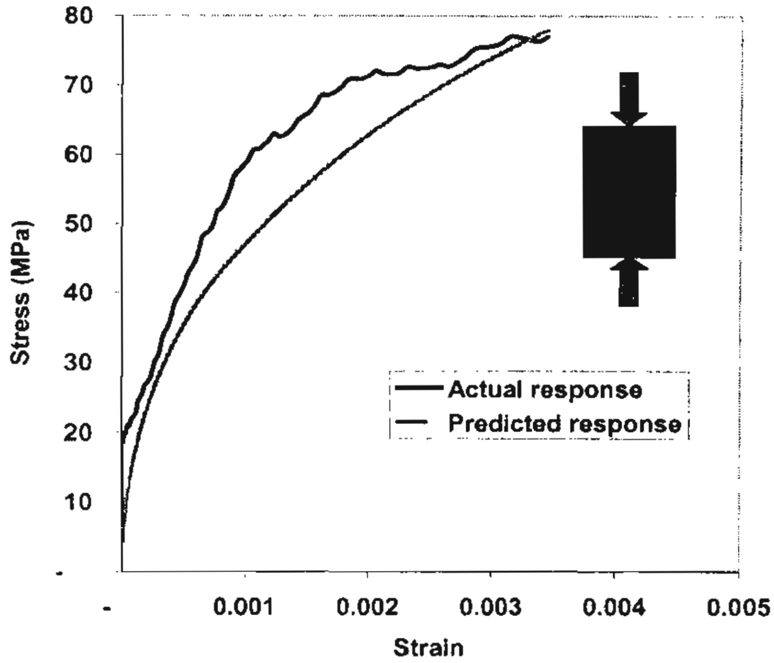

Fig. 4.9 Actual and Predicted Response of Plain Concrete under Impact Compressive Loading at 500mm Drop Height (Impact Energy of 2835 J)

4.2.4 Impact strength prediction

When the ultimate strength is the only concern, it can be determined using CDM together with the relationship between impact/static strength derived from the test results. The impact/static strength ratio of concrete is related to the strain rate by the following expression.

$$\frac{\sigma_c^{'}(imp)}{\sigma_c^{'}(st)} = e^{k(\dot{\varepsilon})} \tag{4.16}$$

where $\sigma_c^{'}(imp)$ = impact strength (MPa)

$\sigma_c^{'}(st)$ = static strength (MPa)

$\frac{\sigma_c^{'}(imp)}{\sigma_c^{'}(st)}$ = impact/static strength ratio

$\dot{\varepsilon}$ = strain rate (1/sec)

k = material constant (0.17-0.26)

From the test results, the strain rate of plain concrete was in the range of 1.38 to 2.96 sec^{-1} for hammer drop heights of 250 and 500mm. The material constant, k, was found to depend on the type of material. The suggested k-values obtained from this study are: k = 0.26 for plain concrete, and k = 0.23-0.26 for 0.5%FRC, depending on the type of fibre.

Replacing stress (σ) with strength ($\sigma_c^{'}$) in Eq. 4.10, and then substituting it into 4.12, yields the impact strength of the material under high strain rate.

$$\sigma_c^{'}(impact) = e^{k(\dot{\varepsilon})} E_{\text{int}} (1 - D_{ult}) \varepsilon_c^{'} \qquad (4.17)$$

Predicted strengths obtained from 4.16 is plotted against the actual strengths in Fig. 4.10. It may be seen that the strengths obtained from Eq. 4.16 are quite close to the actual strengths obtained.

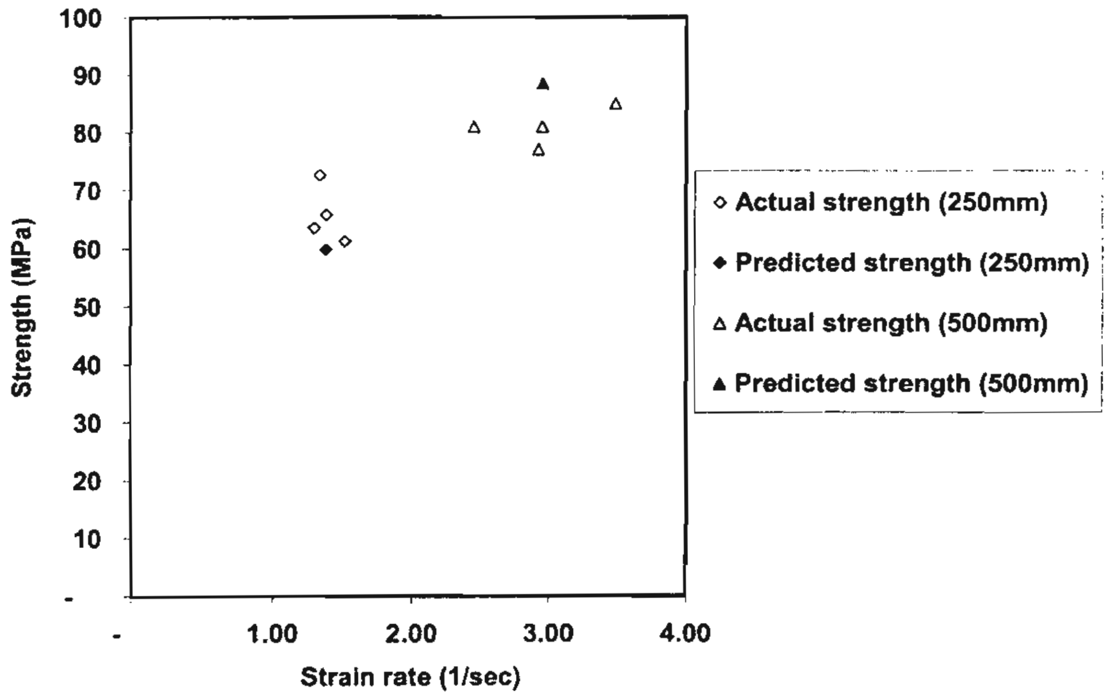

Fig. 4.10 Predicted Impact Strength of Unconfined Plain Concrete

Chapter 5
Conclusions

1. In general, the static behavior of concretes loaded in compression quite typical in terms of the increase in peak load with deflection, the occurrence of linear and non-linearity and so on. Even under impact loading, the typical response of plain concrete is not changed much from its static response; a "single peak" response was found in plain concrete tested under compression. Except that under impact loading, the increase in energy absorption of concrete as well as strength and ultimate strain is observed, though to different degrees (depending on impact velocity). In most cases, the concrete is a rate sensitivity material.

2. The value of damage of concrete at peak load (measured using the methods described here) was found to be around 0.65, 0.85 and 0.95 for concrete subjected to static, impact at 250mm and impact at 500mm, respectively. The change of damage with rate of lading indicated that the damage of concrete at peak is also a loading rate dependent. With increase rate of loading, the appearance damage at peak increase progressively.

3. Scalar damage mechanics (SDM) is a promising approach to predict the pre-peak response of concrete under both static and impact loading. There are several ways to approach the damage of loaded concrete. Under static loading, when the actual test result is available, the degradation of elastic modulus seems to be the best approach. The strain rate variation is more appropriate in the case of impact loading.

4. In all cases, the predicted responses seem to under-predict the actual response. The lack and the ignorance of the information at microstructure level during the loading process are believed to be a cause of that phenomenon.

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1. Newman, K, "Criteria for the Behavior of Plain Concrete under Complex States of Stress," The Structure of Concrete and Its Behavior under Load, Proceedings of an International Conference", pp. 255-274, 1965.

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Output

1. บทความวิจัยจำนวน 2 บทความ เพื่อจะได้ทำการจัดส่งตีพิมพ์ในวารสารวิชาการนานาชาติและงานประชุมวิชาการนานาชาติอย่างละหนึ่งบทความ ในหัวข้อเรื่อง

1.1 <u>Scalar Damage Mechanic Model to Predict a Pre-Peak Compressive Stress-Strain Relationship of Concrete</u> By Piti Sukontasukkul, Pichai Nimityongskul, and Sidney Mindess

1.2

2. ผลงานที่ได้นำไปใช้ประกอบการสอนในวิชาระดับปริญญาโท Advanced Concrete Technology และปริญญาตรี Concrete Technology

Appendix A

Damage of Concrete Subjected to Impact Loading Obtained using the Variations of E

Consider the case where the degradation of E was used as a damage measurement parameter, using the obtained test results, the value of E_{int} and E_{sec} were determined and plotted against the corresponding strains.

