KAJIAN FUNDAMENTAL UNTUK MENINGKATKAN SIFAT-SIFAT KEMULURAN ANGGOTA KONKRIT KEKUATAN TINGGI BERTETULANG

(A FUNDAMENTAL STUDY OF IMPROVING DUCTILITY OF REINFORCED HIGH-STRENGTH CONCRETE (HSC) MEMBERS)

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2007

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ABSTRAK

Sejak kebelakangan ini, penggunaan konkrit berkekuatan tinggi telah menjadi semakin popular dalam pembinaan bangunan dan infra-struktur. Ini kerana konkrit berkekuatan tinggi mempunyai sifat bahan yang berkualiti dan ia dapat mengurangkan kos pembinaan secara keseluruhan. Bagaimanapun, konkrit tersebut lebih rapuh berbanding konkrit berkekuatan biasa. Oleh itu, kurungan sisi secara luaran digunakan untuk meningkatkan keupayaan dan sifat kemuluran konkrit tersebut. Di dalam projek ini, kajian ditumpukan kepada kesan penggunaan jalur logam untuk meningkatkan kekuatan dan kemuluran konkrit berkekuatan tinggi. Kajian ini juga meninjau kesan penggunaan jalur logam yang berlainan kekuatan dan dipasang pada jarak yang berbeza. Semua sampel konkrit kurungan sisi diuji dengan beban mampatan paksi dan hubungan tegasan-keterikan memanjang dan sisi dihasilkan. Mod kegagalan apabila konkrit mencapai kekuatan maksimum direkodkan. Daripada kajian ini, ia menunjukkan penggunaan jalur logam pra-tegangan sebagai bahan kurungan sisi konkrit kekuatan tinggi dapat meningkatkan kemuluran konkrit tersebut. Ia juga menunjukkan penggunaan jalur logam yang mampunyai keterikan yang tinggi akan meningkatkan kekuatan dan kemuluran konkrit berkekuatan tinggi yang dikurung sisi. Kajian lebih lanjut diperlukan untuk mengetahui keberkesanan penggunaan jalur logam sebagai alternatif kepada penggunaan bahan-bahan lain yang lebih mahal seperti polimer bertetulang gentian (FRP).

ABSTRACT

In recent years, the use of high strength concrete (HSC) has become increasingly popular in the construction of buildings and infra-structures. The utilization of HSC has been spurred on by the superior mechanical properties of the material and its cost-effectiveness. However, HSC tends to be more brittle or less tough than normal strength concrete. Therefore, external confinements are used to overcome and enhance the concrete characteristics. This study investigates the effectiveness of using steel straps in increasing the strength and ductility of HSC. Its also investigate the effects of using steel straps with different ultimate tensile strength and placed with different spacings. All the cylinders were tested under axial compression load to study their stress-axial strain and stress-lateral strain characteristics upon loading. Mode of failure of the cylinders has been observed. The results indicated that the confined cylinders have higher ultimate load-capacity and ductility compared to the unconfined cylinders. It also shows that higher strength of steel straps will increase the strength and ductility of confined high strength concrete. Further work needs to be carried out to ascertain the effectiveness of using low-cost steel straps as alternative to more costly confining materials such as Fibre-reinforced plastic (FRP).

KANDUNGAN

SENARAI JADUAL

SENARAI RAJAH

SENARAI SIMBOL

f_c	-	tegasan konkrit
f_{cc}	-	nilai tegasan konkrit dikurung sisi
f_{ce}	-	nilai tegasan konkrit tidak dikurung sisi
ε_c	-	terikan konkrit
ε_{cc}	-	nilai terikan konkrit dikurung sisi
ε_{ce}	-	nilai terikan konkrit tidak dikurung sisi

BAB I

PENGENALAN

1.1 Pendahuluan

Konkrit kekuatan tinggi *(High-Strength Concrete)* adalah satu bahan yang agak baru di Malaysia. Ia mula digunakan sejak awal 1990an di dalam industri pembinaan di negara-negara maju. Di Eropah misalnya, konkrit yang mempunyai kekuatan sekitar 20,000 psi (138 MPa) telah digunakan untuk membina struktur tiang bangunan tinggi dan jambatan (Nawy, 1996). Di Malaysia, Menara Berkembar Petronas KLCC adalah salah satu contoh bangunan yang menggunakan konkrit kekuatan tinggi pada struktur tiangnya.

Konkrit kekuatan tinggi banyak digunakan pada struktur tiang bangunan tinggi untuk meminimakan saiz struktur, struktur jambatan dan pada struktur-struktur yang mengalami dedahan yang teruk. Ini disebabkan kelebihan-kelebihan yang terdapat pada konkrit kekuatan tinggi berbanding konkrit kekuatan normal seperti lebih teguh, tahan lasak dan kurang keliangan. Selain itu, ia juga mempunyai kelebihan yang lain di mana ia sesuai untuk pembinaan yang memerlukan masa penyiapan yang singkat kerana ia dapat mencapai kekuatan yang tinggi dalam masa yang singkat. Oleh itu, konkrit kekuatan tinggi boleh ditanggalkan daripada acuannya lebih awal (Burnett, 1989).

Namun begitu, konkrit kekuatan tinggi juga mempunyai beberapa kelemahan iaitu kadar rayapan dan pengecutan yang tinggi. Ini disebabkan kandungan simen yang tinggi. Namun begitu kelemahan utama konkrit ini ialah ia bersifat rapuh dan kemulurannya lebih rendah daripada konkrit kekuatan normal. Disebabkan kemulurannya yang rendah itu ia akan gagal secara tiba-tiba apabila melebihi kekuatan maksimumnya dan ia tidak menunjukkan tanda-tanda awal yang mencukupi sebelum gagal (Li, 2003). Oleh itu penggunaan pelbagai kurungan sisi telah mula diperkenalkan bertujuan untuk meningkatkan lagi kekuatan konkrit dan mengurangkan sifat kerapuhannya.

Walaupun penggunaan kurungan sisi terhadap konkrit merupakan satu kaedah yang praktikal dalam memperkukuhkan konkrit, namun data-data kajian masih sukar diperolehi terutamanya berkaitan dengan kurungan sisi bagi konkrit kekuatan tinggi. Oleh itu, penggunaannya memerlukan kajian yang lebih lanjut untuk menentukan kesesuaiannya dalam industri pembinaan.

1.2 Kenyataan masalah

Peningkatan kekuatan konkrit akan menyebabkan penurunan kemuluran struktur konkrit terutama pada struktur yang mengalami beban mampatan paksi (Shah, 1990). Masalah ini telah menjadi topik penyelidikan sejak lebih dua abab yang lalu. Hasil ujikaji yang lalu menunjukkan bahan kurungan sisi yang digunakan untuk meningkatkan kemuluran konkrit (samada keluli atau polimer bertetulang gentian) tidak mencapai kekuatan muktamad ketika konkrit gagal, namun kebanyakan model yang dihasilkan mencadangkan nilai kekuatan muktamad semasa membuat anggaran kekuatan konkrit kurungan sisi. Ini menyebabkan berlaku anggaran kekuatan yang lebih daripada nilai sebenarnya. Masalah ini dipercayai akan lebih kritikal pada konkrit kekuatan tinggi kerana sifat pengembangan sisinya yang lebih rendah berbanding dengan konkrit kekuatan normal apabila dikenakan beban mampatan yang sama. Ini juga menyebabkan penggunaan bahan kurungan sisi yang berkekuatan tinggi tidak dapat dioptimumkan sebaik mungkin terutamanya pada konkrit yang mempunyai kekuatan mampatan yang lebih tinggi.

1.3 Objektif kajian

Objektif kajian ini adalah seperti berikut:

i. Mengkaji sifat konkrit kekuatan tinggi yang dihasilkan menggunakan bahan tempatan. Kajian tertumpu kepada sifat ubahbentuk memanjang dan ubahbentuk sisi.

ii. Membangun satu hubungan antara kekuatan mampatan konkrit dan sifat kemuluran dengan menggunakan jalur logam sebagai bahan kurungan sisi.

1.4 Skop kajian

Skop kajian adalah lebih tertumpu kepada kajian terhadap keupayaan konkrit berkekuatan tinggi yang dikurung sisi secara luaran yang menanggung daya mampatan yang tinggi pada paksi memanjang tiang. Spesimen konkrit yang digunakan adalah berbentuk silinder berdiameter 85 mm dan 170 mm panjang. Keberkesanan kurungan sisi menggunakan jalur logam dalam meningkatkan kemuluran konkrit berkekuatan tinggi dibandingkan dengan hasil kajian lain yang menggunakan bahan seperti polimer bertetulang gentian (FRP). Jalur logam dipasangkan pada silinder dengan menggunakan alat penegang (*tensioner*) untuk memberikan sedikit daya kepada kurungan sisi sebelum beban paksi dikenakan kepada tiang. Keputusan kajian ini penting untuk menilai keberkesanan daya tegangan sisi yang dihasilkan oleh jalur logam dalam meningkatkan keupayaan konkrit berkekuatan tinggi.

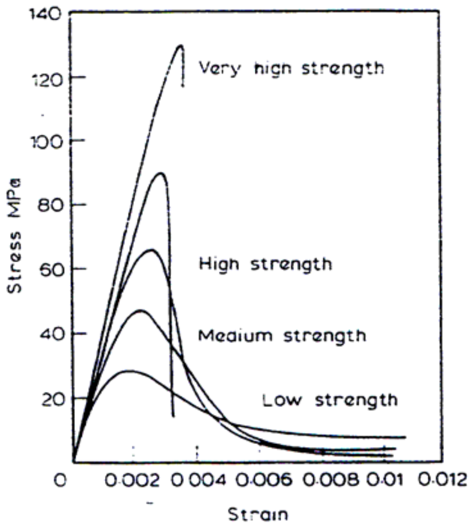
BAB II

KAJIAN LITERATUR

2.1 Konkrit berkekuatan tinggi

Sejak kebelakangan ini, penggunaan konkrit berkekuatan tinggi semakin popular terutamanya dalam pembinaan bangunan tinggi. Ia digunakan kerana terdapat banyak kelebihan seperti saiz tiang dapat dikecilkan, konkrit yang tahan lasak, tempoh pembinaan yang singkat dan sebagainya. Namun demikian, konkrit yang berkekuatan tinggi ini lebih rapuh jika dibandingkan dengan konkrit berkekuatan biasa.

Rajah 2.1 menunjukkan graf tegasan-keterikan konkrit berkekuatan biasa dan konkrit berkekuatan tinggi. Daripada rajah tersebut, dapat disimpulkan bahawa semakin tinggi kekuatan konkrit, semakin rapuh konkrit tersebut. Kelemahan ini menyebabkan pelbagai ujikaji telah dijalankan untuk memperbaiki kelemahan tersebut. Antaranya ialah melalui penggunaan kurungan sisi. Oleh yang demikian, kajian literatur ini meneliti kajian yang telah dilakukan sebelum ini yang menggunakan kaedah kurungan sisi bagi meningkatkan kemuluran dan kekuatan struktur konkrit.



