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CAREER: Innovative Experimental Mechanics for Heterogeneous Construction Materials

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Principal Investigator: Landis, Eric N.
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Organization: University of Maine
Title:
CAREER: Innovative Experimental Mechanics for Heterogeneous Construction Materials

Project Participants

Senior Personnel

Name: Landis, Eric
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Keane, Denis
Worked for more than 160 Hours: No
Contribution to Project:
Participated in microtomography work at NSLS. Was responsible for instrument setup and calibration.

Name: Davids, William
Worked for more than 160 Hours: No
Contribution to Project:
Collaborated on computational model development

Post-doc

Name: Vasic, Svetlana
Worked for more than 160 Hours: Yes
Contribution to Project:
Brings expertise on wood microstructure and fracture to project

Graduate Student

Name: Lu, Shan
Worked for more than 160 Hours: Yes
Contribution to Project:
Working on microstructure characterization and mass transport properties.

Name: Parrod, Perrine
Worked for more than 160 Hours: Yes
Contribution to Project:
Grad research assistant

Undergraduate Student

Name: Petrell, Alina
Worked for more than 160 Hours: Yes
Contribution to Project:
Developing image analysis tools for microtomographic data

Name: Pontau, Robert
Worked for more than 160 Hours: Yes
Contribution to Project:
Fabricated test specimens, assisted in data analysis

Name: Merriman, Heather

Worked for more than 160 Hours: Yes

Contribution to Project:

Developing C programs for image and data analysis

Name: Emery, Eric

Worked for more than 160 Hours: No

Contribution to Project:

Specimen and fixture preparation.

Name: Martin, Aaron

Worked for more than 160 Hours: Yes

Contribution to Project:

Worked on teaching tools. Built simple shaker table

Name: Altenhoff, Julie

Worked for more than 160 Hours: Yes

Contribution to Project:

Worked on image analysis and data visualization.

Name: Severy, Lori

Worked for more than 160 Hours: No

Contribution to Project:

Undergrad research assistant

Name: Fournier, Christopher

Worked for more than 160 Hours: Yes

Contribution to Project:

Undergrad research assistant

Name: Folsom, Travis

Worked for more than 160 Hours: Yes

Contribution to Project:

Technician, Programmer

Name: Rofes, Xenia

Worked for more than 160 Hours: Yes

Contribution to Project:

Ms. Rofes worked on a small closed-loop, piezo-actuated loading frame customized for microtomographic studies of fracture in cements.

Name: Nagy, Edwin

Worked for more than 160 Hours: No

Contribution to Project:

Assisted with experiments at synchrotron. Has substantial experience with microtomography instrumentation.

Other Participant

Research Experience for Undergraduates

Organizational Partners

Rensselaer Polytechnic Institute

Collaboration with researchers in computer engineering department. Agorithm development for analysis and visualization of large 3D data sets.

Ecole Polytechnique Federale de Lausanne

PI worked in EPFL laboratory conducting fracture studies of cement and concrete

Maine Department of Transportation

Collaborating on microstructure characterization to predict mass transport properties of concrete. In addition to financial support, they have provided technician and laboratory support for certain materials testing.

Natl. Inst. for Standards and Technology

Using microstructure data generated by UMaine researchers, NIST scientists are running flow simulations through the porous media. This work is of interest to the Maine Department of Transportation as well.

Exxon Research and Engineering Company

Dr. John Dunsmuir of ERE has provided technical support for operation of the microtomography instruments at the National Synchrotron Light Source.

National Synchrotron Light Source

Microtomography experiments conducted at NSLS beamline X2B.

Northwestern University

Dr. Denis Keane, a research faculty member in the Materials Science Department has participated in the microtomography experiments at the NSLS.

Other Collaborators or Contacts

NDE group at NASA Langley Research Center. Results from that collaboration were limited.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

Beyond the normal graduate and undergraduate training that is a part of being a research assistant, there is one item of interest to report regarding the success we have had with freshman and sophomore undergraduate research assistants. All nine of the undergraduates who worked on this project were hired to do so when they were first-year civil engineering students. There were many advantages of starting them so early. First, these were frequently talented students who benefited from additional challenges beyond the classroom. Second, they developed significant skill sets that they would not have otherwise have had the opportunity to do so. Finally, they add a critical diversity element to the lab, bringing fresh ideas and attitudes that enhanced the research and educational activities.

One particular success case is a student whose work led to a refereed journal paper by the time she finished her sophomore year. Subsequent work led to co-authorship on a second journal paper currently being reviewed. Undergraduates, particularly those in the first and second years of their coursework are clearly an overlooked resource at most research universities, as we found them to be productive contributors.

Outreach Activities:

As educational activities were an integral part of this program, public outreach was included in this work, and is described in more detail in the 'Activities' section of this report. Out reach activities included talks and demonstrations at a local elementary school (Asa Adams School in Orono, Maine) and John Bapst High School in Bangor, Maine. Contact with the Bapst students included a group who visited the Experimental Micromechanics Lab to conduct experiments on different classes of materials to consider possible engineering trade-offs in strength, toughness, and ductility. The laboratory is also a frequent stop for student groups participating in outreach activities sponsored by the UMaine College of Engineering.

Collaboration with local and regional K-12 teachers will continue through the PIÆs participation in an NSF-sponsored GK-12 program, and through the PIÆs RET suppliment to a different NSF grant.