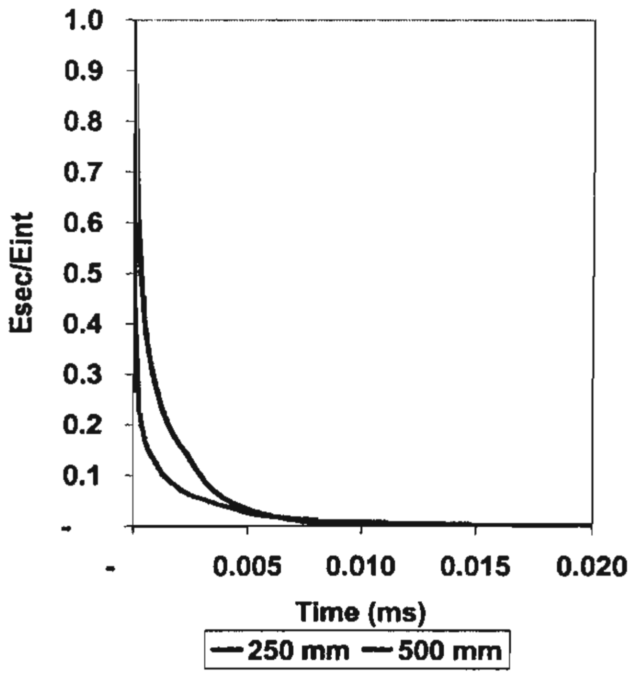

Fig. A1 Absolute E (Esec/Eint) vs Strain

Results from Fig. A1 indicated that the degradation rate of E was faster with increasing impact velocity (i.e., energy). At the initial (undamaged) stage, the E_{sec} was essentially the same as E_{int}. However, with increasing load and deformation, the damage began to build up, cracks started to form and propagate. The specimen continued to disintegrate and loss its stiffness. As a result, the value of E decreased at dramatic rate.

At faster impact velocity (500 mm drop height), cracks were formed and forced to propagate at faster rate, the disintegration of specimen was faster and so did the lost in stiffness, this led the quicker decay rate of E as seen in Fig. A1.

Once E_{int} and E_{sec} already determined, the damage can simply be obtained using the procedure described in 4.1.1. Results were plotted in Fig. A2.

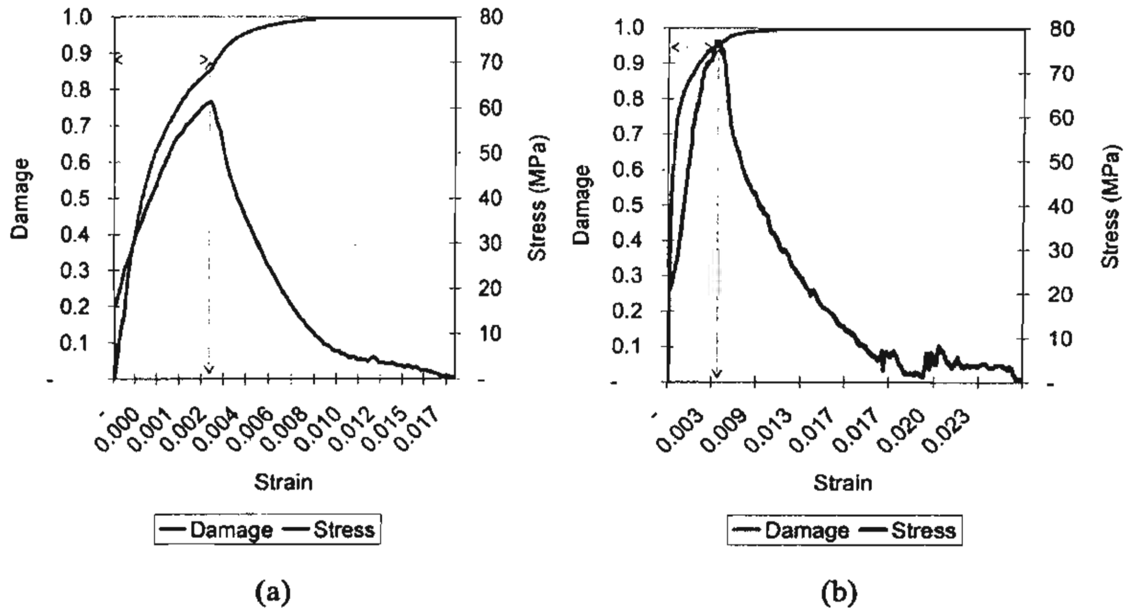

Fig. A2 Relationship between Damage (E) and Strain for Concrete Subjected to Impact Loading at (a) 250 mm and (b) 500 mm Drop Height

At initial stage, undamaged specimen exhibited zero value of D, and then with increasing stress (i.e., strain), the damage started to increase. Prior to the peak, the increasing rate of D was quite fast and almost proportional to the increase rate of stress and strain. The rate of increase was slow down after the peak.

At the peak, the values of D increased to nearly equal to one in both drop heights (0.855 and 0.952, respectively). The large value of D at the peak indicated that the specimen was, in fact, already in the state of high damage and almost corrupted (or fractured). After the peak, the strain energy was large and sufficiently enough to cause crack self-propagation, hence without any further apply load, the damage of the specimen kept on increasing to the value of one.

Similar to the variations of strain rate approach, the value of damage was also affected by the impact velocity. The increasing drop height increased the level of damage in specimen at every corresponding strain.

Appendix B
Manuscripts

Two manuscripts were prepared and ready to be send out for publication. The first paper will be submitted to Canadian Journal of Civil Engineering and the second paper will be Cement and Concrete Composites Journal.

SCALAR DAMAGE MECHANIC MODEL TO PREDICT A PRE-PEAK COMPRESSIVE STRESS-STRAIN RELATIONSHIP OF CONCRETE

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Sidney Mindess

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Abstract

In this study, the theory of scalar continuum damage mechanics is used to predict the pre-peak behavior of concrete under static compressive loading conditions. The modeling begins with the determination of a damage-strain (D-ε) relationship for loaded unconfined concrete based on the actual damage. The actual damage is measured directly from the test results and is expressed in terms of the degradation of the initial E. A comparison between the proposed model and other models is also made. The results indicate that the response obtained from the model proposed here agrees well with the actual response.

1. Introduction

The deformation of materials under load depends on factors such as atomic structure, composition, rate of loading and temperature. In order to understand the deformation characteristics of each individual material completely, an extensive knowledge of its atomic and molecular structure is required. However, in practice, the general constitutive equations of the continuum model (load-deformation relationship) are described without considering the complexity of atomic structure of the real material using variables such as stress, strain and elastic modulus. Under applied loads, the material structure eventually begins to disintegrate and the load carrying capacity is reduced. The state of deterioration of a material was characterized by Kachanov (3) using a dimensionless, scalar variable denoted as damage (D).

Lemaitre (4) also stated that the damage of a material is the progressive physical process by which its breaks. All materials, despite of their composition and structure, show typical behaviours such as: elastic behavior, yielding, plastic or pseudo-plastic strain, damage by monotonic loading or fatigue, and crack growth under static or dynamic loading. This suggests that the properties common to all materials can somehow be explained using the same theory. This is the main reason why it is possible to study material behavior at the meso-scale using the mechanics of continuous media, which can explain the behavior of the material without considering in detail the complexity of the microstructure.

This study is divided into 2 parts. The experimental part consists of casting and testing concrete cylinders under static loading. The modeling part consisted of reviewing the theory of damage mechanics, determining the damage of concrete from the actual test results, creating the model and followed by the comparison with the actual responses.

2. Experimental Program

2.1 Specimen Preparation

The specimens were cast using the following materials:

Cement:	CSA Type 10 Normal Portland Cement (ASTM Type I)
Fine aggregates:	Clean river sand with a fineness modulus of about 2.7
Coarse aggregates:	Gravel with a 10 mm maximum size

The mix proportions shown in Table 2.1 were used.

Table 2.1 Mix Proportions, by weight

Cement	Water	Fine Agg.	Coarse Agg.
1	0.5	2	2.5

Concrete with mix proportion above was prepared in the form of cylinder (Dia-100 x 200 mm.). Prior to the mix, the water content in sand and aggregates was determined to adjust the amount of mixing water. The concrete was mixed using a pan type mixer, placed in oiled steel molds in three layers, then roughly compacted each layer with a shovel before being covered with polyethylene sheets. After 24 hours, the specimens were demoulded and transferred to storage in a water tank for 30 days.

All static tests were carried out at the Department of Civil Engineering, King Mongkut's Institute of Technology-North Bangkok (KMITNB) using a 1500 kN universal testing machine[Ψ] (Fig. 1). Specimens were placed at the center of the machine. The data were collected by a PC-based data acquisition system.

[Ψ] Instron 'Fast-Track 8800'

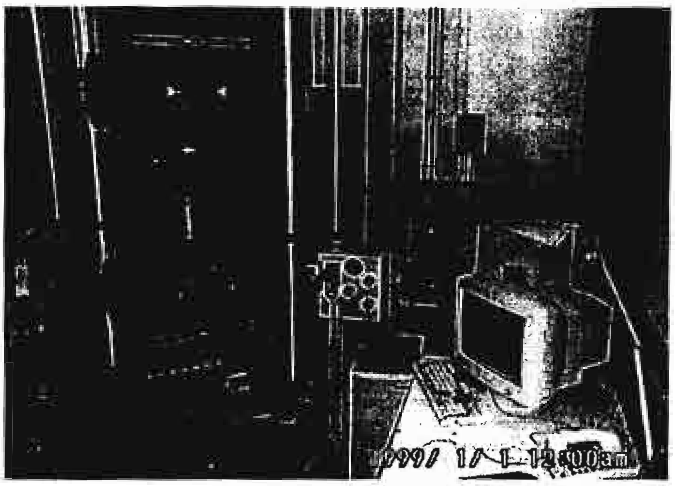

Fig. 1 Universal testing machine

2.2 Test Results

The typical failures modes of concrete specimens under static loading are shown in Fig. 2. Since the tests were carried out using steel loading platens with a relatively high frictional restraint at the contact surface between the loading platens and the specimen, the plain concrete specimens clearly showed an "hour glass (101) or "shear-cone (119)" failure mode (Fig. 2).