Rajah 2.1: Graf tegasan-keterikan bagi konkrit berkekuatan biasa dan konkrit berkekuatan tinggi (Attard *et al.*, 1986)

2.1.1 Definasi konkrit berkekuatan tinggi

Mehta (1986) telah mendefinisikan konkrit yang mempunyai kekuatan 6000 psi atau 41.4 MPa atau lebih dikategorikan sebagai konkrit berkekuatan tinggi. Bertero (1979) pula mengganggap kekuatan yang melebihi 6000 psi (41 MPa) untuk konkrit biasa dan 4000 psi (27 MPa) untuk konkrit *lightweight* sebagai konkrit berkekuatan tinggi.

Nilai ini adalah wajar di mana kebiasaannya kaedah penghasilan konkrit berdasarkan amalan kod rekabentuk dihadkan bagi konkrit yang berkekuatan di antara 3000 psi dan 6000 psi (Salim dan Murat, 1994). Namun begitu, definisi ini berubah-ubah mengikut masa dan tempat (keadaan geografi).

2.1.2 Kelebihan menggunakan konkrit berkekuatan tinggi

Kelebihan menggunakan konkrit berkekuatan tinggi dapat dilihat daripada pelbagai faktor (Nawy, 1996). Antaranya ialah:

a. Saiz tiang
   Ia akan menghasilkan saiz tiang yang lebih kecil. Oleh itu, keluasan ruang sebuah bangunan untuk disewa atau dijual lebih besar.

b. Berat struktur bangunan
   Pengurangan ketebalan papak dan rasuk akan mengurangkan beban yang akan dipindahkan kepada tiang. Seterusnya, ia akan mengurangkan saiz asas bangunan disebabkan oleh pengurangan berat sendiri dan beban daripada tiang yang akan ditanggung olehnya.

c. Ketahanlasakan konkrit
   Konkrit mempunyai kelasakan yang tinggi terhadap serangan kimia, fizikal atau mekanikal seperti tindakan elektrolit, serangan cecair dan gas samada asli dan industri, pencuacaan dan lelasan.

d. Tempoh pembinaan
   Acuan dapat dibuka lebih awal kerana konkrit mencapai kekuatan yang tinggi pada peringkat awal dan ini akan mengurangkan tempoh pembinaan.

2.2 Kurungan sisi

Konkrit yang lazimnya mengalami daya mampatan adalah kritikal di mana ia penting dalam pengukuhan struktur bangunan. Oleh itu, kajian telah dilakukan seawal tahun 1903, di mana Considere (1903) mendapati kebaikan kesan penggunaan kurungan sisi dalam konkrit menggunakan kurungan sisi terhadap kekuatan dan had ubah bentuk. Sejak itu, kajian-kajian yang seterusnya mendapati bahawa apabila konkrit yang dikenakan daya mampatan dikekang daripada berlakunya pengembangan sisi, ia memperlihatkan pertambahan kekuatan konkrit dan menghadkan ubah bentuk pada konkrit tersebut. Ia dipanggil kurungan sisi, di mana secara tradisionalnya telah digunakan dalam anggota mampatan melalui perangkai ricih dalam bentuk segiempat tepat, lingkaran dan gelung.

Kurungan sisi boleh dibahagikan kepada dua bentuk iaitu kurungan sisi secara dalaman (KSD) dan kurungan sisi secara luaran (KSL). Richart *et al.* (1929) telah mengkaji konkrit yang dililit dengan keluli (*spiral hoops*) dibandingkan dengan konkrit tidak dikurung sisi dan mendapati bahawa kekuatan konkrit dikurung sisi lebih tinggi jika dibandingkan konkrit tidak dikurung sisi dengan syarat jarak lilitan tersebut adalah kecil.

Dalam tahun-tahun yang seterusnya, kesan penggunaan kurungan sisi terhadap kekuatan dan had ubah bentuk konkrit telah dikaji dengan lebih mendalam sama ada dalam bentuk eksperimen atau secara teori.

2.2.1 Kurungan sisi secara luaran

2.2.1.1 Kurungan sisi menggunakan plat keluli

Secara tradisionalnya, plat keluli telah digunakan untuk meningkatkan kekuatan struktur konkrit yang telah rosak akibat pengaratan tetulang, beban yang tinggi, kelemahan rekabentuk dan sebagainya. Swamy *et al.* (1989) mendapati teknik pengikatan plat keluli berguna dalam kerja-kerja penguatan struktur konkrit.

Namun demikian, plat keluli ini mudah berlaku pengaratan dan kesukaran untuk memasang plat keluli yang berat di tempat yang terhad menyebabkan alternatif baru dikaji untuk mencari bahan yang lebih efisien dalam menguatkan struktur konkrit.

2.2.1.2 Kurungan sisi menggunakan FRP (*Fiber Reinforced Polymer*)

Penggunaan *Fiber Reinforced Polymer (FRP)* untuk menggantikan plat keluli sebagai kurungan sisi telah dikaji sekitar awal 1980 lagi. Ia adalah bahan yang ringan tetapi mempunyai nisbah kekuatan-berat yang tinggi, tidak terhakis dan bersifat neutral. Selain itu, ia juga tahan lasak pada sebarang suhu dan keadaan persekitaran. Ia telah membuka alternatif yang baru dalam membaiki dan meningkatkan kekuatan struktur konkrit. FRP diperbuat daripada pelbagai jenis bahan sama ada karbon, kaca, polyester, vinylester dan sebagainya.

Terdapat pelbagai bentuk kurungan sisi yang menggunakan FRP sama ada bentuk lingkaran, balutan, tiub, jalur atau plat gentian kaca. Antara kajian-kajian yang telah dijalankan berdasarkan bentuk kurungan sisi adalah seperti berikut:

i. Jalur

Kurungan dibentuk dengan melilitkan jalur gentian bersifat fleksibel yang mempunyai ketebalan dan lebar yang ditetapkan pada tiang konkrit. Jalur tersebut boleh dililit samada secara bersambung atau tunggal. Kaedah kurungan ini dikaji oleh Saadatmanesh *et al.* (1994) di mana mereka menggunakan dua jenis FRP iaitu e-kaca dan karbon sebagai penguat struktur konkrit yang terdedah kepada gegaran gempa bumi.

Dalam kajian ini, konkrit-konkrit tersebut dililit dengan jalur berlainan jarak dan jenis untuk melihat kesannya terhadap kekuatan konkrit tersebut. Kajian mereka mendapati jalur yang mempunyai kekuatan alah yang tinggi akan menghasilkan konkrit yang mempunyai kekuatan dan kemuluran konkrit yang tinggi. Semakin tebal jalur tersebut, semakin kurang kerapuhannya. Namun demikian, kerapuhannya bertambah apabila jarak antara jalur semakin besar.

ii. Plat

Plat tersebut dibalut di sekeliling konkrit dan dilekat menggunakan bahan pelekat seperti gam epoxy dua-komposit dan sebagainya. Kaedah pemasangan plat ini adalah sama dengan plat keluli. Ia adalah lebih efektif kerana FRP tidak mengalami pengaratan dan ia lebih ringan. Rasuk yang diperkuatkan menggunakan plat FRP dapat mengawal konkrit dari berlakunya keretakan dan pesongan (He *et al.* 1997).

iii. Balutan

Penggunaan FRP dalam bentuk balutan ini mendapat perhatian oleh ramai pengkaji disebabkan oleh struktur yang lebih ringan, anti karat dan berkekuatan tinggi. Kaedah ini dikaji oleh Lin *et al.* (2001) di mana tiga keadaan FRP dibalut pada konkrit. Dua jenis FRP digunakan dalam eksperimen ini iaitu gentian karbon dan kaca. Pertama, konkrit dibalut dengan beberapa lapisan FRP. Ia menunjukkan kekuatan konkrit bertambah apabila lapisan FRP bertambah. Pada keadaan kedua, konkrit dibalut dengan lapisan yang diselang-seli antara gentian kaca dan gentian karbon. Keputusan kajian itu mendapati semakin dekat lapisan gentian kaca terhadap permukaan konkrit, semakin tinggi kekuatan konkrit tersebut.

Akhir sekali, konkrit dibalut dengan gentian kaca dan gentian karbon pada bahagian-bahagian tertentu. Dalam keadaan ini, konkrit gagal pada bahagian yang mengandungi lapisan karbon. Oleh yang demikian, kesimpulan yang dapat dibuat ialah lapisan gentian kaca dapat meningkatkan kekuatan struktur konkrit jika dibandingkan dengan gentian karbon.

2.2.2 Kurungan sisi secara dalaman

2.2.2.1 Kurungan sisi menggunakan keluli berbentuk gegelung.

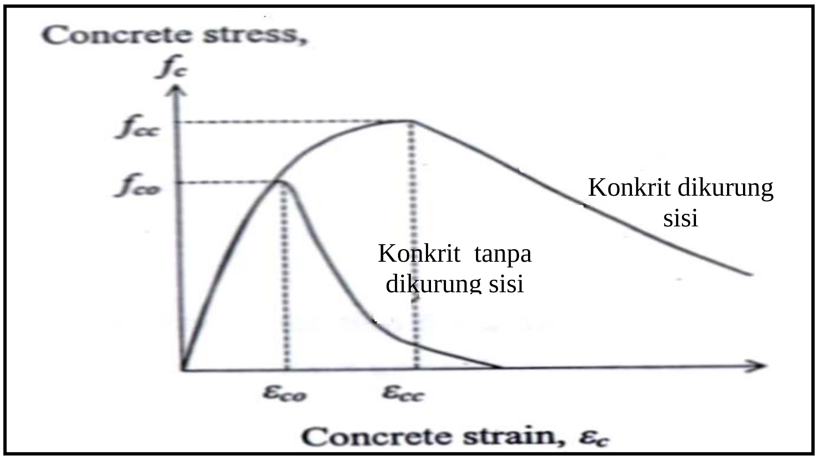
Gegelung keluli ini berfungsi dalam meningkatkan kekuatan dan kemuluran struktur konkrit (Sheikh *et al.,*1993). Dalam satu kajian yang dibuat mereka mendapati jarak di antara tetulang kurungan mempengaruhi sifat konkrit di mana konkrit akan cepat gagal apabila jarak semakin besar.

Perbezaan kekuatan alah tetulang kurungan tidak mempengaruhi kekuatan mampatan konkrit yang dikurung (Ahamd dan Shah, 1992). Hasil daripada kajian yang dijalankan oleh mereka mendapati tegasan maksimum konkrit dikurung sisi adalah sama walaupun menggunakan keluli yang berbeza kekuatan alah. Saiz spesimen yang berbeza menggunakan konkrit yang sama tidak menunjukkan perbezaan sifat konkrit yang ketara jika parameter-parameter seperti kekuatan tetulang, jarak antara tetulang dan lain-lain lagi adalah sama (Sheikh *et al.*, 1993).