Journal Publications

Eric N. Landis, Edwin N. Nagy, Denis T. Keane, and George Nagy, "A Technique to Measure Three-Dimensional Work-of-Fracture of Concrete in Compression", Journal of Engineering Mechanics, p. 599, vol. 125, (6). Published

E. N. Landis and E. N. Nagy, "Three-dimensional work of fracture for mortar in compression", Engineering Fracture Mechanics, p. 223, vol. 65, (2000). Published

E. N. Landis, A. L. Petrell, S. Lu, and E. N. Nagy, "Examination of Pore Structure Using Three Dimensional Image Analysis of Microtomographic Data", Concrete Science and Engineering, p. 162, vol. 2, (2000). Published

E. N. Landis and L. Baillon, "Experiments to relate acoustic emission energy to fracture energy of concrete", Journal of Engineering Mechanics, p. 698, vol. 128, (2002). Published

S. Lu and E. N. Landis, "X-ray Microtomography Studies of Pore Structure and Permeability of Concrete", ACI Materials Journal, p. , vol. , ( ). Submitted

Svetlana Vasic, Ian Smith, Eric Landis, "Fracture Zone Characterization - Micromechanical Study", Wood and Fiber Science, p. 42, vol. 34, (2002). Published

Eric N. Landis, Edwin N. Nagy, and Denis T. Keane, "Microstructure and Fracture in Three Dimensions", Engineering Fracture Mechanics, p. , vol. , ( ). Accepted

Eric N. Landis, Svetlana Vasic, William G. Davids, and Perrine Parrod, "Coupled Experiments and Simulations of Microstructural Damage in Wood", Experimental Mechanics, p. , vol. , ( ). Accepted

William G. Davids, Eric N. Landis, and Svetlana Vasic, "Lattice Models for the Prediction of Load-Induced Failure and Damage in Wood", Wood and Fiber Science, p. , vol. , ( ). Submitted

S. Lu, Eric N. Landis, and Alina L. Petrell, "X-ray Microtomographic Studies of Pore Structure and Permeability", ACI Materials Journal, p. , vol. , ( ). Submitted

Books or Other One-time Publications

E. N. Landis and E. N. Nagy, "Work of Load Versus Internal Crack Growth for Mortar in
Compression", (1998). Book, Published
Editor(s): H. Mihashi and K. Rokugo
Collection: Fracture Mechanics of Concrete Structures
Bibliography: AEDIFICATIO Publishers, pp. 35-46

E. N. Landis, A. L. Petrell, and E. N. Nagy, "Examination Of Pore Structure And Durability Issues Using Three Dimensional Image Analysis
Of Microtomographic Data", (2000). conference proceedings, Published
Editor(s): J. L. Tassoulas
Collection: Proceedings of the 14th ASCE Engineering Mechanics Conference
Bibliography: ASCE, Reston, VA

E. N. Landis, "Experiments and Analysis for Beginners", (2000). conference proceedings, Published
Editor(s): J. L. Tassoulas
Collection: Proceedings of the 14th ASCE Engineering Mechanics Conference
Bibliography: ASCE, Reston, VA

E. N. Landis and D. T. Keane, "X-ray Microtomography for Fracture Studies in Cement-Based Materials", (1999). Book, Published
Editor(s): U. Bonse
Collection: Developments in X-Ray Tomography II
Bibliography: SPIE, Bellingham, WA

E. N. Landis, S. Vasic, P.
Parrod, and W. G. Davids, "Experiments and
Simulations of
Microstructural Damage in
Wood", (2001). proceedings, Published
Collection: Proceedings of the SEM
Annual Conference on
Experimental and Applied
Mechanics
Bibliography: Society for Experimental Mechanics, Bethel, CT

E. N. Landis, "Internal Structure and
Fracture in Three
Dimensions", (2001). proceedings, Published
Editor(s): R. de Borst, J. Mazars, G.
Pijaudier-Cabot, and J. G.
M. van Mier
Collection: Fracture Mechanics of
Concrete Structures
Bibliography: A. A. Balkema Publishers

Shan Lu, "Measurable Microstructural
Properties and Their
Relationship to Chloride
Migration and Durability of
Portland Cement Concrete", (2001). Thesis, Published
Bibliography: Department of Civil &
Environmental Engineering,
University of Maine

Eric N. Landis and William P.
Manion, "Concrete for Freshmen", (2002). Book, Published

Editor(s): P. Balaguru, A. Naaman, and W.
Weiss
Collection: Concrete: Material Science to
Application
Bibliography: ACI SP-206

Eric N. Landis and Lucie Baillon, "Acoustic Emission
Measurements of Fracture
Energy", (2001). Conference Proceedings, Published
Editor(s): R. de Borst, J. Mazars, G.
Pijaudier-Cabot, and J. G. M. van
Mier
Collection: Fracture Mechanics of Concrete
Structures
Bibliography: A. A. Balkema Publishers, Lisse

Eric N. Landis, "Internal Structure and Fracture in
Three Dimensions", (2001). Conference Proceedings, Published
Editor(s): R. de Borst, J. Mazars, G.
Pijaudier-Cabot, and J. G. M. van
Mier
Collection: Fracture Mechanics of Concrete
Structures
Bibliography: Balkema Publishers, Lisse

G. Nagy, T. Zhang, W. R.
Franklin, E. Landis, E. Nagy, and
D. Keane, "Volume and Surface Area
Distributions of Cracks in
Concrete", (2001). Conference proceedings, Published
Editor(s): C. Arcelli, L.P. Cordella, G.
Sanniti di Baja
Collection: Visual Form 2001
Bibliography: Springer-Verlag

Web/Internet Site

URL(s):

http://www.umeciv.maine.edu/landis/XMT

Description:

Web site describes X-ray microtomography, a part of the research component of the award.

Other Specific Products

Contributions

Contributions within Discipline:

The long-term contribution of this work is the basis it provides for developing new modeling strategies where material performance models are based on physical microstructure rather than empirically derived parameters. We are looking to push for paradigm shifts where the performance of structural materials can be predicted from physically measurable material features, rather than the simple statistical correlations, which is frequently the case with heterogeneous materials.

Contributions to Other Disciplines:

The microtomography technique that was used for a significant percentage of this work is gaining wide usage for disciplines ranging from materials science to biology. In all cases researchers are confronted by a common problem: mountains of data (in our case 2GB for a single scan!). 3D image analysis techniques, most notably the 3D connected components routine developed for this project by collaborators at Rensselaer Polytechnic Institute, is being used by other researchers facing similar data analysis problems.