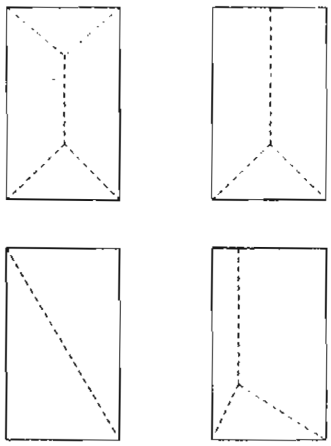

Fig. 2 Failure Patterns of Concrete under Static Compressive Loading

For concrete subjected to uniaxial compression in a machine in which there is significant and friction on the specimens due to the stiff steel platens on the top and bottom, a triaxial state of stress occurs near the contact zones which is in turn due to the differences in Poisson's ratio between the steel ($\nu = 0.33$) and the concrete ($\nu = 0.20$). This end restraint "strengthens" the specimen ends, leading to failure initiating near the mid-height of the specimen. This results in the typical shear-cone type of failure, as was found in this study. Two main diagonal cracks initiate, intersecting at the mid-height of the specimen. Fewer (but longer) cracks are found.

The typical stress-strain responses of concrete cylinders subjected to short-term static loading are shown in Fig. 3. It was found that the linear portion of the $\sigma - \varepsilon$ curve extended up to about 40-60% of peak load. Although a small amount of creep or other non-linearity might occur in this linear portion, the deformation was essentially recoverable. At about 80-95% of the peak load, internal disruption began to occur, and small cracks might appear on the outer surface. These small cracks continued to propagate and interconnect until the specimen was completely fractured into several separate pieces. The formation and coalescence of the small cracks has long been recognized as the prime cause of fracture and failure of concrete, and of the marked non-linearity of the stress-strain curve (1). The deformation associated with cracks is completely irrecoverable, and may in some cases be considered as a quasi-plastic deformation. The load (or stress) at which the cracking became severe enough to cause a distinct non-linearity in the $\sigma - \varepsilon$ curve is often referred to as the point of "discontinuity" (2). At the peak load, the failure of concrete occurred in catastrophic manner, due to the large amount of energy that was released from the testing machine; thus, the full descending branch of the $\sigma - \varepsilon$ curve could not be obtained.

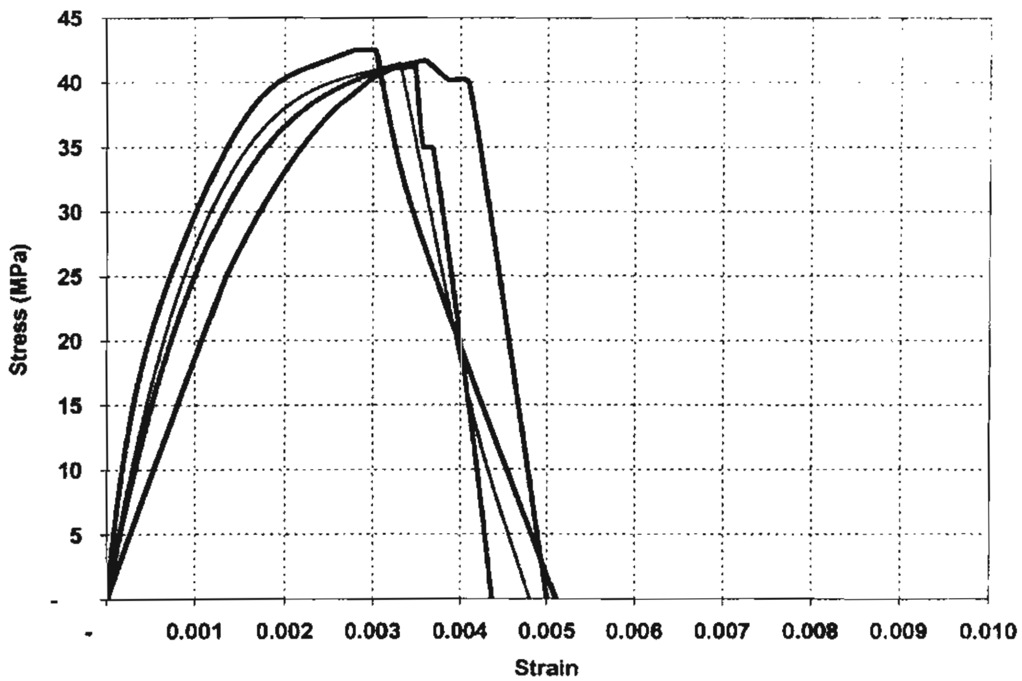

Fig. 3 Responses of concrete subjected to static loading

3. Modeling Process

3.1 Review: The Theory Damage Mechanics

Consider a damaged body (an apple) and a Representative Volume Element (RVE (4)) at a point M oriented in a plane defined by its normal $\vec{n}$ and its abscissa x along the direction $\vec{n}$ (Fig. 4). If δA represents the cross-sectional area of the RVE and δA_d represent the area of microvoids or microcracks that lie in δA, the value of damage, D(M, $\vec{n}$), is:

$$D(M,\vec{n}) = \frac{\delta A_d}{\delta A} \tag{1}$$

From the above expression, it is clear that the value of the scalar variable D is bounded by 0 and 1:

$$0 \le D \le 1 \tag{2}$$

where D = 0 corresponds to the intact or undamaged RVE

D = 1 corresponds to the completely fractured RVE

In the case of a simple one-dimensional homogeneous material, eq. 1 is simplified to:

$$D = \frac{A_d}{A} \tag{3}$$

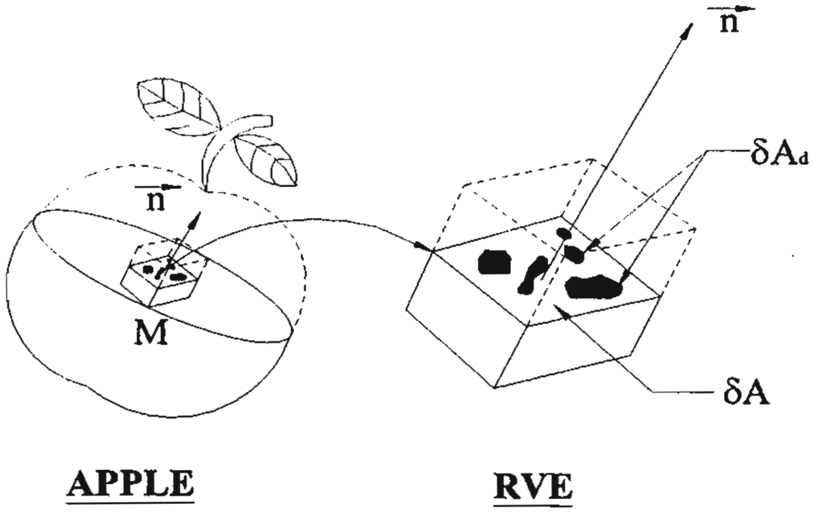

Fig. 4 A Damaged Body and RVE, after Lemaitre (4)

For an RVE with a cross-sectional area of A and loaded by a force F, the uniaxial stress (σ) is:

$$\sigma = \frac{F}{A} \tag{4}$$

If the cracked area on the representative surface of the RVE is A_d, then the effective cross-sectional area becomes $A-A_d$ and the effective stress (σ_{eff}) is:

$$\sigma_{eff} = \frac{F}{A - A_d} \tag{5}$$

Substituting the damage variable (D) from 3 into 5 yields,

$$\sigma_{eff} = \frac{F}{A(1 - A_{eff})} \quad \text{or} \quad \sigma_{eff} = \frac{\sigma}{1 - D} \tag{6}$$

Combining Eq. 7 with Hooke's law, the relationship between strain (ε_e) and damage can be derived as follow:

$$\varepsilon_e = \frac{\sigma}{E(1 - D)} \tag{8}$$

where E is the elastic modulus of the undamaged material.

The elastic modulus of the damaged material or the effective elastic modulus (E_{eff}) is then defined as:

$$E_{eff} = E(1 - D) \tag{9}$$

Rewritten Eq. 9 obtains,

$$D = 1 - \frac{E_{eff}}{E} \tag{10}$$

3.2 Proposed Model

The modeling begins with the determination of a damage-strain (D-ε) relationship for loaded unconfined concrete based on the actual damage. The actual damage for the static case is measured directly from the test results using the procedure described next, and is expressed in terms of the degradation of the initial E. The results indicate that the response obtained from the model proposed here agrees well with the actual response.