2.2.3 Kesan penggunaan kurungan sisi terhadap struktur konkrit

Apabila stuktur konkrit dikenakan daya mampatan, ia akan mengalami pengembangan sisi. Pertambahan daya mampatan akan menyebabkan keterikan konkrit meningkat dan ia akan gagal dalam mampatan apabila konkrit tersebut telah mencapai kekuatan muktamadnya. Oleh itu, kurungan sisi digunakan untuk meningkatkan kekuatan konkrit terhadap daya mampatan. Tekanan sisi yang dihasilkan oleh kurungan sisi akan mengurangkan keupayaan konkrit tersebut daripada berlakunya pengembangan sisi.

Rajah 2.2 menunjukkan perbezaan graf konkrit dikurung sisi dibandingkan dengan konkrit tanpa dikurung sisi. Daripada rajah tersebut, dapat disimpulkan bahawa kekuatan dan kemuluran konkrit dapat ditingkatkan dengan adanya kurungan sisi.



Rajah 2.2: Graf tegasan-keterikan bagi konkrit dikurung sisi dibandingkan dengan konkrit tanpa dikurung sisi. (Saadatmanesh *et al.*, 1994)

Berdasarkan kajian-kajian yang telah dijalankan, didapati bahawa keberkesanan kurungan sisi sebagai penguat konkrit bergantung kepada bahan dan bentuk kurungan yang digunakan. Semakin tebal kurungan tersebut, semakin tinggi darjah kemulurannya dan semakin besar jarak antara lilitan pada konkrit tersebut, semakin tinggi kerapuhannya.

2.3 Kurungan sisi menggunakan jalur logam

Ramai pengkaji sejarah berpendapat bahawa pusat utama dalam pembuatan logam berasal dari India sejak 3000 tahun dahulu. Pada permulaannya, bijih logam dicairkan pada suhu yang tinggi dengan menggunakan arang dan menukul bahan tersebut untuk membentuk besi tempa. Lebih daripada tiga unsur yang diketahui oleh manusia adalah terdiri daripada logam. Logam umumnya mempunyai struktur hablur dengan sifat pengaliran elektrik dan terma yang baik, kekuatan dan kekakuan yang tinggi secara relatif dan bersifat mulur.

2.3.1 Sifat-sifat logam

Pemilihan sesuatu bahan yang diperbuat daripada logam untuk membuat sebarang komponen bergantung kepada beberapa faktor (Hamzah *et al.*, 1999). Antaranya ialah:

a. Kekerasan
   Kekerasan ditakrifkan sebagai keupayaan sesuatu logam untuk tahan calar atau pelekukan oleh bahan keras yang lain dan ia merupakan petunjuk kepada rintangan terhadap kehausan sesuatu logam.

b. Kemuluran

Ini adalah sifat logam yang boleh dibentuk atau dipanjangkan apabila dikenakan beban. Misalnya, logam yang boleh ditarik menjadi bentuk dawai yang halus tanpa patah boleh dikatakan mempunyai kemuluran yang tinggi.

c. Kerapuhan

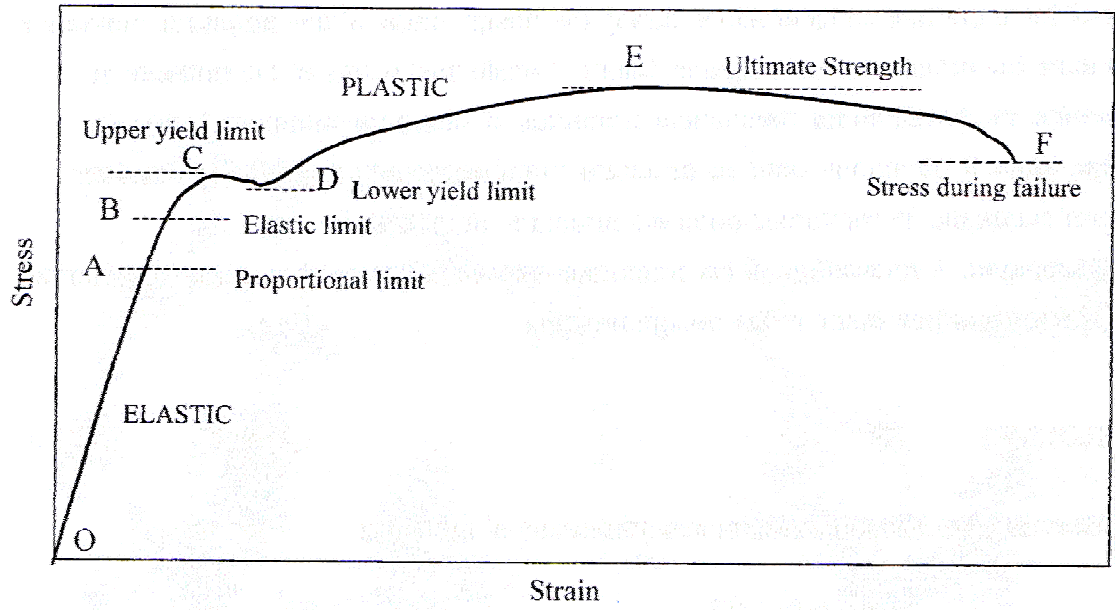
Ini adalah sifat logam yang mudah patah apabila diketuk atau ditegang. Logam yang rapuh bermakna ia tidak boleh ditegangkan dan mempunyai sifat kemuluran yang rendah.

d. Kebolehtempaan

Ini adalah kebolehan sesuatu logam yang boleh menanggung tukulan dan boleh dibentuk tanpa patah atau retak.

2.3.2 Hubungan tegasan-keterikan bagi logam

Rajah 2.3 menunjukkan hubungan tegasan-keterikan bagi logam apabila dikenakan daya tegangan. Keterikan logam bertambah apabila daya yang dikenakan bertambah. Logam mencapai had elastiknya pada titik B. Selepas titik itu, logam berada dalam keadaan plastik dan ia tidak akan kembali kepada bentuk asal. Titik C dipanggil Had Alah di mana apabila tegasan melebihi titik ini, logam mengalami keterikan secara mendadak. Selepas titik D, pertambahan keterikan hanya dapat diperolehi dengan peningkatan daya tegangan. Daya tegangan yang berterusan akan menyebabkan keterikan bertambah sehingga mencapai kekuatan muktamad (titik E) dan berkurang sehingga ia gagal.



Rajah 2.3: Graf tegasan-keterikan bagi logam

2.3.3 Kebaikan penggunaan jalur logam sebagai kurungan sisi

Kebaikan penggunaan jalur logam adalah seperti berikut (Hamzah *et al.*,1999):

i. Tingkatkan kekuatan – Daya sisi yang dihasilkan oleh jalur logam tersebut akan meningkatkan kekuatan konkrit untuk menanggung beban yang lebih besar.

ii. Bentuk jalur – Jalur logam tersebut mudah ditempa di mana ia mudah dan senang untuk dililit pada konkrit yang berbentuk segiempat atau bulat.

iii. Murah – Jalur logam tersebut boleh didapati dengan senang dan murah di mana ia dapat dibeli di kedai-kedai menjual barang logam.

iv. Meningkatkan kemuluran – Kurungan sisi oleh jalur logam tersebut menyebabkan konkrit akan gagal pada keterikan yang lebih besar jika dibandingkan dengan konkrit tanpa kurungan sisi. Tahap kemuluran akan dapat dihasilkan dengan lebih tinggi bergantung kepada darjah kurungan sisi tersebut.

v. Mudah dibuka – Jalur logam bukan bersifat kekal di mana ia boleh dibuka jika ingin mengubah kedudukannya.

vi. Nilai estetika –Logam tersebut berketebalan nipis di mana ia tidak akan mencacatkan rupa bentuk konkrit.

vii. Ringan - Sifat logam yang ringan akan mempercepatkan penyediaan konkrit dan mengurangkan kos pengangkutan.

BAB III

METODOLOGI

3.1 Pengenalan

Untuk menghasilkan konkrit berkekuatan tinggi, pemilihan bahan-bahan yang digunakan adalah lebih teliti jika dibandingkan dengan konkrit berkekuatan rendah. Dalam bab ini, penerangan akan diberikan mengenai bagaimana data-data yang digunakan dalam kajian ini diperolehi. Semua ujikaji yang digunakan akan diterangkan dengan lebih mendalam pada bahagian ini. Data-data yang digunakan merupakan ujikaji yang dilakukan sendiri. Kekuatan konkrit yang direkabentuk untuk kajian ini ialah 80 MPa. Konkrit yang telah dibancuh akan diawet selama 28 hari sebelum diuji.

3.2 Proses penyediaan konkrit

3.2.1 Penyediaan acuan

Acuan yang digunakan ialah acuan berbentuk silinder di mana ia berukuran 200 mm tinggi dan berdiameter 85 mm untuk ujian mampatan konkrit. Acuan ini diperbuat daripada PVC seperti dalam Rajah 3.1.

Rajah 3.1: Penyediaan acuan silinder

Sebelum digunakan, semua acuan hendaklah dibersihkan. Selepas itu, minyak pelincir disapu pada bahagian dalam acuan untuk memudahkan sampel dikeluarkan selepas konkrit mengeras. Selepas disapu dengan minyak, acuan disusun bagi memudahkan kerja menuang konkrit.

3.2.2 Penyediaan bahan-bahan

Dalam proses penyediaan konkrit, kualiti konkrit adalah bergantung kepada kualiti bahan-bahan mentah yang akan digunakan iaitu batu baur kasar, batu baur halus, simen Portland biasa, air dan bahan tambah. Terdapat dua jenis bahan tambah yang akan digunakan iaitu *superplasticizers* dan *silica fume.*

3.2.2.1 Batu Baur Kasar

Batu baur mestilah bersih daripada debu-debu yang terdapat pada permukaan batu tersebut. Selepas itu, ia dikeringkan dalam ketuhar selama 4 jam untuk menghasilkan permukaan batu yang kering (*surface dry*). Batu baur kasar yang digunakan adalah jenis hancur yang mana saiz maksima batu baur yang digunakan adalah 10 mm.

3.2.2.2 Batu baur halus

Batu baur halus (pasir) yang digunakan adalah terdiri daripada jenis pasir sungai yang saiznya tidak melebihi 2.36 mm. Saiz pasir terkecil yang digunakan ialah 150 µm. Batu baur halus perlu diperiksa kualitinya supaya memenuhi sifat-sifat yang dikehendaki. Untuk itu, analisis ayakan dilakukan supaya penggredan pasir dapat dilakukan. Ayak-ayak yang digunakan bersaiz 2.36 mm, 1.18 mm dan 150 µm.

3.2.2.3 Simen

Simen yang digunakan ialah Simen Portland Biasa Jenis I. Jenis simen yang digunakan adalah *cap Seladang*. Jenis simen ini dipilih kerana ia adalah halus dan kurang berketul-ketul jika dibandingkan dengan jenis simen yang lain. Simen yang halus akan menghasilkan konkrit yang memberikan kesenangan kerja yang tinggi dan kurang mengeluarkan air lelehan.