Contributions to Human Resource Development:

Nearly 20 students contributed in this project as research assistants of various levels. As described in the ôTraining and Developmentö section, these students developed significant skill sets that they would not have otherwise have had the opportunity develop as a part of their regular curriculum.

Contributions to Resources for Research and Education:

The introduction of a ôrealö engineering course at the start of the undergraduate curriculum is not the norm for most programs, which typically load up on math and science the first year. However, there is a growing interest across the country in ways to introduce engineering design earlier in the curriculum. We have found this idea to be desirable, and we have developed ways to do it. Our approach can serve as one possible model for others seeking to introduce engineering courses into the first year curriculum.

Course information can be found at: http://www.umeciv.maine.edu/cie110

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Any Product

Contributions: To Any Beyond Science and Engineering

Findings

Described below are highlights of the research and educational findings established under this award. Details can be found in the references listed in the "Publications" section of the report.

Research Findings

The basis for most of the research supported by this award was the development and application of innovative experimental techniques. In the description below, the techniques are discussed, followed by results of specific experiments.

X-Ray Microtomography

X-ray microtomography is a technique to obtain high resolution three dimensional information about a material's internal structure. Hundreds of radiographs of a sample are taken at small angular increments over 180 degrees of sample rotation. A computer algorithm inverts this data to produce the 3-D absorption map. X-ray microtomography can resolve volume elements approaching 1 micron in size. This is much higher resolution than traditional CAT-scan techniques used in medical application. High resolution is obtained by combining an extremely bright x-ray source (synchrotron) with a high-resolution x-ray detector. The experiments conducted as a part of this research were conducted at the National Synchrotron Light Source (NSLS) on a beamline owned by Exxon Research and Engineering. A schematic of this facility is illustrated in Figure 1.

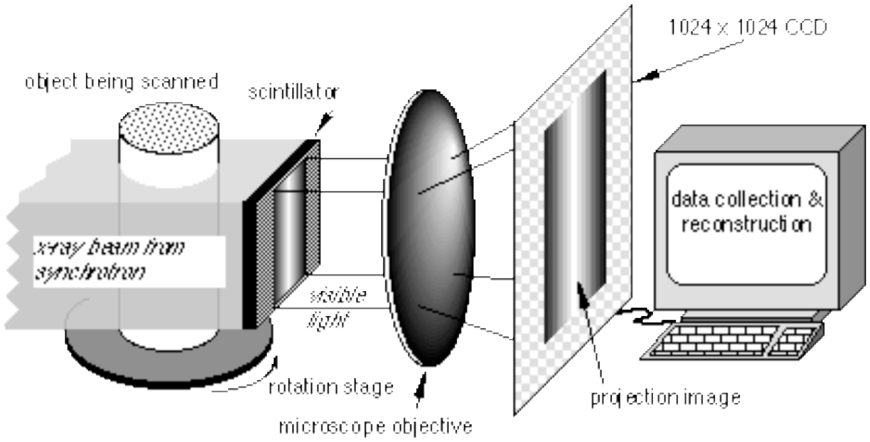


Figure 1. Illustration of experimental setup used for microtomography work.

Examples of objects scanned with the system of Figure 1 are shown in Figure 2. These images illustrate two ways to represent tomographic data. The first is the common "slice" image where data is presented as a cross sectional slice through the object. Each tomographic scan produces several hundred of these slices, each representing a different vertical position through the object. The second image was created by "stacking up" hundreds of slice images, and rendering them as a three-dimensional object using appropriate rendering software. Rendering software can typically cut away section and display whatever the user desires. In this case an uneven specimen was cut up so that only a cubic volume element within the specimen is rendered.

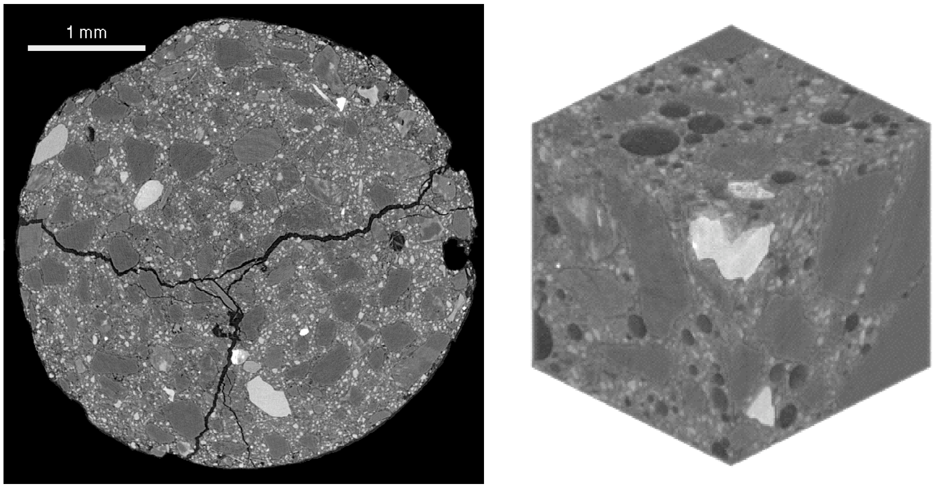


Figure 2. Example presentations of tomographic data.

3D Image Analysis

While the images of Figure 2 are useful for making qualitative observations of internal concrete structure, the real benefit is the quantitative information that can be extracted from the three dimensional data sets. This is because the tomographic data sets represent a 3D map of the material's x-ray absorption profile. The intensity of each image voxel (a voxel is a "volume element" or 3D pixel) is directly proportional to the elemental composition of the material contained in that voxel.

The type of information we wish to extract dictates the particular image analysis techniques employed. In this work we were looking at internal cracks and pore space, which may be broadly classified as void space. Therefore we can condense our problem into three steps: first, identify the void space in the images, second, determine the connectivity of that void space, and third, make measurements.