This section describes the use of CDM to predict the response of concrete under static compressive loading. For a brittle material such as concrete, a modification of equation 3.10 is necessary to make it more suitable. In ductile materials, E_{eff} is basically the change of E with respect to strain (or damage) after the loading goes beyond the linear stage and enters the plastic region (Fig. 5a). However, for plain concrete, the response is different; after reaching peak load, failure occurs abruptly (Fig. 5b). Therefore, to use CDM in concrete, the undamaged E is replaced by the initial E (E_{int}), while for the damaged E (E_{eff}), the secant E is used instead. Eq. 10 is then rewritten as:

$$D = 1 - \frac{E_{sec}}{E_{int}} \tag{11}$$

The damage curve obtained from the test results can be assumed to have the following form:

$$D = A\ln(\varepsilon) + B \tag{12}$$

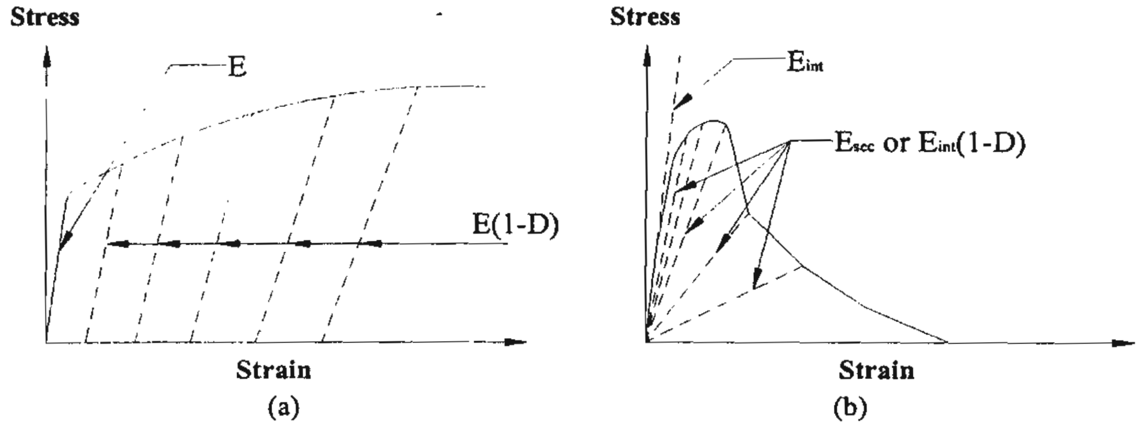

Fig. 5 Measurement of E for (a) Ductile Material and (b) Brittle Material

Applying the following conditions: at D = 0, $\varepsilon = \varepsilon_0$ and at D = D_{ult}, $\varepsilon = \varepsilon_c^{'}$, yields:

$$0 = A\ln(\varepsilon_0) + B \tag{13}$$

$$D_{ult} = A\ln(\varepsilon_c^{'}) + B \tag{14}$$

From Eq. 13,

$$B = -A\ln(\varepsilon_0) \tag{15}$$

Substituting Eq. 15 into Eq. 14, and solving for A:

$$A = \frac{D_{ult}}{\ln(\varepsilon_c^{'}/\varepsilon_0)} \tag{16}$$

Substituting A in to Eq. 4.5, one obtains B equal to:

$$B = \frac{-D_{ult}}{\ln(\varepsilon_c^{'}/\varepsilon_0)}\ln\varepsilon_0 \tag{17}$$

where D is the damage

ε_0 is the assumed initial strain (>0)

D_{ult} is the damage at peak load

$\varepsilon_c^{'}$ is the strain at peak load

D_{ult} is the damage value at the peak and can be obtained directly from the test results.

For the elastic modulus degradation, D_{ult} is equal to $1 - E_c/E_{\text{int}}$ where E_c is the secant modulus at peak load and E_{int} is the initial modulus. Substituting D_{ult} into Eqs. 16 and 17, A and B can be rewritten as:

$$A = \frac{1 - E_c/E_{\text{int}}}{\ln\left(\varepsilon_c^{'}/\varepsilon_0\right)} \tag{18}$$

$$B = \frac{E_c/E_{\text{int}} - 1}{\ln\left(\varepsilon_c^{'}/\varepsilon_0\right)} \ln \varepsilon_0 \tag{19}$$

To obtain A and B, the secant modulus at peak load (E_c), the initial modulus (E_{int}), the strength ($f_c^{'}$) and the strain at peak ($\varepsilon_c^{'}$) must be known. These values are quite easy to obtain as they are well documented in the literature or can be obtained directly from experiments. After obtaining the corresponding damage (D) for any strain, the stress can then be determined as:

$$\sigma = E_{\text{int}}(1 - D)\varepsilon \tag{20}$$

3.3 Obtained Damage

The damage obtained by Eq. 11 was plotted against the stress Fig. 6, it may be seen that the damage of plain concrete can be represented by a nonlinear curve up to the peak and a linear curve after the peak (as it increases nonlinearly with strain from 0.0 up to 0.65 when it begins to slow down and, right after the peak strain, it forms another straight line).

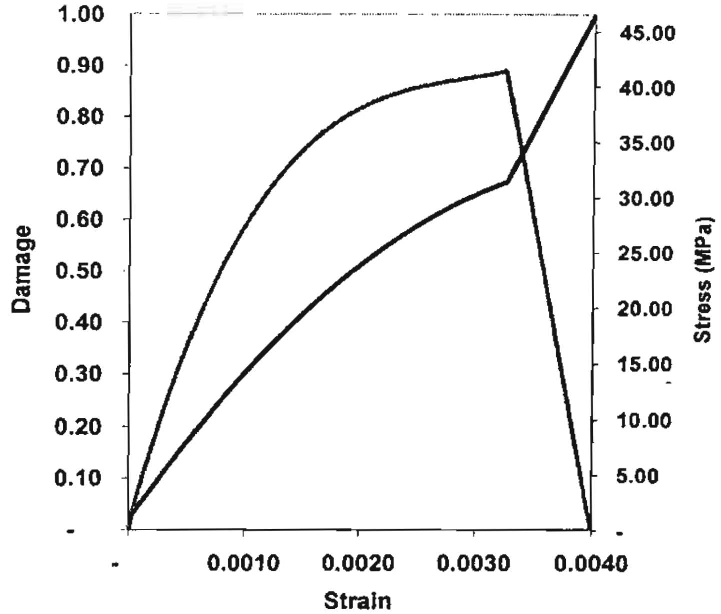

Fig. 6 Damage of Concrete Subjected to Static Loading

The damage of plain concrete under static loading was found to be around 0.65 at the peak load. Upon the fracture (at peak), because of the brittleness, the amount of energy in the machine was released immediately, this resulted in a sudden and catastrophic failure. The catastrophic failure also led to a quick increase of damage up to 1 without loading.

3.4 Predicted Response vs Actual Response

To predict the response, the following values were assumed (based on actual experimental results):

$$E_{int} = 35.4 \text{ GPa}, \; f_c^{'} = 41.6 \text{ MPa and } \varepsilon_c^{'} = 0.0036$$

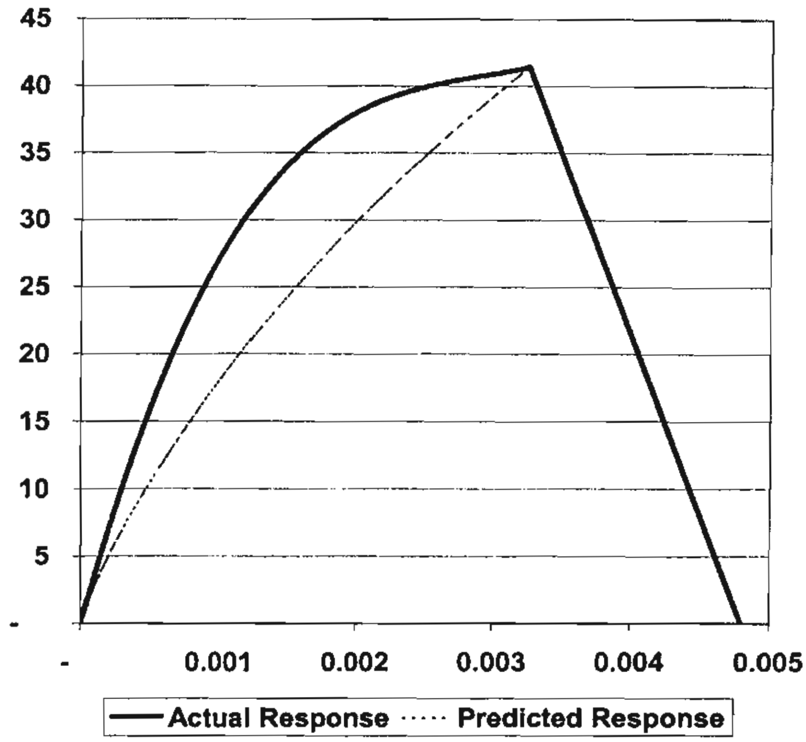

Fig. 4.3 Actual and Predicted Response of Concrete Subjected to Static Loading

The c omparison b etween the actual responses and the predicted responses w ere given in Fig. 4.3. From Fig. 4.3, it may be seen that the damage of plain concrete can be represented by a nonlinear curve, as it increases linearly with strain from 0.0 up to 0.001 when it begins to slow down and then turns into a nonlinear line. The proposed model gave a slightly lower value in the middle of the loading event; however, the overall prediction was in fair agreement with the actual response. The under-prediction of the values in the middle is believed to cause by the complexity in the occurrence of micro-cracks which is essentially ignored by the theory of damage mechanics.

4. Conclusions

- The level of damage of concrete at peak load (obtained using the degradation of E approach) was found to be around 65% for concrete subjected to static loading. Beyond this point the damage of concrete increase to one without any further apply load.