3.2.2.4 Bahan tambah

Ia dicampur dalam konkrit dengan kadar tertentu semasa membancuh, menggaul atau gaul semula bertujuan mengubah ciri-ciri konkrit pada peringkat konkrit basah dan konkrit keras. Terdapat dua jenis bahan tambah yang digunakan iaitu *superplasticizers* dan *silica fume.*

(i) S*uperplasticizers*

Bahan tambah jenis ini digunakan adalah untuk meningkatkan kebolehkerjaan konkrit. Ia akan merendahkan kandungan nisbah air-simen, dengan demikian akan menghasilkan konkrit yang lebih kuat. Selain itu, ia akan mengurangkan penggunaan simen di samping pengurangan haba penghidratan.

(ii) *Silica fume*

Penambahan *silica fume* akan mengurangkan konkrit basah daripada berlakunya lelehan bagi konkrit yang menggunakan nisbah air-simen yang rendah. Disebabkan oleh kehalusan dan kandungan silika yang tinggi, ia juga akan meningkatkan kekuatan konkrit pada tahap awal.

3.2.2.5 Air

Dalam ujikaji ini, air paip biasa digunakan dalam bancuhan konkrit. Air adalah diperlukan untuk proses penghidratan simen serta meningkatkan kebolehkerjaan konkrit. Air yang digunakan untuk membancuh konkrit tidak boleh mengandungi banyak bendasing kerana ia boleh memberikan kesan buruk kepada pengerasan, kestabilan isipadu dan kelasakan serta boleh menyebabkan konkrit peroi dan berlaku perubahan warna.

3.3 Rekabentuk bancuhan konkrit

Rekabentuk bancuhan dibuat berdasarkan pengalaman dan data-data dalam literatur. Beberapa ciri perlu ditetapkan untuk mengawal kualiti konkrit yang akan dihasilkan. Ciri-ciri ini ialah kesenangan kerja konkrit basah, kekuatan mampatan pada umur yang ditetapkan dan kelasakan (menetapkan kandungan minimum simen atau nisbah maksimum air (bebas-simen) konkrit tersebut)

Jadual 3.1 menunjukkan kuantiti bahan-bahan yang digunakan bagi menghasilkan 1 m^3 konkrit berkekuatan tinggi:

Jadual 3.1: Kuantiti bahan-bahan yang diperlukan

Bahan	Jenis	Kuantiti
Simen (kg)	Portland	480
Silica Fume (kg)	Serbuk kering / MB-SF	30
Batu baur halus (kg)	Pasir Sungai	757
Batu Baur Kasar (kg)	10mm	1011
Superplasticizer (mL)	Glenmium C380	5355
Air (kg)		153

3.4 Kerja membancuh konkrit

Konkrit digaul dengan menggunakan mesin pembancuh konkrit. Pertama sekali, sebanyak 70 % jumlah air, batu baur dan *silica fume* dimasukkan ke dalam mesin bancuhan. Bancuhan digaul antara 4 hingga 5 minit. Kemudian, S*uperplasticizers* dimasukkan ke dalam bancuhan. Simen dimasukkan apabila bancuhan tadi telah digaul dengan rata. Selepas itu, pasir dimasukkan sedikit demi sedikit dan dibiarkan bancuhan digaul antara 2 hingga 3 minit.

Akhir sekali, baki jumlah air dimasukkan ke dalam bancuhan dan dibiarkan gaul sehingga bancuhan rata. Ketika mesin berputar, hentikan sebentar dan ratakan campuran secara manual bagi memastikan campuran diaduk rata. Rajah 3.2 menunjukkan konkrit basah yang telah siap digaul.

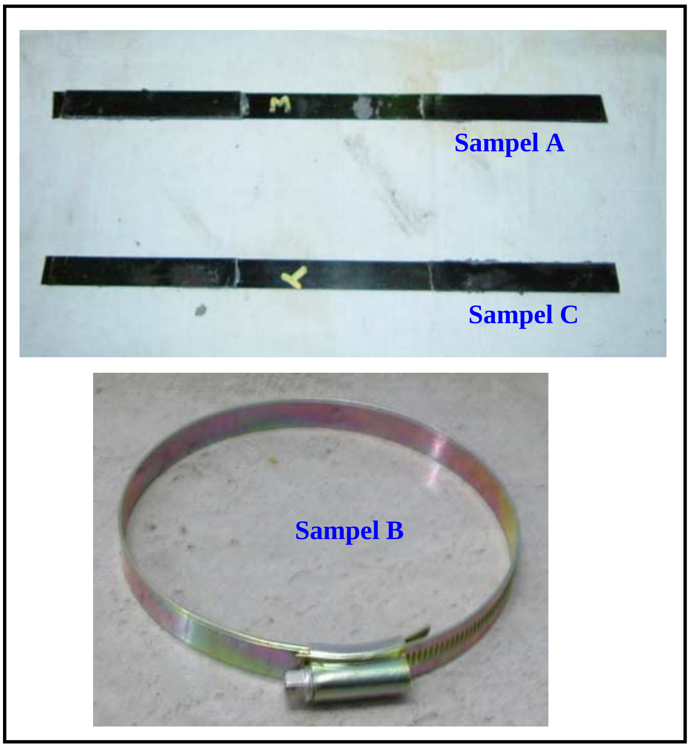
Kemudian, konkrit dimasukkan ke dalam acuan secepat mungkin selepas selesai proses bancuhan. Acuan-acuan tersebut ditutup dengan plastik untuk mengelakkan berlakunya kehilangan lembapan yang akan memberi kesan kepada proses pemejalan dan pengerasan. Kerja-kerja membuka acuan dilakukan pada keesokan harinya iaitu selepas 24 jam. Ia perlu dilakukan dengan berhati-hati supaya konkrit tidak rosak. Kemudian, konkrit-konkrit ini direndam dalam air bagi proses pengawetan selama 28 hari .

Rajah 3.2: Konkrit yang telah siap dibancuh kelihatan lebih basah daripada konkrit biasa

3.5 Kaedah melilit logam pada silinder

Selepas proses pengawetan selama 28 hari, kesemua sampel dikeluarkan daripada air dan dibiarkan kering selama beberapa hari. Kemudian, permukaan atas sampel dilicinkan menggunakan mesin pengisar. Proses ini bertujuan untuk meghasilkan permukaan yang licin agar beban yang akan dikenakan seragam ke seluruh permukaan atas sampel-sampel tersebut.

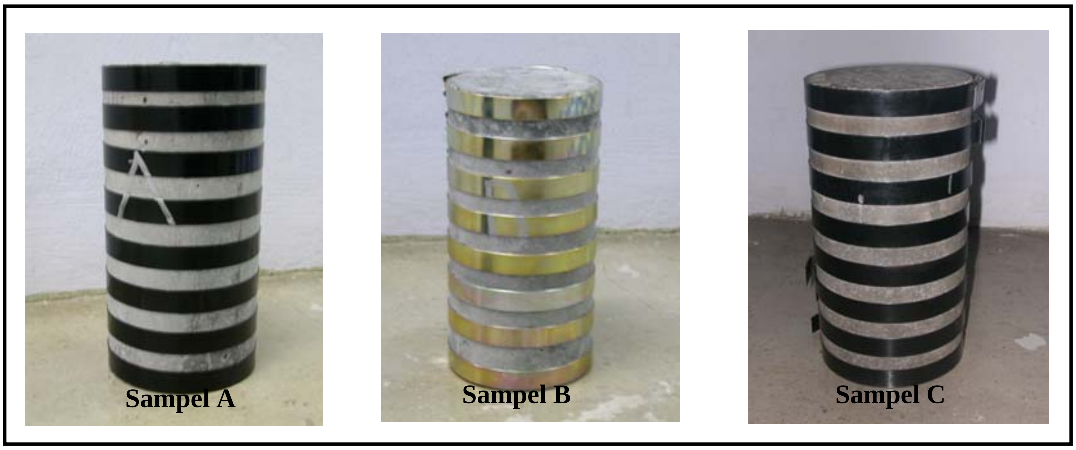
Kemudian, sampel dililit secara luaran di mana jarak antara jalur-jalur logam telah ditetapkan kepada 10 mm. Jarak ini didapati paling efektif di mana ia telah dikaji sebelum ini. Terdapat tiga jenis jalur logam yang digunakan di mana ketiga-tiganya berlainan kekuatan alah. Logam-logam tersebut banyak digunakan dalam industri pembinaan dan perkhidmatan penghantaran barang. Rajah 3.3 menunjukkan jalur logam yang digunakan bagi ujikaji ini.



Rajah 3.3: Jalur-jalur logam yang digunakan dalam ujikaji ini

Jalur-jalur tersebut diketatkan menggunakan alatan khas di mana ia ditunjukkan dalam Rajah 3.4. Rajah 3.5 pula menunjukkan sampel-sampel yang telah dililit dengan jalur logam yang berlainan jenis. Kaedah mengetatkan jalur logam bagi sampel B adalah berlainan di mana pemutar skru digunakan untuk mengetatkan jalur logam tersebut. Rajah 3.6 menunjukkan kaedah mengetatkan jalur logam bagi sampel B.

Rajah 3.4: *Tensioner* yang digunakan untuk mengetatkan jalur logam



Rajah 3.5: Sampel-sampel yang telah dililit dengan jalur logam

Rajah 3.6: Kaedah mengetatkan jalur logam sampel B

3.6 Ujian mampatan konkrit

Ujian ini aadalah berdasarkan kepada spesifikasi yang telah ditetapkan dalam BS 1881 Part 116: 1983 di mana ia bertujuan untuk menguji kekuatan mampatan konkrit yang dihasilkan.

Sampel-sampel silinder diuji pada hari ke-7, 14 dan 28 menggunakan mesin mampatan.

3.7 Ujian mampatan konkrit dikurung sisi

Ujian ini dijalankan dengan menggunakan mesin *DARTEC* berkapasiti 1200KN. Ujian dijalankan pada mod anjakan pada kadar 0.05 mm/saat. Beban dikenakan sehingga sampel gagal. Rajah 3.7 dan 3.8 masing-masing menunjukkan mesin yang digunakan dan sampel ujian.

Rajah 3.7: Mesin *DARTEC*

Rajah 3.8: Contoh sampel yang diujikaji

BAB IV

KEPUTUSAN DAN PERBINCANGAN

4.1 Pendahuluan

Bab ini membincangkan secara ringkas keputusan ujian mampatan paksi konkrit kurungan sisi dan ujian tegangan jalur logam. Perbincangan lebih terperinci boleh dirujuk di dalam dua kertas kerja yang telah dibentangkan seperti di **Lampiran A**.

4.2 Ujian kekuatan tegangan jalur logam

Maklumat jalur-jalur logam yang diuji adalah seperti Jadual 4.1.