Void space was determined by simple image segmentation. A histogram of voxel intensities shows overlapping distributions of greyscale and dark sections of the image. We choose a threshold value as a minimum between these two distributions. Voxel values above that value are considered black (air), while voxel values below that are considered white (solid). This is illustrated in Figure 3.

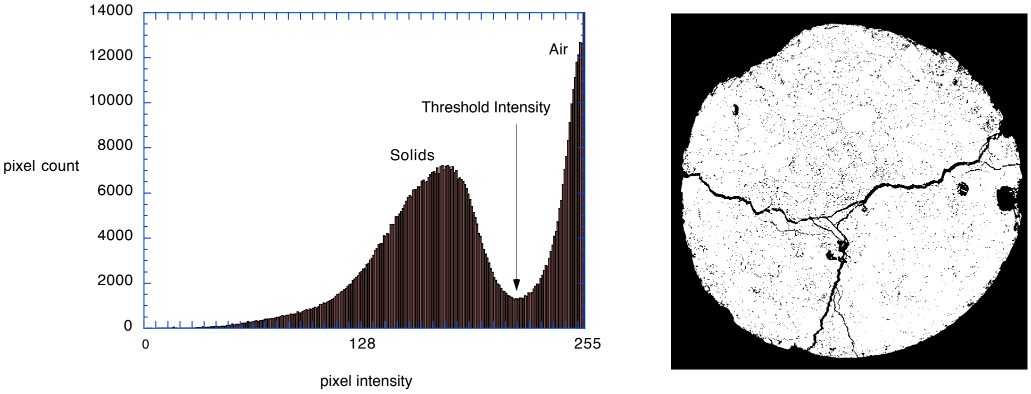


Figure 3. A pixel intensity histogram and a binary (segmented) image.

Once a body is separated into solid and air, we can analyze the connectivity of the void space using a three-dimensional connected components algorithm. This algorithm examines the image voxel by voxel and looks for adjacent voxels of the same color. If it finds them, it considers the connected voxels to be part of the same feature. Through this analysis we can identify each pore space or crack and measure its properties. In this work the properties of interest were surface area and volume.

Damage and Fracture of Concrete

Given this the microtomography and image analysis techniques, we wanted to quantify changes in internal structure that result from damage. To do that we built a small loading frame in which we could load a small specimen of concrete. The specimen would then be scanned in an undamaged state, and the repeatedly scanned after successive loading cycles as shown in Figure 4.

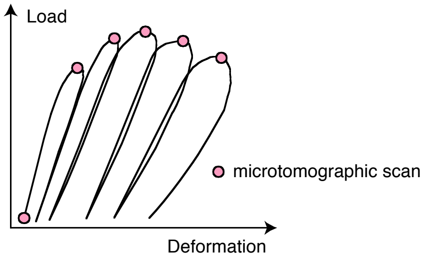


Figure 4. Loading-unloading cycles used in microtomographic studies of damage evolution.

Figure 5 shows examples of crack evolution in a specimen subjected to uniaxial compression. The images shown are in a plane perpendicular to the axis of loading. The image sequence illustrates both the formation of new cracks as well as the widening of existing cracks. Quantitatively we can see increases in crack volume and surface area.

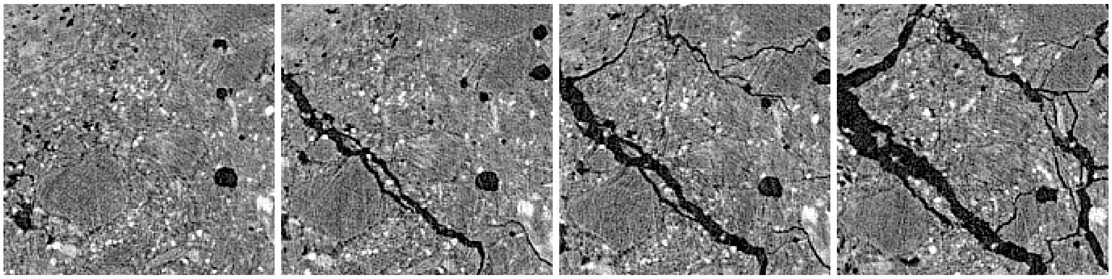


Figure 5. Microtomographic Slices at Four Different Levels of Damage

A unique fracture mechanics approach was used on the resulting data. Since we were able to make high-resolution measurements of internal crack surface area (using techniques described above), we could calculate fracture energy by relating the net work of external load to the resulting change in crack surface area. Figure 6 illustrates the cumulative work of fracture of two specimens. Several important issues are addressed by the results shown in this plot. The first is that crack initiation and crack propagation can be distinguished buy the nominally bi-linear plot. The toughening mechanisms known to work for cement-based composites are not mobilized until the cracks have grown to a certain size. From the graph it can be seen that crack initiation energy is roughly one fourth of crack propagation energy. The second issue is that although the specimen was loaded in compression, the measured fracture energies are comparable to results measured for similar materials in tension.

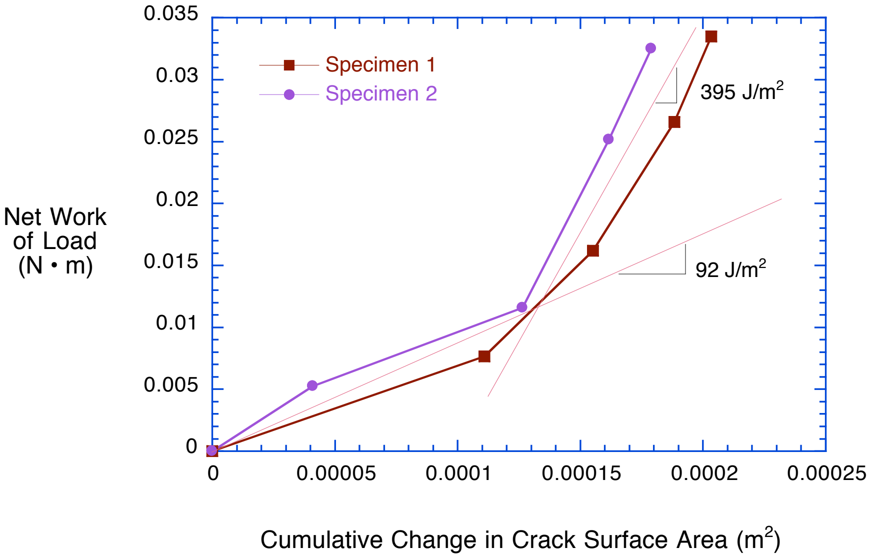


Figure 6. Work of fracture for concrete loaded in compression.