- Scalar damage mechanics (SDM) is a promising approach to predict the pre-peak response of concrete under static loading. There are several ways to approach the damage of loaded concrete. Under static loading, when the actual test result is available, the degradation of elastic modulus seems to be the best approach.

- In all cases, the overall predicted responses agree somewhat fairly to the actual response. However, the proposed model seems to under-predict the response in the middle range. The lack and the ignorance of the information at microstructure level during the loading process are believed to be a cause of that phenomenon.

5. Acknowledgement

Authors would like to thank the Ministry of University Affairs and the Thailand Research Fund (TRF) for financially support this study.

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EFFECT OF LOADING RATE ON DAMAGE OF CONCRETE

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Abstract

In this study, the theory of damage mechanics were used directly to determine the damage of concrete subjected to static and impact compressive loadings. Two approaches based on the variations of parameters like 1) Elastic modulus (E) and 2) Strain rate ($\dot{\varepsilon}$), were used. Results from both approaches indicated that the damage concrete at peak depended mainly on the rate of loading as it increased with increasing loading rate. The specimens subjected to impact loading were found to suffer higher damage than those subjected static loading as seen by the larger value of D at peak load (0.8-0.9 for concrete subjected to impact loading and 0.65 for concrete subjected to static loading). Beyond the peak, the strain energy was sufficiently enough to cause the damage to increase to one (D=1) without any further applied load.

1. Introduction

Damage of concrete subjected to loadings can be measured in several ways. One approach is to use the theory of scalar continuum damage mechanics (SCDM). For a given set of test results, the damage can be determined directly using SCDM by means of measuring the variations of parameters such as, the elastic modulus (E), energy, microhardness, density, and the strain rate.

In this study, the variations of two parameters: 1) E and 2) strain rate are introduced and used to determine the damage (D_i) of concrete subjected to static and impact loadings. Results were compared and discussed in terms of the differences on each approach and the effect of loading rate on the damage level.

2. Theory of Damage Mechanics (1,2)

Briefly, the deformation of materials under load depends on factors such as atomic structure, composition, rate of loading and temperature. In order to understand the deformation characteristics of each individual material completely, an extensive knowledge of its atomic and molecular structure is required. However, in practice, the general constitutive equations of the continuum model (load-deformation relationship) are described without considering the complexity of atomic structure of the real material using variables such as stress, strain and elastic modulus. Under applied loads, the material structure eventually begins to disintegrate and the load carrying capacity is reduced. The state of deterioration of a material was characterized by Kachanov (1) using a dimensionless, scalar variable denoted as damage (D).

To define Damage (D), let consider a damaged body (Fig. 1), if δA represents the cross-sectional area of the body and δA_d represent the area of microvoids or microcracks that lie in δA, the value of damage, D (M, $\vec{n}$) can be defined as:

$$D(M,\vec{n}) = \frac{\delta A_d}{\delta A} \tag{1}$$

From the above expression, it is clear that the value of the scalar variable D is bounded by 0 and 1:

$$0 \le D \le 1 \tag{2}$$

where D = 0 corresponds to the intact or undamaged body

D = 1 corresponds to the completely fractured body

In the case of a simple one-dimensional homogeneous material, Eq. 1 is simplified to:

$$D = \frac{A_d}{A} \tag{3}$$

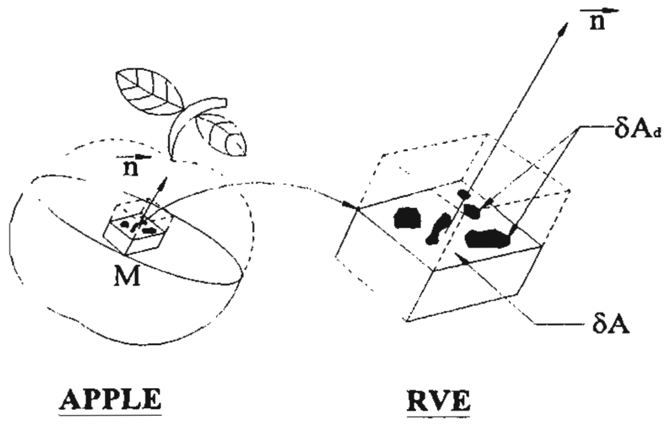

Fig. 1 A Damaged Body and RVE, after Lemaitre (2)

Variations of E Approach

For any ductile material, the damage can be determined using the variations (degradation) of E as

$$D = 1 - \frac{E_{eff}}{E} \qquad (4)$$

For a given load-deflection curve, Eq. 4 can be used to determine the damage of a loaded body.

However, in the case of a brittle material such as concrete, a modification of equation 4 is necessary to make it more suitable. In ductile materials, E_{eff} is basically the change of E with respect to strain (or damage) after the loading goes beyond the linear stage and enters the plastic region (Fig. 2a). However, for a brittle material like plain concrete, the response is quite different; after reaching peak load, failure occurs abruptly (Fig. 2b). Therefore, to use CDM in concrete, the undamaged E is replaced by the initial E (E_{int}), while for the damaged E (E_{eff}), the secant E is used instead. Eq.4 is then rewritten as:

$$D_s = 1 - \frac{E_{sec}}{E_{int}} \qquad (5)$$

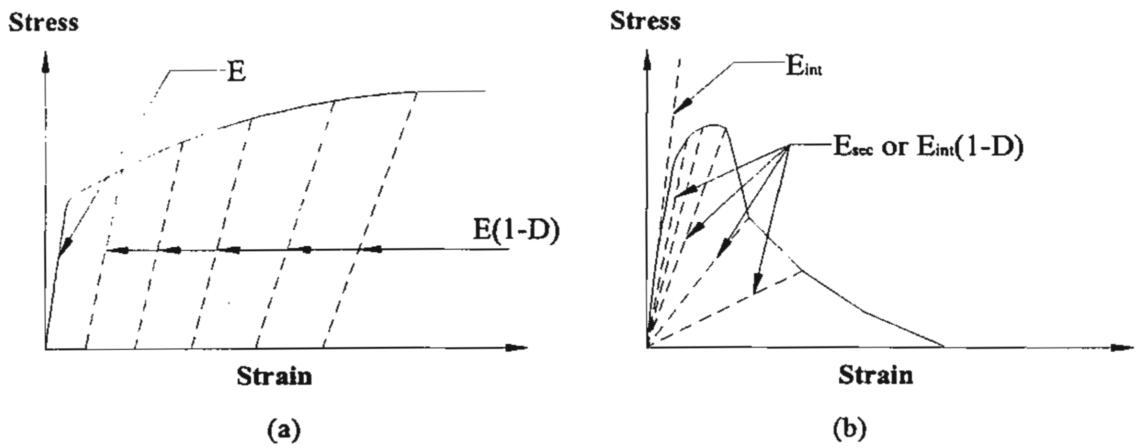

Fig 2 Measurement of E for (a) Ductile Material and (b) Brittle Material

Strain Rate Variation Approach

In general drop-weight impact test, the increase in strain up to the peak load is normally assumed to be linear (constant strain rate) in order to simplify the analysis. However, the actual test results indicate that the strain rate is, in fact, not constant. The strain rate was slower at the beginning of the impact event, and then began to increase with the accumulation of damage (3).

As a result, the damage of the material subjected to time-dependent loading can be expressed as (Fig.3):

$$D_i = 1 - \left(\frac{\dot{\varepsilon}_{\text{int}}}{\dot{\varepsilon}(t)} \right)^{1/N} \tag{6}$$

where $\dot{\varepsilon}_{\text{int}}$ is the minimum or initial strain rate (sec^{-1})

$\dot{\varepsilon}(t)$ is the strain rate at any time t (sec^{-1})

N is a temperature-dependent constant (assumed equal to 1)

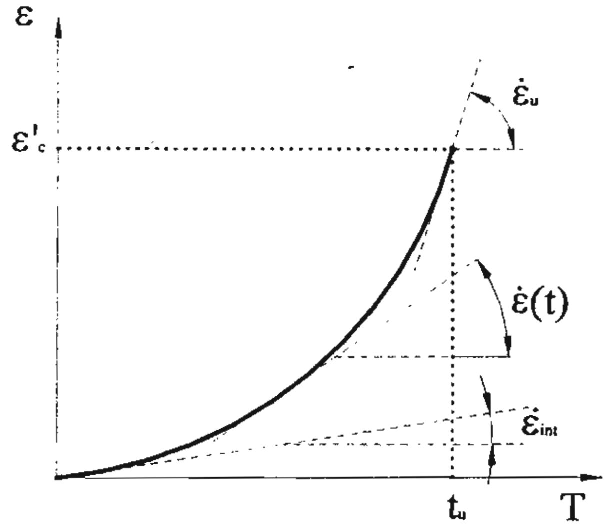

Fig. 3 Schematic Illustration of the Initial and the Ultimate Strain Rate, and the Strain Rate at Any Time t

3. Experimental Program

The specimens with mix proportion of 1:0.5:2:2.5 (C:W:F:A) were cast using the following materials:

Cement:	CSA Type 10 Normal Portland Cement (ASTM Type I)
Fine aggregates:	Clean river sand with a fineness modulus of about 2.7
Coarse aggregates:	Gravel with a 10 mm maximum size

Concrete was prepared in the form of cylinder (Dia-100 x 200 mm.). Prior to the mix, the water content in sand and aggregates was determined to adjust the amount of mixing water. The concrete was mixed using a pan type mixer, placed in oiled steel molds in three layers, then roughly compacted each layer with a shovel before being covered with polyethylene sheets. After 24 hours, the specimens were demoulded and transferred to storage in a water tank for 30 days.