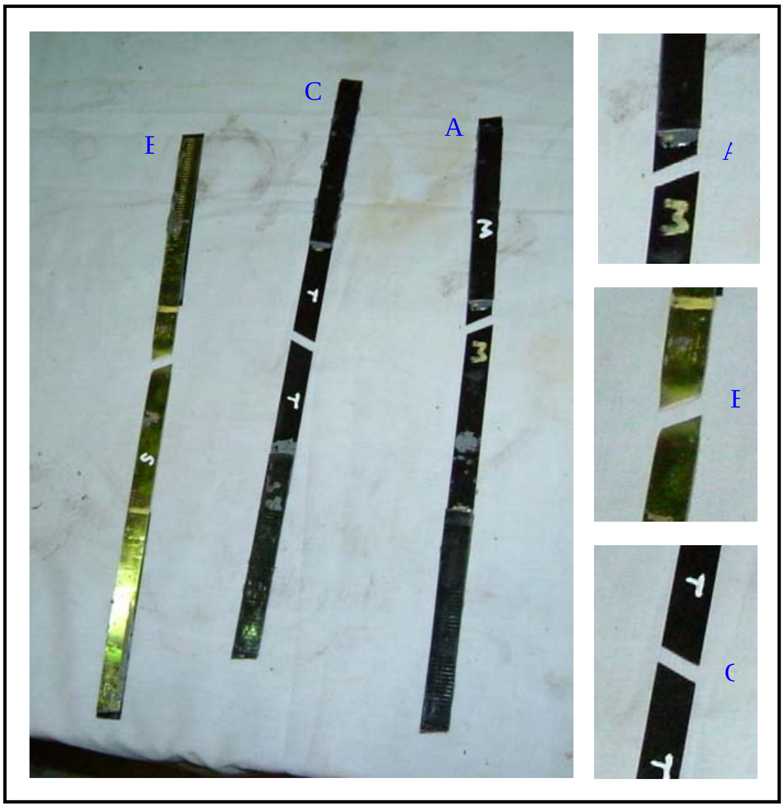
Jadual 4.1: Maklumat mengenai sampel logam yang diuji

Sampel	Panjang (mm)	Tebal (mm)	Lebar (mm)
A	102	0.46	12.72
B	104	1.00	11.97
C	102	0.49	12.73

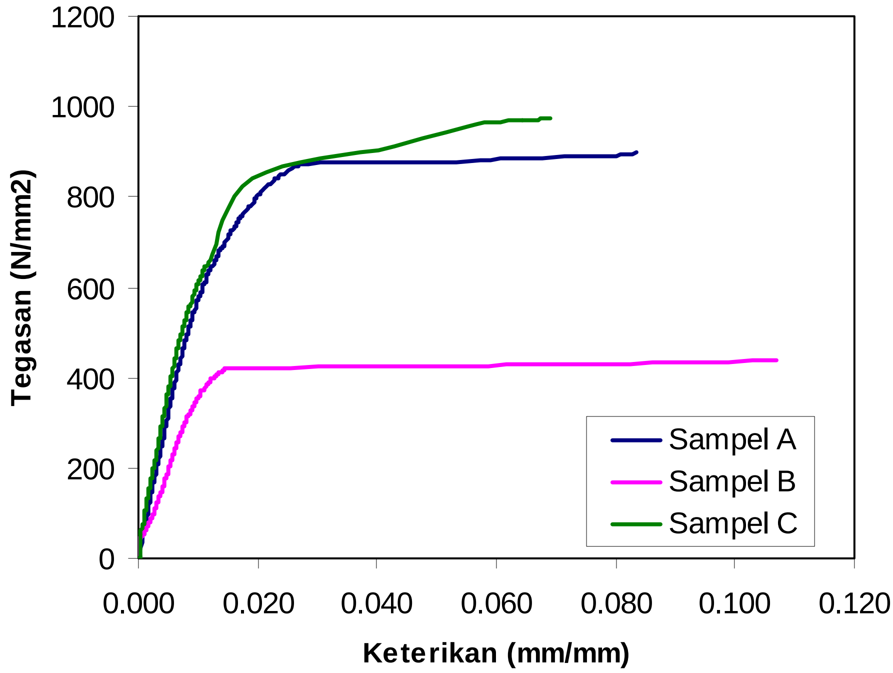
Jalur-jalur logam (seperti di dalam Rajah 4.1) ini diuji menggunakan mesin *DARTEC* berkapasiti *250 KN*. Jadual 4.2 menunjukkan keputusan ujian, manakala Rajah 4.2 menunjukkan hubungan tegasan-keterikan bagi setiap jalur tersebut. Berdasarkan Jadual 4.2, didapati nilai kekuatan jalur logam C menghasilkan kekuatan tegangan yang paling tinggi iaitu 975 N/mm^2 diikuti jalur logam B dan C masing- masing 439.1 N/mm^2 dan 897.1 N/mm^2.

Jadual 4.2: Data yang diperolehi daripada ujian tegangan jalur logam

Sampel	Beban Maksimum (KN)	Keterikan (mm/mm)	Tegasan Maksimum (N/mm^2)
A	5.249	0.084	897.1
B	5.256	0.107	439.1
C	6.083	0.069	975.2



Rajah 4.1: Mod kegagalan jalur logam



Rajah 4.2: Graf tegasan-keterikan bagi jalur-jalur logam yang digunakan

4.4 Ujian mampatan konkrit

Silinder diuji kekuatan mampatannya pada hari ke 7, 14 dan 28. Nilai kekuatan yang dicatatkan adalah mewakili kekuatan silinder yang akan digunakan sebagai sampel ujikaji. Kadar bebanan yang dikenakan adalah antara 0.2 N/(mm^{2}s) dan 0.4 N/(mm^{2}s) mengikut B.S 1881-116 1983. Jadual 4.3 menunjukkan data-data yang diperolehi bagi ujian mampatan konkrit pada hari ke 7, 14 dan 28. Keputusan ujian mampatan pada hari ke-7 ditunjukkan dalam jadual tersebut di mana kekuatan konkrit adalah 2/3 daripada kekuatan mampatan konkrit yang ingin dicapai iaitu 80 MPa. Keputusan ujian mampatan pada hari ke-28 pula menunjukkan kekuatan mampatan konkrit adalah melebihi kekuatan yang ingin dicapai (*target mean strength*).

Jadual 4.3: Kekuatan mampatan konkrit pada hari ke-7, 14 dan 28

Hari	Kekuatan Mampatan Konkrit (N/mm^2)		
	7	14	28
Sampel 1	51.3	61.6	84.4
Sampel 2	61.6	70.3	86.8
Sampel 3	58.3	70.9	84.6

4.5 Ujian mampatan konkrit dikurung sisi

Antara data-data yang diperolehi daripada ujian mampatan terhadap konkrit dikurung sisi adalah termasuk kekuatan muktamad konkrit, keterikan maksimum dan mod kegagalan.

4.5.1 Ubahbentuk sisi dan pugak

Perbincangan lebih terperinci berkenaan ubahbentuk sisi dan pugak telah dibentangkan di dalam dua kertas kerja di **Lampiran A**.

Jadual 4.4 menunjukkan peratus kenaikan keterikan pugak bagi setiap sampel kurungan sisi. Penggunaan kurungan sisi dapat meningkatkan keterikan pugak konkrit di mana jalur logam digunakan dengan efektif dalam mengekalkan struktur konkrit daripada berlakunya kegagalan pada beban kenaan yang rendah.

Jadual 4.4: Keterikan pugak bagi setiap sampel

Sampel	Keterikan Pugak Maksimum (mm/mm)	Peratus kenaikan (%)
Tanpa kurungan sisi	0.048	-
A	0.061	27..08
B	0.080	66.67
C	0.061	27.08

4.5.3 Mod kegagalan

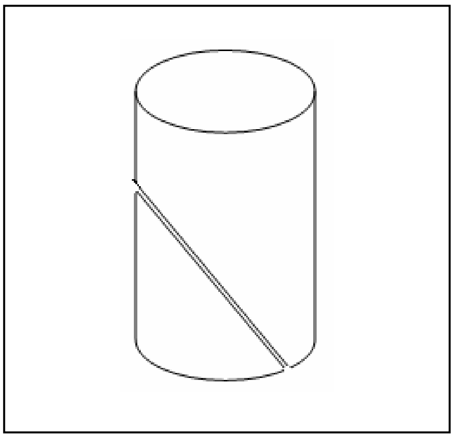
Rajah 4.5 menunjukkan kegagalan yang berlaku pada sampel A dan sampel C. Melalui rajah ini, ia dapat diperhatikan kegagalan berlaku disebabkan oleh pengikat yang tidak efektif dalam mengekang pemgembangan sisi struktur konkrit.

Rajah 4.5: Mod kegagalan sampel A dan C

Rajah 4.6: Mod kegagalan bagi sampel B

Rajah 4.6 menunjukkan mod kegagalan bagi sampel B di mana jalur logam tersebut gagal pada bahagian jalurnya. Apabila struktur konkrit tidak dapat menahan daya kenaan semakin tinggi, jalur-jalur logam tersebut bertindak dengan meningkatkan keterikan konkrit tersebut agar konkrit tidak gagal awal. Kurungan sisi ini dapat meningkatkan kekuatan dan kemuluran konkrit sehingga ke satu tahap di mana apabila jalur-jalur logam tersebut telah mencapai keterikan maksimumnya, struktur konkrit dan jalur-jalur logam tesebut akhirnya gagal.

Daripada Rajah 4.5 dan Rajah 4.6, mod kegagalan konkrit bagi ketiga-tiga sampel adalah sama. Semua sampel tersebut gagal dalam keadaan gelincir di mana ia retak dan menghasilkan sudut ke permukaan mendatar yang diilustrasikan pada Rajah 4.7. Kegagalan ini adalah seperti kajian yang dilakukan oleh Ge (1992) di mana beliau menyatakan kegagalan konkrit berkekuatan tinggi berlaku dalam bentuk gelinciran.



Rajah 4.7: Mod kegagalan konkrit

4.5.4 Kekuatan muktamad

Jadual 4.5 merumuskan kekuatan muktamad setiap sampel yang diperolehi daripada ujian mampatan konkrit dikurung sisi. Konkrit yang dikurung sisi menunjukkan peningkatan kekuatan dalam menanggung beban kenaan yang lebih tinggi jika dibandingkan dengan konkrit tanpa kurungan sisi. Oleh itu, jelas kelihatan bahawa kurungan sisi dapat meninggikan kekuatan muktamad konkrit berkekuatan tinggi. Walaupun sampel A dan C gagal disebabkan oleh pengikat jalur logam, ia masih menunjukkan peningkatan kekuatan muktamad yang lebih tinggi.