It should be emphasized that these measurements were made without any assumptions about fictitious cracks, damage zones, or any other devices to account for the nonlinearity traditionally observed in concrete fracture. The nonlinear fracture phenomena typically associated with concrete fracture can be reduced to a linear analysis when three dimensional analysis is used.

Pore Structure and Durability of Concrete

Given this powerful scanning technique (x-ray microtomography), we next applied it to problems of pore structure and the corresponding influence on chloride ingress. Pore space and pore size distribution was determined using image segmentation and 3D object connectivity analysis.
An example of the type of image analysis that can be done is shown in Figure 7 below. The figure illustrates a three-dimensional rendering of pore space in a sample of air-entrained concrete. The section is approximately 1.2 mm on a side. The pore space has been isolated and colored according to connectivity. Green indicates pore space that connects with the far left-hand specimen surface, while amber indicates the pore space that is connected to the near right-hand surface. Blue indicates pores that are not connected to the surface. “Connected” in this case means that the pore network exceeds the detectable limit of the scan, which for this example is 6 microns.

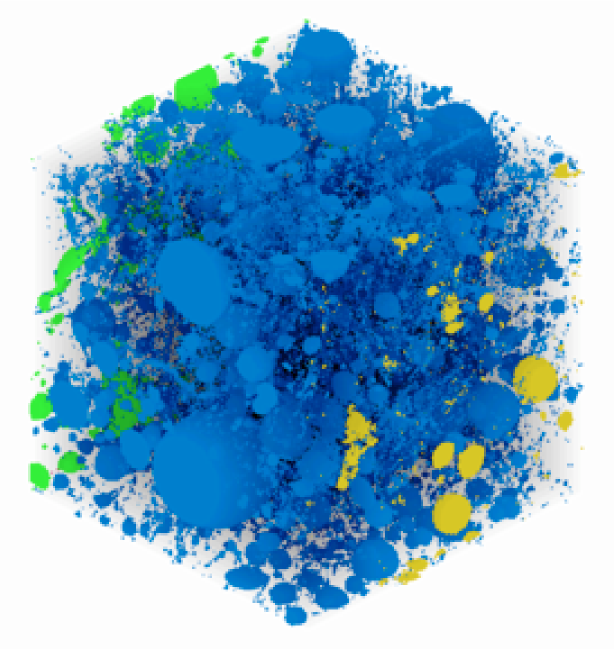


Figure 7. Three Dimensional Renderings of Concrete and Concrete Pore Network

The technique of isolating connected pore networks was applied to four different concrete mixes: a conventional normal strength concrete, and three concretes modified with different pozzolanic admixtures. The images below represent only the pore space connected with either the top or bottom surface of the cubic section. The images illustrate the substantial difference in connected pore space between conventional concrete and high performance concrete. Clearly the reference concrete has a much larger network of connected pore space in that volume. Not surprisingly when all mixes were subjected to both chloride ponding tests and rapid chloride permeability tests, as well as air permeability tests, the reference concrete showed much greater permeability than the high performance mixes. We defined what we termed "unconnected flow length" as the minimum distance between unconnected pore networks in the tomographic data. In these images we can see that the reference concrete has a very small unconnected flow length, while the silica fume and slag mixes have a large unconnected flow length. This microstructural parameter correlated well with all permeability measurements, and could be considered as a good indicator of durable concrete.

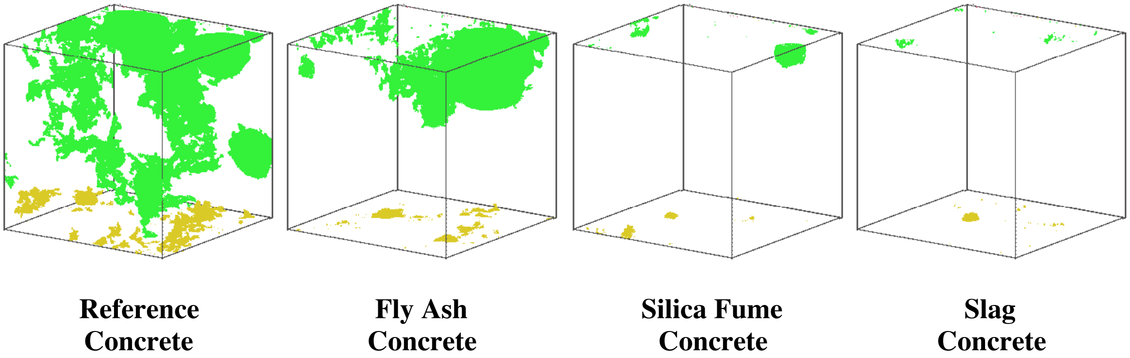


Figure 8. Isolated Pore Networks that Connect with Specimen Surfaces

Acoustic emission measurements of fracture energy

In an effort to develop an experimental technique that can be used to quantify damage accumulation in arbitrary structures, acoustic emission (AE) was used to measure energy associated with fracture of standard concrete test specimens. The goal of the work was to identify ways in which acoustic emission measurements could be used to tune damage models.