3.1 Static tests

All static tests were carried out at the Department of Civil Engineering, King Mongkut's Institute of Technology-North Bangkok (KMITNB) using a 1500 kN universal testing machine[Ψ] (Fig. 4). Specimens were placed at the center of the machine. The data were collected by a PC-based data acquisition system.

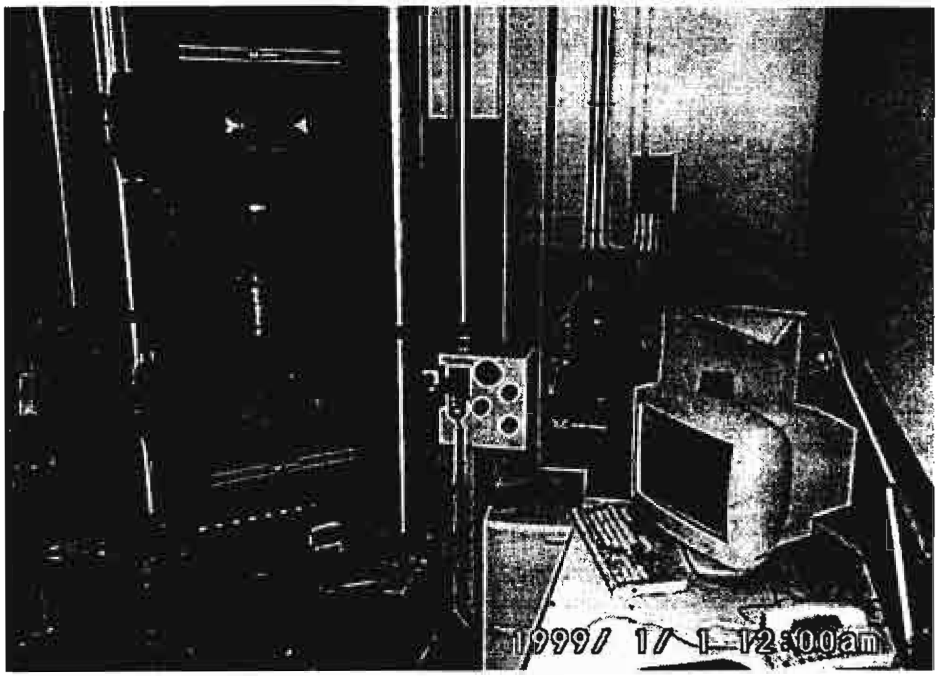

Fig. 4 Universal testing machine

3.2 Impact testing

All impact tests were carried out using an instrumented, drop-weight impact apparatus designed and constructed in the Department of Civil Engineering, University of British Columbia (UBC), and having the capacity of dropping a 578 kg mass from heights of up to 2500 mm on to the target specimen. The impact machine is shown schematically in Fig. 5.

[Ψ] Instron 'Fast-Track 8800'

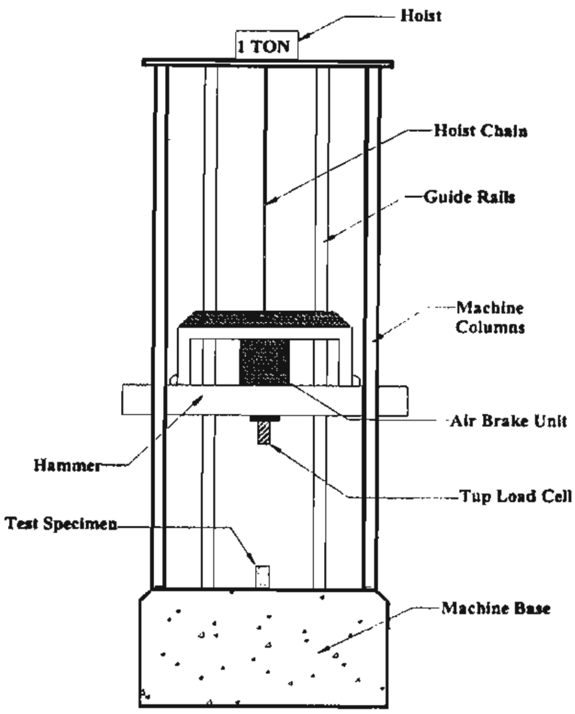

Fig. 5 Impact Machine at UBC

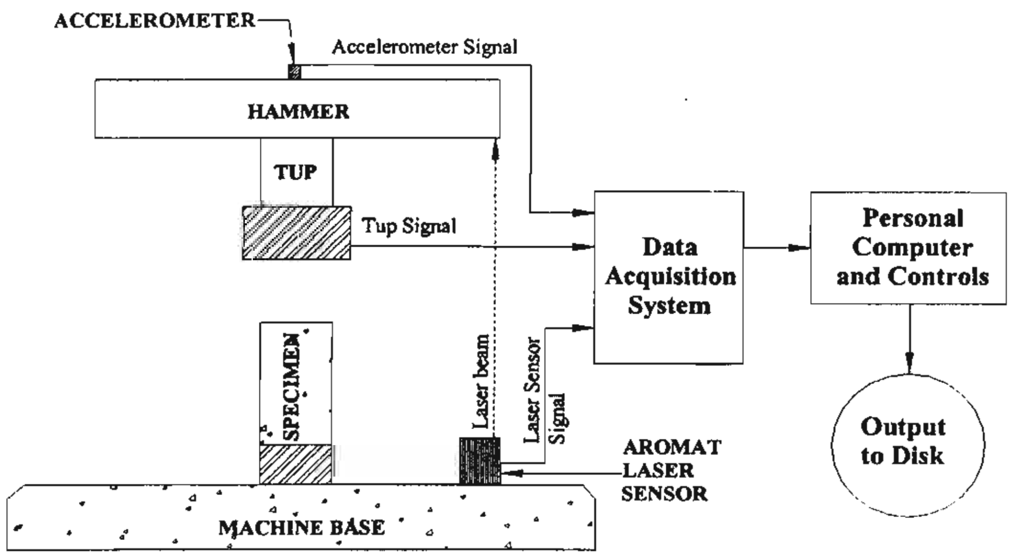

Fig. 6 Schematic Illustration of the Impact Testing Setup

The specimen was placed vertically on a 100*100 mm rigid steel base located at the center of the impact machine as shown in Figs. 5 and 6. The hammer was dropped from 250 and 500 mm heights to provide two different striking velocities of 2.21 and 3.13 m/s, respectively, and impact energies of 1417 and 2835 J, respectively. The PCB accelerometer and the Aromat Laser Analog Sensor (ALAS) were used to measure the specimen deformation. The PCB accelerometer was mounted on the hammer, while the ALAS was mounted on the machine with the laser beam pointing vertically at an extension part of the hammer. The testing program is summarized Table 1.

Table 1 Testing Program

Designation	**Description**	**Drop Height (mm)**	**Number of Specimen**
Static Test			
PLN	Concrete subjected to static loading	-	3
Impact Test			
PL250	Concrete subjected to impact loading	250	3
PL500	Concrete subjected to impact loading	500	3

4. Results and Discussion

4.1 Experimental Results

Static loading

The typical stress-strain responses of concrete cylinders subjected to short-term static loading are shown in Fig. 7. It was found that the linear portion of the $\sigma - \varepsilon$ curve extended up to about 40-60% of peak load. Although a small amount of creep or other non-linearity might occur in this linear portion, the deformation was essentially recoverable. At about 80-95% of the peak load, internal disruption began to occur, and small cracks might appear on the outer surface. These small cracks continued to propagate and interconnect until the specimen was completely fractured into several separate pieces. The formation and coalescence of the small cracks has long been recognized as the prime cause of fracture and failure of concrete, and of the marked non-linearity of the stress-strain curve (4). The deformation associated with cracks is completely irrecoverable, and may in some cases be considered as a quasi-plastic deformation. The load (or stress) at which the cracking became severe enough to cause a distinct non-linearity in the $\sigma - \varepsilon$ curve is often referred to as the point of "discontinuity" (5). At the peak load, the failure of concrete occurred in catastrophic manner, due to the large amount of energy that was released from the testing machine; thus, the full descending branch of the $\sigma - \varepsilon$ curve could not be obtained.