Jadual 4.5: Kekuatan muktamad setiap sampel

Sampel	Kekuatan Muktamad (N/mm^{2})	Peratus pertambahan (%)
Tidak Dikurung sisi	59.367	-
A	99.158	67.03
B	121.761	105.1
C	99.158	67.03

BAB V

KESIMPULAN DAN CADANGAN

5.1 Kesimpulan

Berdasarkan kajian dan analisis makmal yang dijalankan sepanjang kajian ini boleh disimpulkan bahawa:

i. Bahan-bahan tempatan seperti simen dan batu baur mempunyai ciri-ciri yang sesuai untuk menghasilkan konkrit kekuatan tinggi. Peningkatan kekuatan mampatan konkrit akan menghasilkan konkrit yang lebih rapuh atau kurang kemuluran.

ii. Teknik kurungan sisi adalah satu kaedah yang berkesan untuk meningkatkan kemuluran konkrit. Kurungan sisi menggunakan jalur logam yang di pra-tegang amat berkesan dalam meningkatkan kemuluran konkrit kekuatan tinggi.

iii. Jalur logam berkekuatan rendah menunjukkan peningkatan kemuluran yang lebih baik bagi konkrit kekuatan tinggi. Ini menunjukkan bahawa konkrit yang mempunyai kekuatan yang lebih tinggi tidak semestinya perlu dikurung sisi menggunakan bahan kurungan yang berkekuatan tinggi. Jalur logam berkekuatan rendah dan mempunyai kemuluran yang baik boleh menghasilkan konkrit kurungan sisi yang baik dengan menggunakan teknik pra-tegangan.

5.2 Cadangan ujikaji selanjutnya

i. Jalur logam mempunyai potensi yang baik sebagai bahan kurungan sisi konkrit kekuatan tinggi dan menjadi bahan alternatif kepada bahan moden seperti *FRP*. Tetapi kajian yang lebih lanjut adalah perlu bagi pengikat jalur logam yang lebih berkesan untuk mengelakkan kegagalan awal. Kajian juga perlu diluaskan kepada pelbagai kekuatan mampatan konkrit (50 – 120 MPa) supaya hasil yang lebih baik dapat dicapai.

ii. Setelah mendapati keberkesanan jalur logam sebagai bahan kurungan sisi konkrit kekuatan tinggi, kajian perlu dilanjutkan kepada keupayaan lenturan, kilasan dan seumpamanya. Kajian ini perlu dilakukan pada saiz tiang yang lebih besar dengan menggunakan mesin mampatan yang berkapasiti lebih tinggi.

iii. Ujian terhadap beban *cyclic* adalah dicadangkan untuk mengkaji keberkesanan konkrit kekuatan tinggi kurungan sisi terhadap beban gempabumi atau seumpamanya.

iv. Ujian rayapan dan pengecutan terhadap konkrit kurungan sisi menggunakan jalur logam adalah perlu untuk melengkapkan data kajian.

RUJUKAN

Surendra P.Shah, Fracture Toughness for High Strength Concrete, ACI Material Journal, May-June 1990, 260-265.

Attard. M. M. dan Mendis P.A, Ductility of High Strength Concrete Columns, Australian Civil Engineering Transactions, V 35, No 4, October 1993, 295-306.

P. Kumar Mehta, *Concrete: Structure, Properties And Materials*, Englewood Cliff, New Jersey: Prentice Hall, 1986.

Bertero, V. V., Inelastic Behavior of Structural Elements and Structures, Proceedings of Workshop on High Strength Concrete, University of Illinois at Chicago Circle, Dec. 1979, 91-98.

Edward G. Nawy, *Fundamentals Of High Strength High Performance Concrete*, Tottenham Court Road, London: Longman Group Limited, 1996.

Considere, A., Experimental Researches on Reinforced Concrete, McGraw Publishing Co., New York, 1903, 188.

Richart F.E., Brandtzaeg A. dan Brown R.L, The Failure of Plain and Spirally Reinforced Concrete in Compression, University of Illinois, Urbana, Engineering Experiment Station Bulletin No. 190, 1929.

Swamy, R.N., Jones, R. Charif, A., Repair dan Retrofit of a Full-scale Five-storey Masonry Research Building, Structural System Laboratory Test Report No. TR-93/04, Singapore, 1989.

Ahmad S.H, Khaloo A.R. dan Irshaid A., Behavior of Concrete Spirally Confined by Fiberglass Filaments, Magazine of Concrete Research, V.43, No. 156, Cement and Concrete Association, London, UK,1991, 143-148.

Saadatmanesh H., Ehsani M.R. dan Li M.W., Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps. ACI Structural Journal,V.91, No 4, July-August 1994, 434-447.

He J.H, Pilakoutas K. dan Waldron P., Strengthening of Reinforced Concrete Beams with CFRP Plates, Proceedings of the Third International Symposium on Non-metallic (FRP) Reinforcements for Concrete Structures, Vol. 1, 343-350.

Huei-Jeng Lin and Chin-Ting Chen 2001, Strength of Concrete Cylinder Confined by Composite Materials, Journal of Reinforced Plastics and Composites, Vol. 20, No. 18/2001, 1577-1600.

Shanim A.Sheikh dan Murat T.Toklucu, Reinforced Concrete Columns Confined by Circular Spirals and Hoops, ACI Structural Journal, V.90, no. 5, September-Oktober 1993, 542-553.

S.H Ahmad dan S.P. Shah, Stress-Strain of Concrete Confined by Spiral Reinforcement, ACI Structural Journal, November-Disember 1992, 484-490.

Esah Hamzah, Jasmi Hashim, Noor Hisham Abd Hamid, Norhayati Ahmad, Nota Sains Bahan, Jabatan Kejuruteraan Bahan, Fakulti Kejuruteraan Mekanikal, UTM, Edisi Kedua 1999.

Manual Makmal Kejuruteraan Awam II, Pejabat Akademik, Fakulti Kejuruteraan Awam, UTM, April 2003.

Ge, H.B and Lisani, T. (1992), *Strength of concrete-filled thin-walled steel box column: experiment,* Journal of Structural Engineering, Vol. 122, No. 11, 1327-1336.

LAMPIRAN A

1. Kertas kerja bertajuk *"Improving the Ductility of High-Strength Concrete Using Steel Straps Confinement"* telah dibentangkan di Seminar Kebangsaan Penyelidikan Kejuruteraan Awam (SEPKA 2005) anjuran Fakulti Kejuruteraan Awam, Universiti Teknologi Malaysia pada 5-6 Julai 2005, Sofitel Palm Resort, Johor Bahru, Johor.

2. Kertas kerja bertajuk *"Preliminary Experimental Investigation on the Performance of Laterally Confined High-Strength Concrete Columns Using Steel Straps"* telah dibentangkan di *2nd ACF International Conference,* Bali, Indonesia pada 20-21 Nov 2006.

IMPROVING THE DUCTILITY OF HIGH-STRENGTH CONCRETE USING STEEL STRAPS CONFINEMENT

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ABSTRACT: This paper presents the preliminary work on lateral confinement technique that uses relatively low cost steel straps, with the goal of minimizing the brittleness failure of high-strength concrete columns. The steel straps applied along the height of 85 mm diameter and 170 mm high of cylindrical specimens using a tensioner and sealer. Detail description of the preparation of high-strength concrete is presented. The effects of confining straps on increasing ductility and strength of high-strength concrete were explored; with the main focus was on the ability of the concrete to deform under monotonic compressive load. The confined concrete effectively restrained microcracking and improved crack stability, leading to improved ductility and strength of the tested specimens.

Keywords – high-strength concrete; ductility; stress-strain relationship; steel straps confined concrete; axial compressive load.

1. INTRODUCTION

High-strength concrete is relatively new structural material and has superior performance in engineering applications. With the development of concrete technology, concrete strength of up to 100 MPa and higher can be reached using the ordinary materials that used in the production of normal-strength concrete without difficulties. It has been noted that high-strength concrete will play an increasingly important role in future applications.

High-strength concrete is produced basically by improving the compactness of the fresh concrete with a low water-cement ratio. This increases the strength of both the paste and the interface between the paste and the aggregates. However, an increase in the strength of the concrete results an increase in its brittleness and smoother failure surface. These phenomena are indicated by very rapid and explosive type of failure under various type of loading.

The lack of ductility in the high-strength concrete is indicated by steep ascending slope followed by the very steep descending slope of the stress-strain curve in axial compression as shown in Fig. 1 (Attard and Setunge 1996; Candappa et al. 2001). A few methods are known to increase the ductility of members under compression of high-strength concrete, such as the incorporation of steel fibers or composite construction like column of a steel tube filled with high-strength concrete. The above-mentioned methods sometimes are disadvantageous with regard to costs and workability.

Other possibility is the use of lateral confinement reinforcement in compressive loaded columns. It has been established that concrete can be confined effectively to obtain an essentially flat descending region of the stress-strain curve (Nawy, 2001). Confining the concrete not only increases the ductility of concrete significantly, but also increases the strength of concrete. Many research works (Roy, 1964; Priestley, 1981; Mander, 1988) have started since a century ago studying various aspects of confinement parameters particularly for conventional concrete. As a result, the confinement mechanism is now well understood for concrete with compressive strength up to 50 MPa. However, as the higher strength concrete behaviour deviates from that of normal-strength concrete, these findings may be questioned and may not be as effective or as safe when they are applied to high-strength concrete (ACI363R-92, 1997; Bayrak, 1998). On the other hand, research on confined high-strength concrete is relatively new and the results obtained so far were not conclusive.

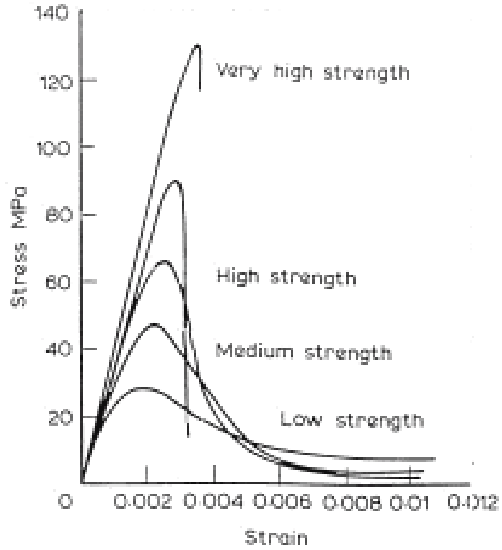

*Fig. 1. **S**tress-strain curve of a various strength of concrete (ACI 363R-92 1997)*

Nowdays, confinement of concrete in structural members is commonly provided by an expensive FRP composite. The problem with FRP confinement of concrete is that the strength of the FRP jacket is not utilised until the lateral strain in the confined concrete is very high (Pilakoutas, 1997). In some cases, the concrete will crush before the FRP jacket is fully utilised. In this study, the relatively low cost steel straps were used to confine high-strength concrete cylinders. The ability of the confined concrete subjected to monotonic compressive load to deform was investigated.

2. EXPERIMENTAL PROGRAMME

2.1 Mix Proportion and Test Specimens

Table 1 presents the mix proportion of concrete of targeted strength of 80 MPa.

Table 1. Concrete mix proportion for high-strength concrete

Materials	Cement	Silica Fume	Coarse Aggregate	Fine Aggregate	Plasticiser	Water
Type	OPC	Dry Powder MB-SF	Crushed granite	River sand	Glenium C380	
Proportion	480 kg	30 kg	1011 kg	757 kg	5100 mL	153 kg

The cement used in the project was Type I Portland cement. It complies with Malaysian Standard MS 522: Part 1: 1989 Specifications for Ordinary Portland Cement as well as BSEN 196. The coarse aggregate was crushed granite and a maximum size of 12.5 mm. It was pre-washed to eliminate dust and impurities. The crushing value of the coarse aggregate was 18. The fine aggregate was a 2.36 mm of river sand with a fineness modulus value of 2.8. Both of the aggregates comply with Malaysian Standard MS 30: 1995 Methods of Testing Aggregate and BS 812: Part 1: 1975. The water binder ratio of 0.3 was used in the mix.