A series of mortar and concrete specimens of different compositions were tested for fracture energy, G_f while simultaneously being monitored for acoustic emission energy release. As shown in Figure 9 below, a reasonable correlation between the two quantities was observed for fine-grained specimens, however the relationship was not as good for coarse-grained specimens. Toughening mechanisms such as friction are believed to be responsible for the poor relationship observed in the course-grained materials. The results indicate that AE energy release can be related to actual crack formation energy but not to friction and other internal energy dissipation or toughening mechanisms.

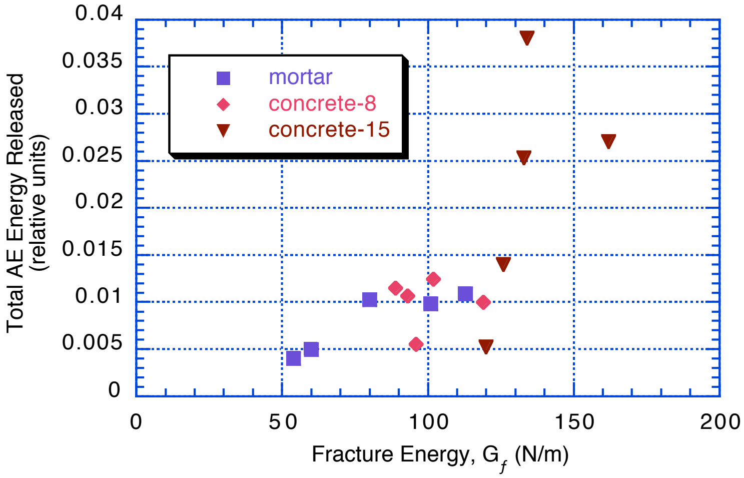


Figure 9. AE energy versus concrete fracture energy.

Damage and fracture of wood

In order for the array of experimental techniques employed and microstructural information gathered to be of any use, they must be related to engineering performance parameters. A computational modeling approach based on physical properties of the material's microstructure was developed. Because of the facilities and resources available at the University of Maine, wood was adapted as the material to demonstrate this approach, but there is no reason that the methods can't be applied to other materials.

An example of such a model is shown in Figure 10 below, where a fibrous material such as wood is represented by an array of fibrous elements bound together by a lattice of spring elements. In modeling this way we sidestep a common paradox in modeling heterogeneous materials. Traditionally the heterogeneous medium is first homogenized to average properties over a representative volume, then it is discretized to acquire a finite element solution. In the approach proposed here, the heterogeneous medium is represented as a heterogeneous medium eliminating the errors associated with both homogenization and discretization.

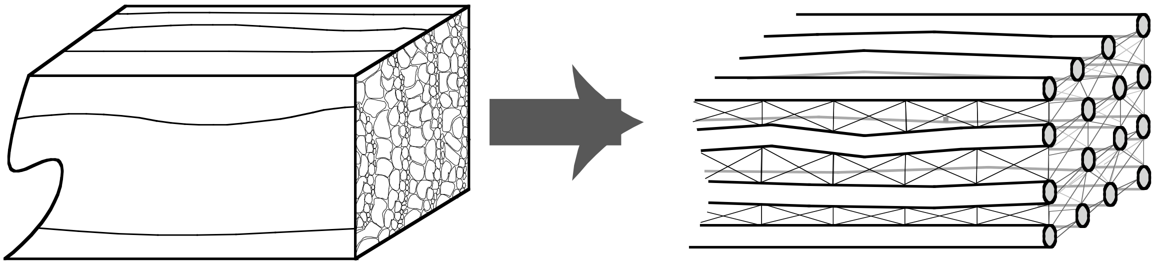
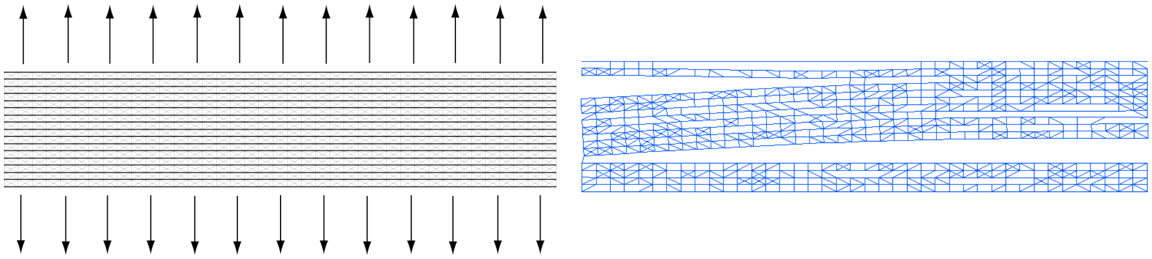


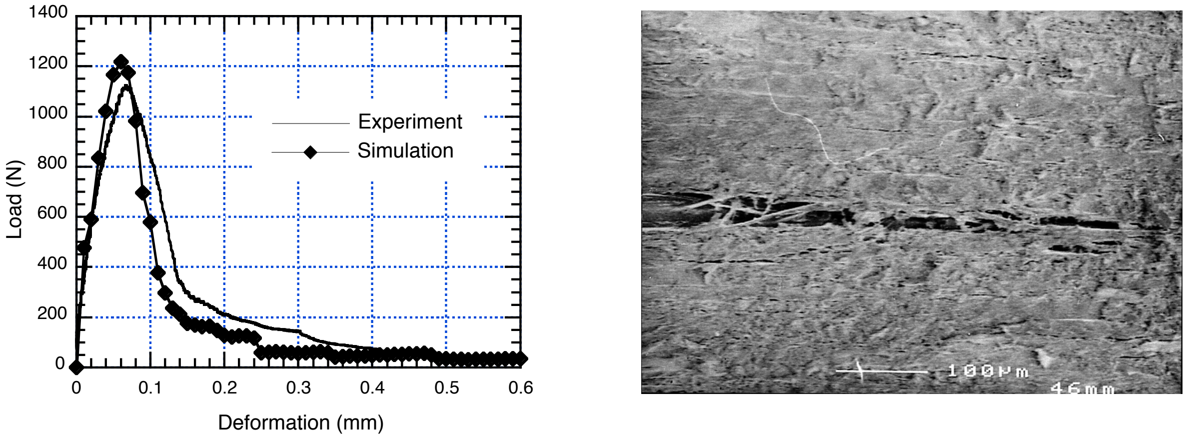
Figure 10. Illustration of a “morphology-based model”

Examples of preliminary studies is shown below. A 2D lattice representing spruce was loaded perpendicular to the grain. The figures show the preliminary lattice model is capable of predicting the both crack patterns and load-displacement curve. Removal of the failed elements simulates the microcracks that occur in the wood specimen. These microcracks further grow and at peak load localize into a single main crack. The main crack is however not continuous, because overlaps and crack face bridges of different sizes develop. At the end of the steep drop in the descending branch the crack has traversed the cross-section completely. The long tail can be explained by crack face bridging, as illustrated in the micrograph shown.