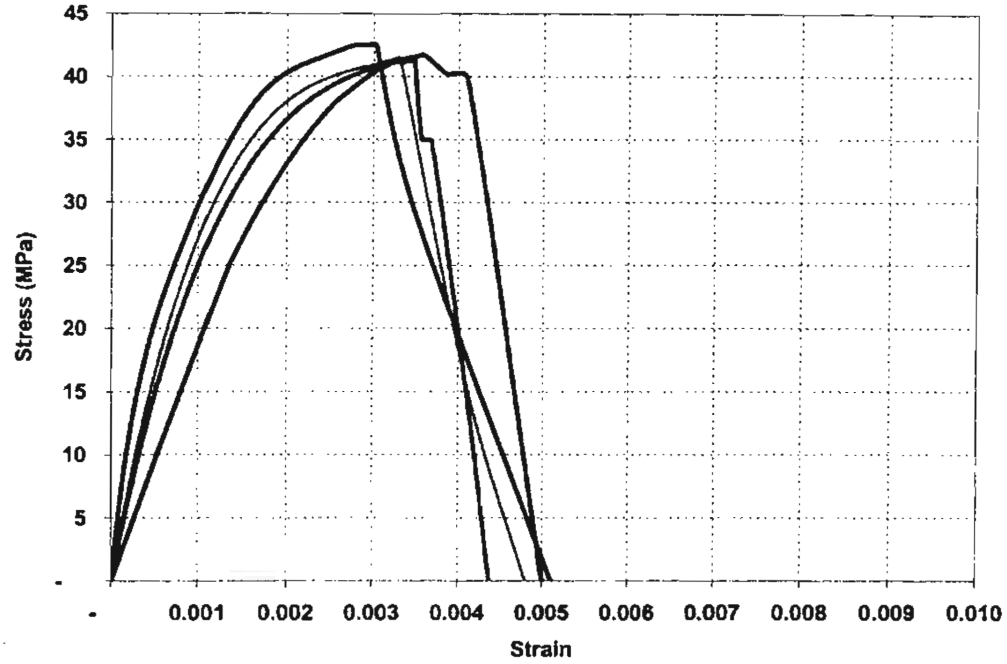

Fig. 7 Responses of concrete subjected to static loading

Impact loading

The concrete subjected to impact loading exhibited a quite different behavior from that subjected to static loading. The material behaved in a more brittle manner, and increases in strength, toughness, and modulus of elasticity were found as the rate of loading increased. Typical responses are given in Fig. 8

For the specimens tested under impact loading, the linear portion of the $\sigma - \varepsilon$ curve extended to higher stress values than for specimens tested under static loading. This linear portion was also found to increase with increased rates of loading, as seen in the specimen tested at the highest rate of loading. Theoretically, the small cracks that cause the non-linearity in the static case are forced to propagate much more quickly under impact loading. Thus, the cracks tend to propagate through rather than around aggregate particles, leading to an increase in strength and toughness, and a decrease in the non-linear portion of the $\sigma - \varepsilon$ curve.

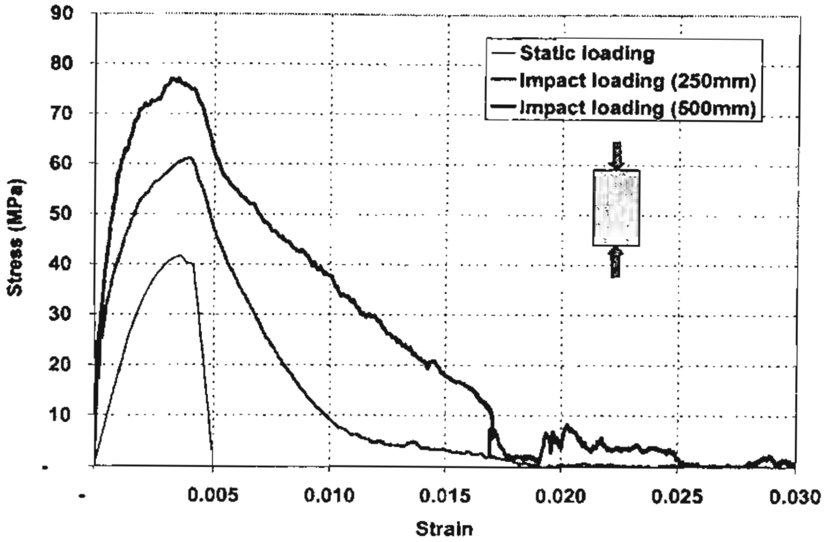

Fig. 8 Stress-Strain Curves of Plain Concrete Subjected to Static and Impact Loading

4.2 Damage of Concrete

4.2.1 Variations of E Approach

Using the obtained test results, the absolute value of E (E_{int}/E_{sec}) were determined and plotted against the corresponding strains (Fig. 9).

Results from Fig. 9 indicated that the degradation rate of E was faster with increasing loading rate. At the initial (undamaged) stage, the E_{sec} was essentially the same as E_{int}. However, with increasing load and deformation, the damage began to build up, cracks started to form and propagate. The specimen continued to disintegrate and loss its stiffness. As a result, the value of E decreased at dramatic rate.

At faster loading rate (impact loading), cracks were formed and forced to propagate at faster rate, the disintegration of specimen was faster and so did the lost in stiffness, this led the quicker decay rate of E as seen in Fig. 9.

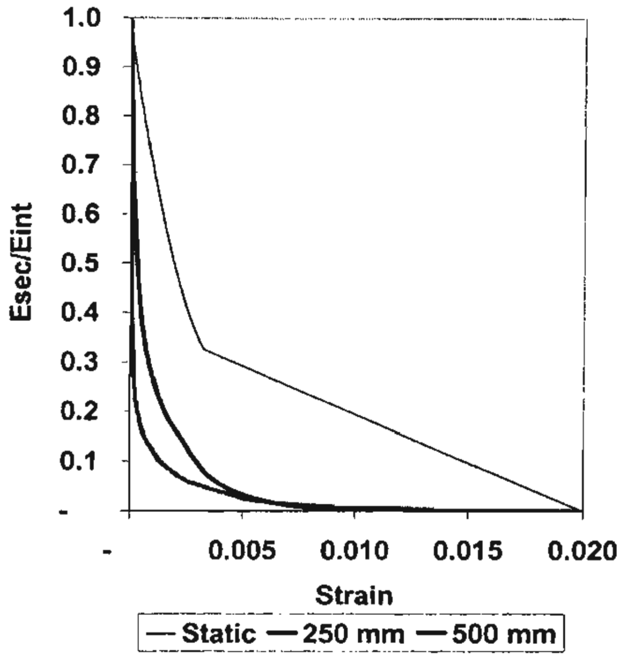

Fig. 9 Absolute E (Esec/Eint) vs Strain

Once E_{int} and E_{sec} already determined, the damage can simply be obtained using the procedure described earlier. Results were plotted in Figs. 10 and 11

Under static loading, it could be seen that the damage of plain concrete can be represented by a nonlinear curve up to the peak and a linear curve after the peak (Fig. 10) (as it increases nonlinearly with strain from 0.0 up to 0.65 when it begins to slow down and, right after the peak strain, it forms another straight line).

The damage at peak of plain concrete under static loading was found to be around 0.65. Upon the fracture (at peak), because of the brittleness, the amount of energy in the machine was released immediately, this resulted in a sudden and catastrophic failure. Partly, the catastrophic failure also led to a quick increase of damage up to 1 without loading.