The MB-SF brand of silica fume used in this study was a dry compacted, ultra-fine material and formulated to produce concrete with special performance qualities. The silica fume addition rate used was 6% by weight of cement. The silica fume was added to the first 60-80% of mixing water and the coarse aggregate at start of the mixing process, and the adequate time of mixing was allocated. This is to ensure that the agglomerations that make up the densified silica fume broke down; and the silica fume distributed uniformly throughout the concrete. The Glenium C380 type of superplasticiser used was free from chlorides and complies with ASTM C494 Types A and F. It is differentiated from conventional superplasticisers in that it was based on modified polycarboxylic with long lateral chains. This greatly improves cement dispersion. The Glenium was poured into the concrete mix right after the addition of the silica fume. Thorough mixing was required for complete dispersion throughout the mix. Both of the materials were supplied by the MBT (Malaysia) Sdn. Bhd.

The addition of the mixing materials into the revolving mixer was in a sequence as follows: 60-80% of water, coarse aggregate, silica fume, superplasticiser, cement, fine aggregate and the remaining 20-40% of water. An additional time of 2 to 3 minutes was allocated after the addition of each material. The sequence and adequate time of mixing are very important to ensure that the required workability of concrete is achieved. Initial workability may drop rapidly with time after mixing. The workability of the fresh concrete was a flow type of 500 mm diameter.

Twenty-four cylindrical specimens with a diameter of 85 mm and a height of 170 mm, and six cubes with dimensions of 100 mm were prepared. The diameter of the cylinder was designed to suit with the capacity of the testing machine available in the Structures and Materials Laboratory. It was estimated that the capacity of confined concrete cylinder would be up to four times of the unconfined one. All cylindrical specimens were cast using PVC moulds as shown in Fig.2. The mould was placed in plywood bracings in order to ensure its stability and to obtain perfectly horizontal top and bottom surfaces.

Fig.2. Concrete cast into PVC moulds

Six cylinders and six cubes were tested to determine the concrete compressive strength at age of 7 and 28 days. The compressive strength derived from the tests are reported in Table 2. All samples were cured in water under room temperature until tested. Top face of each cylinder specimen was capped with a composite material in order to reduce imperfections of the surface and guarantee an even distribution of the applied load. High-strength concrete cylinders were more susceptible to end imperfections than normal strength concretes due to the higher stresses in the concrete specimen. Therefore, the ends have to be smooth, parallel to each other and perpendicular to the axis of the cylinder.

Table 2. Test result on concrete cylinder control specimens

Sample No.	7-day		28-day	
	Cube	Cylinder	Cube	Cylinder
	f_c (MPa)	f_c (MPa)	f_c (MPa)	f_c (MPa)
1	81.4	83.1	98.9	84.4
2	78.9	73.8	87.6	86.8
3	83	81	92.5	89.5
Average	81.1	79.3	93	86.9

2.2 Confined Concrete Cylinders

Two types of steel straps with different strengths were used to confine the concrete cylinder laterally. Fig. 3 shows the stress-strain properties of the straps. The dimensions of cross-section of both straps were 10 mm width and 0.4 mm thick. The tensile capacity of the straps was 900 and 500N/mm^2 for steel type S1 and S2 respectively. The straps were placed and sealed along the length of the specimens using tension and seal machines. The spacing between straps was maintained to 8 mm. The straps were slightly pulled to guarantee that it was fully grips to the concrete before applying the load. Fig.4 shows the confined concrete before testing is carried out. All specimens were loaded concentrically using a Dartex Universal Testing Machine with a capacity of 5000 kN and were tested to failure. The longitudinal and lateral strains were measured using LVDTs and strain gauges, respectively and all of them were taken in the middle half of the cylinders. In addition, the ram displacement was also measured, but it was not used directly for estimating strains.

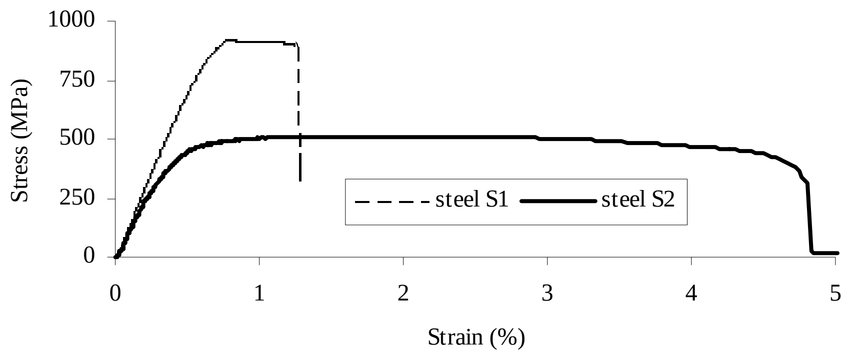

Fig.3. Stress-strain properties of steel straps

Fig.4. Concrete confined with different type of steel straps

3. RESULTS AND DISCUSSION

3.1 Failure Modes

Some of the typical modes of failure of unconfined high-strength concrete are shown in Fig.5. It was observed that the fracture surface of high-strength concrete was smoother and the cracks propagated through both the matrix and aggregates without any discontinuity. This observation was not seen in an ordinary concrete that the fracture only occurs along the aggregate-matrix interface; the aggregates were not broken. This results in rough failure surface of the normal strength concrete.

Fig.5. Unconfined concrete after failure

For the confined concrete cylinders subjected to compressive load, in this preliminary study, it was observed that the failure occurred mainly at the top face of the concrete. In general, the whole length of concrete cylinders remained intact except for only few small cracks of concrete between the steel confinements. However, the failure at the top should be avoided, in order to ensure that the actual effects of the confinement materials were achieved. It was noticed that the failure was due to the lacking of confinement at the top ends of cylinders. As a result, a substantially more confinement at the top and bottom to avoid the end effects will be used in the subsequence works. Failure at the top may also be due to segregation of the concrete. To avoid segregation, more sand is required in the mix, in a way to offer support to the aggregates.

It also observed that the confinement materials were not mobilised until the concrete crushed. This may be due to the lateral dilation of high-strength concrete occured in a slow rate especially at the beginning of loading phase to induce lateral pressure to the confining materials. In order to fully mobilise the steel straps, the technique of pre-tensioning may be applied in initiating the confining pressure to the concrete. This technique will be investigated in the future works.

3.2 Stress-Strain Relationships

Fig.6 and 7 show the stress-strain diagrams for the specimen tested with steel straps of type S1 and of type S2, respectively. Each graph shows the results for the unconfined cylinders as well as for the confined samples. Strain measurements shown, are the average values from three longitudinal LVDT gauges and two lateral strain gauges.

From Fig. 6 it can be seen that, the strength has increased by about two times that of the unconfined concrete whilst the strains increased by almost three times in both the lateral and longitudinal directions. The stress-strain curve of the confined concrete remains linear at a higher axial stress. This means that the internal microcracking that occurs in concrete as load was applied was delayed, and therefore the elastic response to compression was extended.

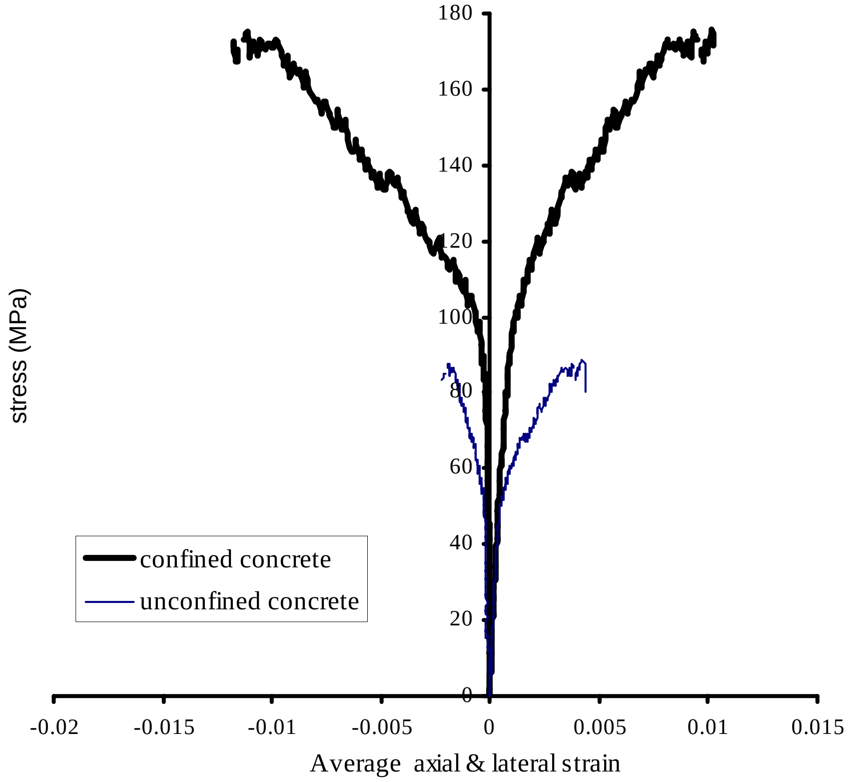

Fig.6. Axial and lateral strains for confined and unconfined concrete (using steel strap type S1)

Fig. 7 shows the amount of strength increased is slightly lower than the value in the Fig. 6. But, in contrast, the strains have increased by almost four times in the both lateral and longitudinal directions. This implies that the concrete confined by the steel with less tensile strength and high elongation is more effective in term of improving the ductility of concrete. The ductility of concrete was indicated by the descending or softening portion of the axial-stress–axial-strain curve.

Both figures show that the behaviour of ascending portion of the axial-stress–axial-strain curve of confined concrete was remained as same as the unconfined behaves. This means that the key material parameters such as the modulus of elasticity were not affected by the steel confinement. Also as shown in figures, the total area under the stress-strain curves that represent the amount of energy absorbed by the concrete under loading was considerably increased. Moreover, the axial-stress–lateral-strain behaviour of the concrete shown in both figures indicate that the volumetric behaviour of concrete was changed due to lateral reinforcement. The volumetric behaviour of confined concrete is important to predict the level of passive confinement provided by lateral reinforcement.