(a) Initial load

(b) Simulated damaged specimen



(c) Load-deformation response

(d) Micrograph of damaged spruce

Figure 11. Experiments and simulations of spruce loaded perpendicular to grain.

Additional simulations and experiments have been applied to a fairly wide range of stress states, from simple to complex. In each case we are able to simulate both microstructural variations and load-deformation response using a single set of model parameters. An example of the real and simulated crack patterns for a small bending specimen are shown in Figure 12. While much work is necessary before the approach can be applied to practical engineering problems, the initial results are quite promising.

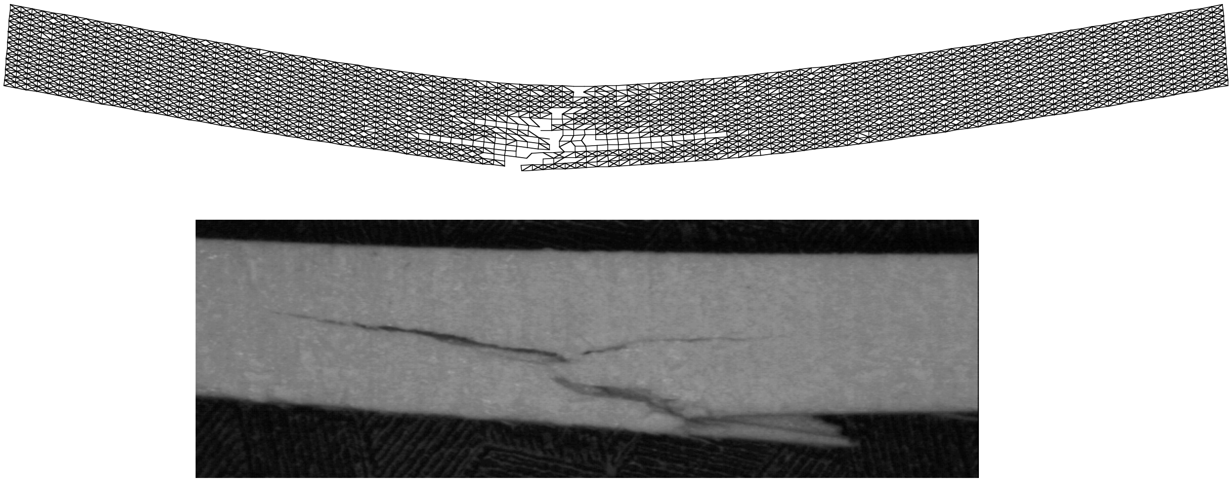


Figure 12. Spruce in bending simulated and real crack patterns.

Educational Findings

Materials Course for First Year Students

The primary educational finding is related to this award is the UMaine civil engineering course CIE 110 – Materials. This course is recommended for first semester, first year civil engineering students, and it is used as both an introduction to construction materials, but also to engineering analysis in general. The course uses issues in materials engineering as a model for general problems in engineering design and analysis, and thus covers a fairly wide range of subjects. The course is part of an overall curriculum modification intended in part to improve retention among civil engineering students during their first year or two by putting at least one required civil engineering course in each semester in the suggested curriculum.

The course being described here is typical of undergraduate construction materials courses. A three credit-hour lecture course is taken concurrently with a one credit hour laboratory session. The topics covered include structure, properties and testing of metals, portland cement concrete, wood, bituminous concrete mixtures, and composite materials. The ABET course Goals are as follows:

> The students will learn basic physical, mechanical and chemical properties of different construction materials.
>
> The students will be introduced to various tools of engineering problem solving including statistical and experimental analysis.

The ABET Course Outcomes are:

> The student will demonstrate the ability to perform a simple statistical analysis of experimental data, including fitting data to standard models, and making predictions based on those models.

The student will demonstrate understanding of stress, strain, strength, toughness, durability and fatigue, and the student will be able to perform calculations that involve those quantities.

The student will demonstrate an understanding of the role of microstructure in material properties.

The student will demonstrate an understanding of production and properties of steel, concrete, wood and wood composites, and FRP composites.

The student will be able to identify the critical design issues in material selection.

While these goals and outcomes are typical, the challenge in this course is to cover the topics in sufficient depth without the aid of traditional prerequisites such as chemistry, physics, and/or calculus.

In addition, because it is the first engineering course in which most students enroll, we try to cover as broad an array of general engineering topics as possible. These topics include the engineering design process, marginal economic analysis, probability-of-failure and safety factors. Additionally, we like to cover as many "professional engineering" issues as is practical. In the laboratory sessions we emphasize broad concepts of statistical distributions of properties, precision and accuracy. Design problems include design of concrete mixtures and sizing of structural members. Here the students must take into account technical considerations uncertainty, safety, economy, and intangibles.

Because the students do not have much basic math and science background, the availability of a suitable textbook is problematic. In lieu of a general textbook we use a large number of handouts developed by the instructor. We do require the students purchase a copy of the PCA design manual (2) as a guide for our coverage of concrete.