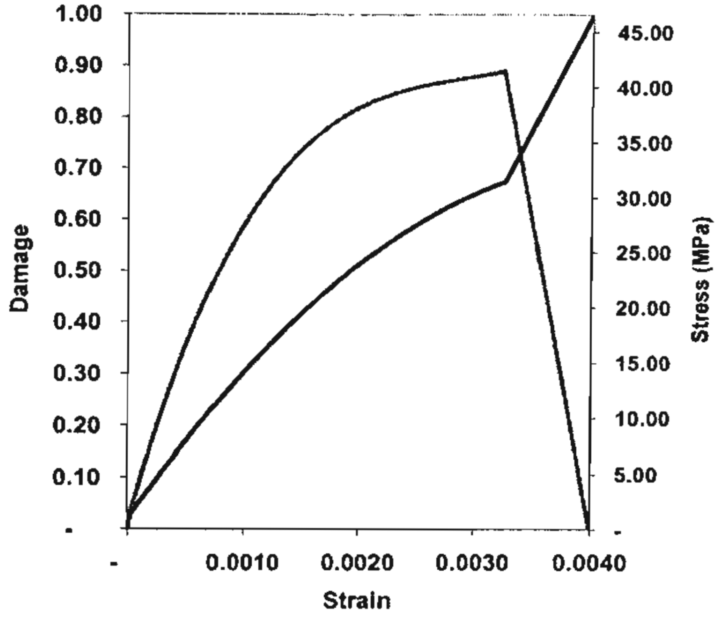

Fig. 9 Damage of Concrete Subjected to Static Loading

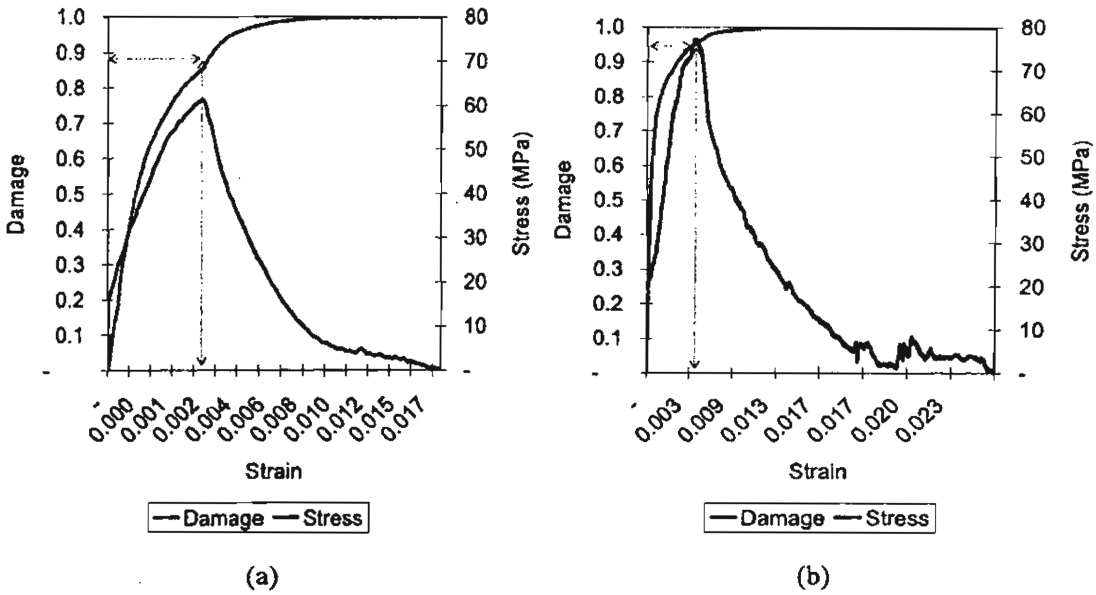

Fig. 10 Relationship between Damage (E) and Strain for Concrete Subjected to Impact Loading at (a) 250 mm and (b) 500 mm Drop Height

Under impact loading, similar to the static loading, undamaged specimen exhibited zero value of D, and then with increasing stress (i.e., strain), the damage started to increase. Prior to the peak, the increasing rate of D was quite fast and almost proportional to the increase rate of stress and strain. The rate of increase was slow down after the peak.

At the peak, the values of D increased to nearly equal to one in both drop heights (0.855 and 0.952, respectively). The large value of D at the peak indicated that the specimen was, in fact, already in the state of high damage and almost corrupted (or fractured). After the peak, the strain energy was large and sufficiently enough to cause crack self-propagation, hence without any further apply load, the damage of the specimen kept on increasing to the value of one.

The damage (value of D) was also found to be affected by the rate of loading. Consider Figs. 9 and 10, the value of D at the peak of specimen subjected to higher impact velocity (500mm) was larger than that subjected to lower impact velocity (250mm) and static loading. This gave us an idea that, with increasing rate of loading, the specimen was tortured at higher level and pushed closer to a complete fractured state.

4.2.2 Variations of Strain Rate

In addition to the variations of E, the variation of strain rate was also used to determine damage of concrete subjected to impact loading. Based on the test results, the change of strain with respect to time was plotted as shown in Fig. 11. As mentioned earlier, under impact loading, the strain rate was actually changed with time. At undamaged stage, the specimen was highly stiff and strong, thus the rate of deformation (strain) was quite low. However, with further loading, the stiffness decreased gradually and the rate of deformation started to jump to a faster rate.

Once the strain rate corresponding to each strain was established, the damage can also be determined using the procedure described earlier. Results are plotted in Fig. 12.

Prior to the peak, the damage obtained by the strain rate variations approach (0.858 and 0.930) were quite similar to that obtained by the variations of E approach (0.855 and 0.952). Both were found increase with stress in the similar manner and up to the peak, the values of D were drawn to near one. However, the difference was that, in this case, the value of D after peak would never reach the value of one even at the complete fracture. This was believed to cause by a limitation of the Eq. 6 itself. For any given initial strain rate, the last term of Eq. 6 which was the ratio between initial strain rate and strain rate at any time t, would not turn into zero. Therefore, it is recommended here that this method should be used only to determine the damage up to the peak.

Similar to the variations of E approach, the value of damage was also affected by the impact velocity. The increasing drop height increased the level of damage in specimen at every corresponding strain.

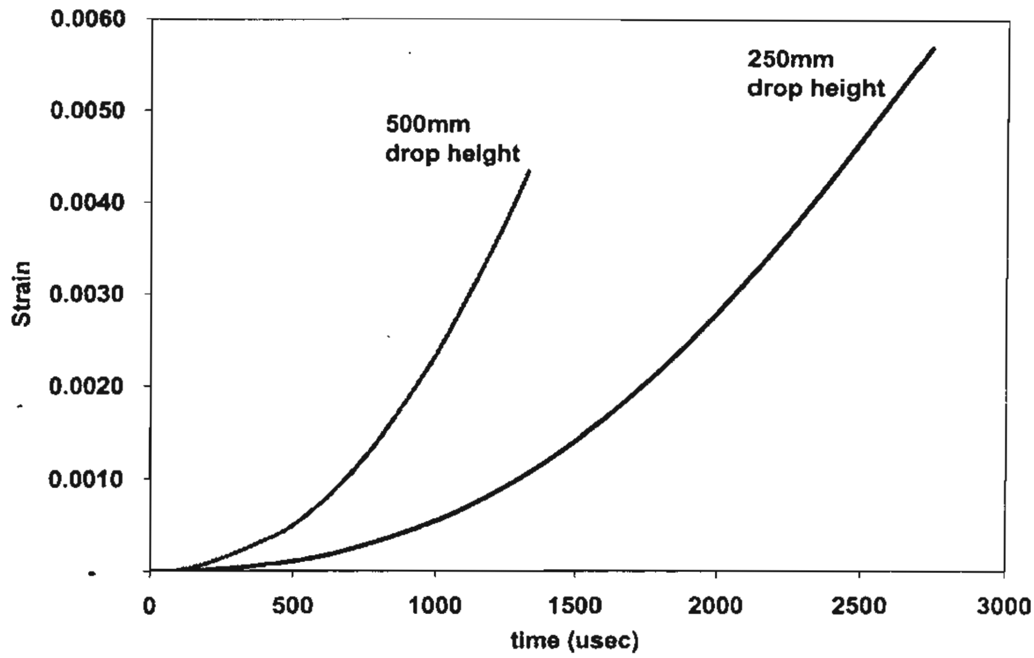

Fig. 11 Change of Strain with Time of Concrete Subjected to Impact Loading

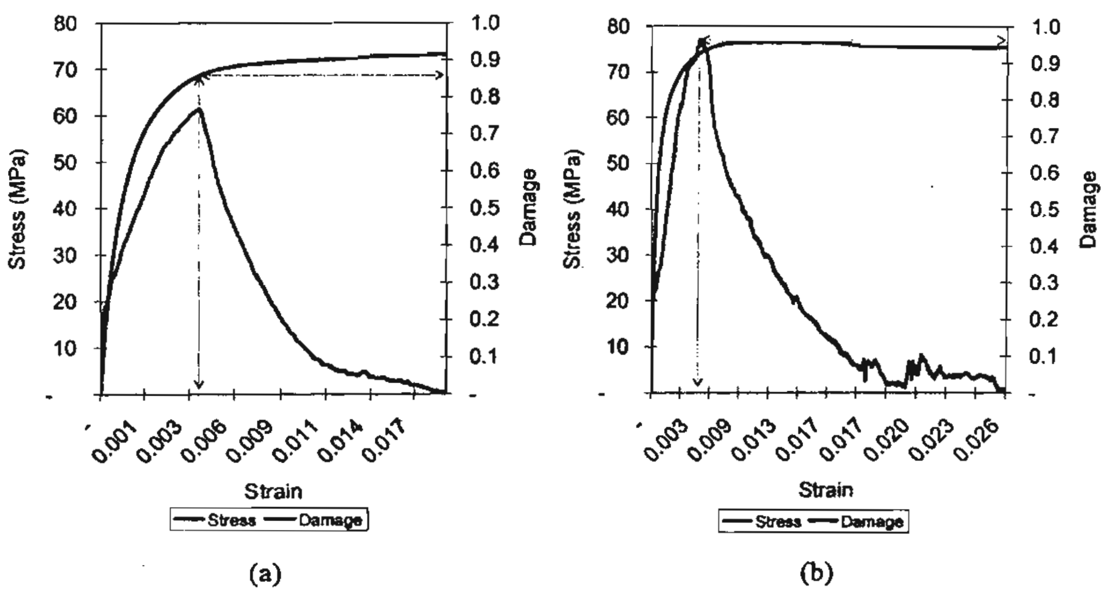

Fig. 12 Relationship between Damage (strain rate) and Strain for Concrete Subjected to Impact Loading at (a) 250 mm and (b) 500 mm Drop Height

5. Conclusions

- Theory of damage mechanics can be used effectively to determine the damage of specimen subjected to static and impact loadings.
- Both approaches (strain rate variation and degradation of E) exhibit similarity in determining damage prior to peak of concrete subjected to impact loading.
- After the peak, the degradation of E approach becomes more realistic than the strain rate variation approach as seen by the convergence of D to value of one at the completed fracture.
- It is found that the degradation of E and the level of damage of concrete at peak are both affected by the rate of loading. The degradation of E is faster and the level of damage at peak is found to be higher under the high rate of loading (impact loading). The level of damage, especially, under impact loading is essentially high (0.8-0.9) and closed to the level of fracture ($D = 1$).
- We can also conclude that after the peak, the strain energy is large enough to cause the damage to increase up to one (complete fracture) without having to apply any further load.

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MUA

TRF

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