
In-State Travel	$400
Expendable Supplies and Materials	$17,000
Participant Support	$10,000
Total Direct Costs	$128,812
Overhead - 25%	$32,203
Total Project Cost	**$161,015**

Table 3: Breakdown of Expendable Supplies and Materials

Item	Budget
Portland Cement/Silica Fume/Fly Ash	$2,000
Admixtures	$2,000
Fine/Coarse Aggregates	$1,000
Steel Fibers	$3,000
Rebar	$1,000
Formwork	$1,500
Cylinder Molds	$1,000
Slab Surface Preparation Equipment	$3,000
Structural Testing Data Acquisition	$1,500
Misc Supplies	$1,000
Total	**$17,000**

Table 4: Pay Rate and Benefits
removed from publicly posted proposal

Table 5: Project Budget by Task

Task	Budget
0 - Project Management	$8,783
1 - Literature Review	$16,231
Deliverable: Task 1 Report	$1,411
2 - Material Evaluation	$35,875
Deliverable: Task 2 Report	$3,120
3 - Application(s) Experimental Design	$33,575
Deliverable: Task 3 Report	$2,920
4 - Testing	$36,816
Deliverable: Task 4 Report	$3,201
5 - Analysis of Results and Reporting	$19,082
Total	**$161,015**

Table 6: Project Budget by State Fiscal Year

Item	State Fiscal Year		
	2022	2023	2024
Salaries	$38,710	$42,229	$3,519
Benefits	$7,771	$8,477	$706
In-State Travel	$183	$200	$17
Expendable Supplies and Materials	$7,792	$8,500	$708
Participent Support	$2,500	$5,000	$2,500
Total Direct Costs	$56,956	$64,406	$7,451
Overhead	$14,239	$16,102	$1,863
Total Project Cost	**$71,194**	**$80,508**	**$9,313**

11 Staffing

Dr. Kirsten Matteson will be the Principal Investigator (PI) and will be the primary manager and sole point of contact with the MDT project manager. The Principal Investigator will be responsible for ensuring that the objectives of the study are accomplished, executing the project tasks, and preparing the written reports. Dr. Michael Berry will be the Co-Principal Investigator and will assist Dr. Matteson in project management and research related tasks. One graduate student will be employed to assist with all aspects of the proposed project and one undergraduate student will be employed for assistance in the laboratory.

The research team is well qualified, experienced, and available to conduct this research, and, to the best of its ability, will deliver a quality finished product in a timely and efficient manner. The level of effort proposed for principal and professional members of the research team will not be changed without prior consent of the Technical Panel. The following subsections describe some of the qualifications and experience of the project personnel in addition to each person’s role in this study.

11.1 Dr. Kirsten Matteson – Principal Investigator

Dr. Matteson is an Assistant Professor in the Civil Engineering Department at MSU, joining the Department in August of 2018. Her primary research interest involves investigating new materials and their possible structural applications, especially materials with potential for a positive global change. Her research experience includes investigating composite materials for structural elements and numerical modeling. Her modeling background is with both the finite element method and the discrete element method. She has performed extensive FEA simulations on composite materials, including plastic-aluminum composite I-beams and multi-layered ceramic capacitors. She is currently the faculty advisor for the American Society of Civil Engineers student section at MSU.

11.2 Dr. Michael Berry – Co-Principal Investigator

Dr. Berry is an Associate Professor in the Civil Engineering Department at MSU and has a research background in reinforced concrete structures and the behavior of these structures subjected to earthquake excitations. More recently his work has focused on concrete materials and their use in transportation applications and structural elements. He currently serves on several ACI committees including: Committee 341A - Earthquake-Resistant Bridge Columns, Committee 555 - Recycled Materials in Concrete, and Committee 306 - Cold Weather Concrete.

11.3 Graduate and Undergraduate Students

This research effort will be supported by qualified graduate and undergraduate research assistants, who will work part-time on this project throughout its duration. The graduate student will assist with collecting and reviewing existing design/analysis methodologies, specimen preparation, testing, organizing and analyzing data, and helping to synthesize information for the final report. The undergraduate student will mainly provide assistance with specimen preparation and testing.

11.4 Research Team Hours and Availability

It is anticipated that the proposed work associated with this research project will take 3,451 person hours. The number of hours committed to the project by each member of the research team during this time period is shown in Table 7. Key personnel assigned to accomplish the work associated with this project are generally available throughout the duration of this project. In the event that the level of effort proposed for the principal investigator requires significant modification, written consent will be sought from the Technical Panel to justify and approve this change.

Table 7: Summary of Person Hours by Task

Name of Principal, Professional, Employee, or Support Classification	Task 0	1	2	3	4	5	Total
Kirsten Matteson	60	16	100	100	100	40	416
Michael Berry	30	16	100	100	60	40	346
Graduate Student	0	400	400	400	400	400	2000
Undergraduate Student	0	133	133	133	133	133	667
Business Mgr.	8	0	0	0	0	0	8
Admin Staff	4	2	2	2	2	2	14
Total	102	567	735	735	695	615	3451

12 Facilities

The required equipment is already available in the Civil Engineering Department at MSU and at WTI.

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