The unifying framework for the discussion of all materials is the general relationship between microstructure and properties. No student passes the course without recognizing microstructure as the key to modifying properties. An underlying theme is the relationship between microstructural order and performance predictability. This is done through discussions of both microstructural features, and statistical distributions of different properties.

COURSE ASSESSMENT

In terms of our ABET 2000 accreditation, we have used the course to develop student proficiency in the following areas:

Proficiency in construction materials.

Application of mathematical and physical principles.

Ability to perform civil and environmental engineering design.

Understanding of professional practice issues.

Ability to conduct laboratory experiments and to critically analyze and interpret data in the area of materials.

Ability to communicate effectively both orally and in writing.

This is a large number of outcomes, and in fact it has more outcomes than any other course in the four-year curriculum. We believe we have been reasonably successful in meeting these outcomes based on both instructor assessments and student assessments.

Meeting all these outcomes, however, does not come without some cost to the basic subject matter of materials. First, as the students do not necessarily have much background in basic math or sciences, our coverage, particularly of materials science, cannot be as deep as would be found in a junior or even sophomore level course. There is some sacrifice of chemistry and chemical properties of materials in this course. Second, as the students have not had basic courses in mechanics (statics and strength of materials) we must spend time introducing basic concepts of stress and strain, at the expense of more materials coverage. However, as the broad scope of the course extends beyond the title subject, we accept the assumption that there is an overall net gain in the undergraduate's engineering experience.

Research and Education Activities

As detailed in the proposal, this program focused on development and applications of experimental and computational tools to characterize material performance as a function of microstructure. Initial work focused on cement and concrete, while subsequent work dealt with wood and wood-based composites.

Laboratory Facilities

Equipment money from the NSF Engineering Directorate as a part of this grant was used as seed money to establish the Laboratory for Experimental Micromechanics in the Civil & Environmental Engineering Department at UMaine. The laboratory features an array of digital microscopy, NDE, and computational equipment for heterogeneous material characterization. Most of the research and research-based educational activities were conducted in this laboratory.

Personnel

A relatively diverse group of personnel worked on this project or collaborated in various aspects. Two graduate students, and nine undergraduate students were supported by this project at various times. The nine undergraduates do not include eight additional students who collaborated as a part of a series of REU sites managed by the PI (NSF #'s 9732218 and 0097500 – the latter one still in progress).

Research Activities

The research activities covered three broad categories: Damage & fracture of cement and concrete; pore structure and permeability of concrete; and damage & fracture of wood and wood composites.

Damage and Fracture of Concrete

This work was the primary focus of the first two years of the project. Microtomographic scans of small concrete (mortar) specimens under load allowed us to make unique quantitative measurements of damage and fracture progression. As detailed in the "Results" section, a technique was developed to measure internal damage from the 3D data sets. These measurements allowed us to verify some previously held views of different toughening mechanisms, while challenging others. The long-term contribution of this work is the basis it provides for developing new modeling paradigms where material performance models are based on physical microstructure rather than empirically derived parameters.

Additional related work involved the application of acoustic emission (AE) techniques to independently monitor fracture energy of a specimen subjected to a common concrete fracture test. The goal was to develop a technique that could be used to quantify internal damage for arbitrary stress states. The work was conducted in collaboration with researchers at the Swiss Federal Institute of Technology in Lausanne.

Durability of Concrete

This work was the primary focus of the third year of the project, and was conducted with contributing funds from the Maine Department of Transportation. The work focused on relating measurable microstructural features to standard tests for chloride permeability. Quantitative 3D image analysis was done on microtomographic data of four different types of concrete (normal strength, fly ash enhanced, silica fume enhanced, and slag enhanced) that were also subjected to both ponding tests and rapid chloride permeability tests. Through the image analysis we were able to isolate the pore network (greater than 1 micron) that connects to the surface. This network represents the preferential path for ingress of chloride ions and other solutes.

Damage and fracture of wood

This work was the primary focus of the fourth year of the project. It involved a tight integration of micromechanical experiments with computational modeling, and it represents the next logical step in the research relating microstructural observations to bulk properties. We applied lattice-based models in an attempt to simultaneously capture *both* load-deformation response of materials *and* corresponding microstructural changes. The lattice model consists of an array of small beam elements that represent bundles of wood fibers, and an array of connecting spring elements.

Educational Activities

While the educational activities were tightly integrated with the research activities, it is separated here for sake of clarity. The primary educational activities included development of a first semester/first year course in civil engineering materials, development of a graduate course in experimental mechanics, high school and junior high school demonstration modules, and materials modules for undergraduate reinforced concrete design.

First year course in Civil Engineering Materials

The civil engineering course taught first semester freshman year continues to be refined to cover the broad range of both academic and professional issues we wish to introduce to our students early on. A manuscript to serve as the course textbook was prepared, and is continually being refined (with help from students), and the lab sessions are being balanced between illustration of basic concepts with simple experiments with the incorporation of more high tech lab tools. The labs have been developed such that both lab manuals and lab notebooks are computer based for easily updating and data sharing.

Graduate course in Experimental Mechanics

The graduate course “Experimental Analysis of Structures” was developed to reflect latest measurement technologies in both small and large scale testing, including the technologies developed in the research portion of this project.

K-12 Outreach

Several demonstration modules were developed for use with local schools with students of various levels. These include a shake table demonstration of seismic loads on buildings (along with instrumentation to illustrate analysis techniques), a discussion of the historical development of materials, mechanics, and structures. Demonstrations were made at a local elementary school, and a local high school. Interaction with local K-12 school teachers will continue through an RET supplement to another NSF grant, and through the PI’s participation in a GK-12 program in UMaine’s College of Engineering.

Modules in Reinforced Concrete Design

A module (two lectures and a lab session) on concrete materials issues in reinforced concrete design was implemented two successive years. The goal was to introduce students to the innovations in concrete technology that will be working their way into codes in the coming years. Particularly, the developments in high performance concrete and the responsible microstructural changes, and how those changes might influence structural design codes were discussed.