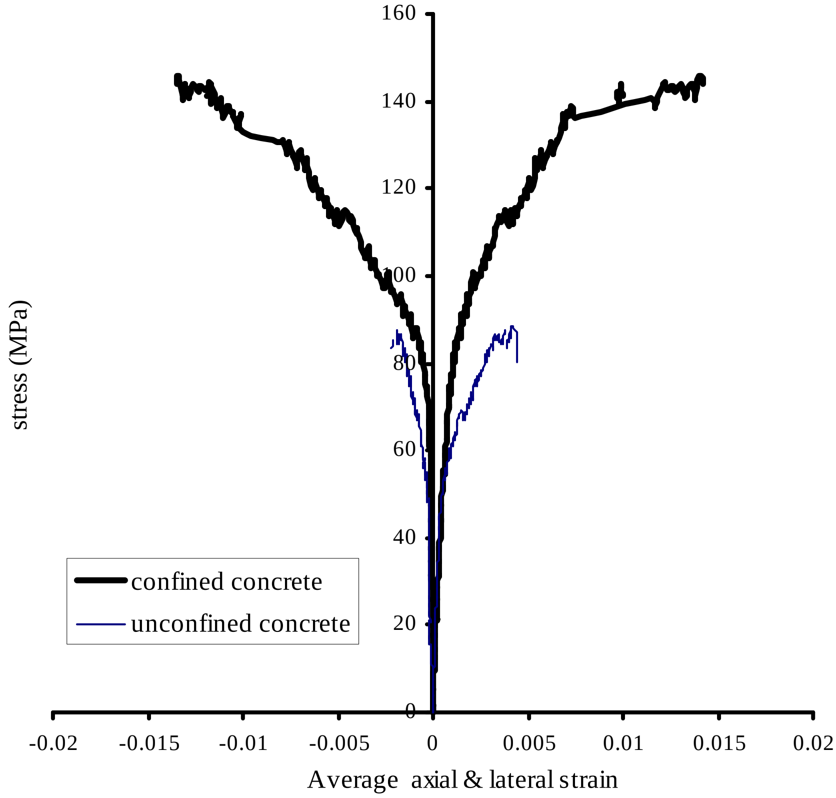

Fig.7. Axial and lateral strains for confined and unconfined concrete (using steel strap type S2)

4. CONCLUSIONS

It is shown that the relatively low cost steel strapping can be utilised to improve the ductility of the high-strength concrete. The confining high-strength concrete results in an outstanding new ultrahigh-strength concrete in the vicinity of 180 MPa.

This study has demonstrated that the confinement steel straps with a high tensile strength improved the strength of the confined high-strength concrete significantly. On the other hand, straps that with a higher ductility have been observed were more effective in improving the ductility of the confined concrete but not as good as for increasing the strength of concrete.

5. ACKNOWLEDGMENTS

The research reported in this paper was supported by the Research Grant Vot. No. 75136 with funds given by the Universiti Teknologi Malaysia. The authors gratefully acknowledge this generous support. The authors would like to acknowledge the University of Sheffield, UK, which provided the collaborative support throughout the project. The authors are also grateful to Research Assistance, Shamsul Kamil Abdul Karim, whose laboratory assistance and support made this investigation possible.

6. REFERENCES

ACI363R-92. (1997). "State-of-the-Art Report on High-Strength Concrete." American Concrete Institute.

Attard, M. M., and Setunge, S. (1996). "Stress-Strain Relationship of Confined and Unconfined Concrete." *ACI Materials Journal*.

Bayrak, O., and Sheikh, S. A. (1998). "Confinement Reinforcement Design Consideration for Ductile High Strength Concrete Columns." *Jounal of Structural Engineering*, 124(9), 999-1010.

Candappa, D. C., Sanjayan, J. G., and Setunge, S. (2001). "Complete Triaxial Stress-Strain Curves of High-Strength Concrete." *Journal of Materials in Civil Engineering*, 13(3), 209-215.

Mander, J. B., Priestley, M. J. N., and Park, R. (1988). "Theoretical Stress - Strain Model for Confined Concrete." *Jounal of Structural Engineering*, 114(8,), 1804-1826.

Nawy, E. G. (2001). *Fundamentals of High-Performance Concrete*, John Wiley & Sons, Inc., New York.

Pilakoutas, K., and Mortazavi, A. A. (1997). "Ductility Through External Lateral Confinement of RC Members with FRP." *Proceeding of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, 1, 225-232.

Priestley, M. J. N., Park, R., and Potangaroa, R. T. (1981). "Ductility of Spirally-Confined Concrete Columns." *Jornal of the Structural Division*, 107, 181-202.

Roy, H. E. H., and Sozen, M. A. "Ductility of Concrete." *Flexural Mechanics of Reinforced Concrete, Proceedings of the International Symposium*, Miami, Florida, 213-235.

PRELIMINARY EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF LATERALLY CONFINED HIGH-STRENGTH CONCRETE COLUMNS USING STEEL STRAPS

Wahid Omar[1], Kypros Pilakoutas[2] and Abdullah Zawawi Awang[3]

ABSTRACT: This paper presents the preliminary results of an experimental investigation on confined high-strength concrete, which is ongoing in the Faculty of Civil Engineering, Universiti Teknologi Malaysia. The results of the present preliminary study which is limited to concentrically loaded cylinders show that laterally tensioned high-strength concrete with a low cost steel straps greatly increases its strength and results in outstanding new ultrahigh-strength concrete and improves its ductility. It is shown that the confinement efficiency for higher concrete compressive strength increases with laterally pre-tensioning of steel straps. Comparison between the experimental results and some available confinement models was made and indicates that HSC confined with relatively low cost steel straps has an excellent and a comparable performance.

KEYWORDS: high-strength concrete; ductility; lateral confinement; steel strapping; axial loads.

1. INTRODUCTION

The demand for high-strength concrete (HSC) has increased considerably since the last few decades and HSC now being used in many parts of the world. It is more frequently used in columns of high-rise and medium-rise buildings, in pre-cast concrete industries, and in beams of long span bridges. The concrete has been used widely in structures where durability is an important design consideration. Besides that it has a higher compressive strength property, HSC has greater modulus of elasticity, and great savings resulting from the section reduction. In Malaysia, the Petronas Twin Towers with a height of 425 m from sea level, the second highest building in the world (after Taipei 101) have utilised the high-strength concrete with a compressive strength of 83 MPa in the lower storey columns.

The definition of HSC varies and depends on many factors such as geographical, material, technology, time, etc. Therefore, there is no unique definition of HSC. For example, in the United State a concrete with a compressive strength of 41 MPa has been specified as a lower limit of HSC (ACI 363R-92 1997).

As a result of recent developments in material technology, the higher strength concrete even of a compressive strength greater than 100 MPa can be produced reliably in the field. Concrete with strength in the region of 200 MPa is also producible under laboratory conditions. The HSC is produced basically by improving the compactness of the fresh concrete with a low water-cement ratio. This increases the strength of both the paste and the interface between the paste and aggregates. However, the increase in the strength of the concrete results in an increase in brittleness.

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In this paper, the experimental results of HSC columns laterally confined with a low cost steel straps are presented and discussed. The aim of the study is to investigate the effectiveness of steel straps in improving the ductility of HSC. The technique is simple and easy to apply in real structures.

2. THE LACK OF DUCTILITY OF HSC

The characteristics of higher strength concrete are indicated by steep ascending slope followed by the very steep descending slope of the stress-strain curve in axial compression as shown in Figure 1.

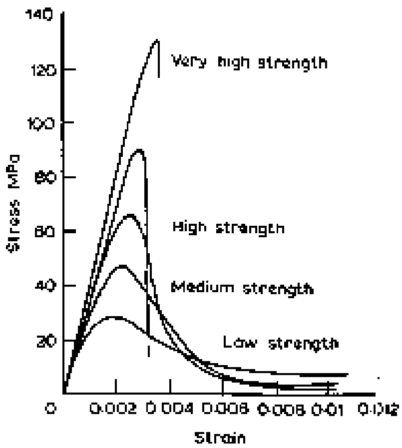

Figure 1. Stress-Strain Curves of HSC and NSC (ACI 363R-92 1997)

The curves indicate that several aspects of the material behaviour of HSC differ significantly from those of normal strength concrete (NSC). Those aspects include elastic and nonlinear behaviours of the materials and strain softening which is related to the internal cracks propagation. Therefore, HSC should not just be regarded as NSC with higher strength. HSC is more brittle in nature because cracks in this material do not always follow the aggregate-hardened cement paste interfaces as occurs in NSC. This is due to improved interfacial bond strength of HSC. The cracks may cut right through the hardened cement paste and even the aggregate particles as shown in Figure 2. This phenomenon may lead to rapid propagation of the cracks and sudden or sometimes explosive failure of the concrete.

Figure 2. Crack in High-Strength Concrete.

2.1 Lateral Confinements of HSC

Lateral reinforcement or confinement in reinforced concrete columns plays an important role in enhancing the strength and ductility. The confinement may in the forms of rectilinear ties, hoops or spiral reinforcements. When a concrete column is laterally reinforced and subjected to axial compression loads, concrete dilation in the lateral direction of the column section

exerts “internal” pressure. The pressure activates the lateral steel, which confines the column by exerting “external” lateral pressure. The resistance of the steel may restrain the core concrete to a degree, prevents from cracking and gains more strength compared to unconfined concrete. The effectiveness of lateral steel is related to Poisson’s effect of concrete. It is known that Poisson’s effect for concrete is not constant as load increases; it increases with axial strain increments. This characteristic may help in activating lateral confinement. However, the role of confining reinforcement in HSC is still questionable. It is found that the lateral expansion capacity of HSC is lower than that of NSC (Persson 1999).
The degree of confinement is established by various confinement parameters. However, it is not easy to explicitly measure the mechanical behaviour of confined concrete because of various interdependent parameters and variables involved. Such parameters are the confinement type, the compressive strength of concrete, the volumetric ratio and the strength of confinement reinforcements, etc. In general, the mechanical behaviour of confined concrete is measured by the increment in compressive strength and compressive strain at peak stress with respect to the unconfined compressive strength and strain at peak, respectively.

There have been many attempts to investigate the effectiveness of transverse steel reinforcement in confining HSC with respect to various parameters. Saatcioglu and Razvi (1992) and Razvi and Saatcioglu (1999) observed that the HSC columns need stronger confinement to maintain the effective ductility. Assuming that the strength and ductility of confined concrete are closely related to the tie stress, Cusson and Paultre (1995) proposed a method to determine the stress of lateral ties as an important index to measure the confinement degree. On the other hand, Chung et al. (2002) observed that the volumetric ratio of ties is a more important parameter in enhancing strength and improving ductility than is the tie strength. However, the increase in volumetric ratio is normally achieved by placing a closed spacing of transverse steel. The closed spacing of steel will create congestion and causing the formation of a weak plane between cover and core concrete. In addition, many studies have shown (Bae and Bayrak 2003; Forster et al. 1998) that early cover spalling has been observed in columns with HSC under axial compression loads. This may due to either the buckling of the cover shell or restrained shrinkage in the cover shell combined with shrinkage of the HSC around the reinforcing steel. The strength of HSC columns affected by spalling of the cover and the concrete core is no longer able to carry increased loads after the cover is spall off prematurely.

More recently the interest in using composite material like fiber reinforced polymer (FRP), for HSC column confinement has led to more research. It was shown (Campione and Miraglia 2003) that the use of FRP materials offers almost always an increase in strength and ductility. FRP has also several advantages compared to traditional reinforcements, such as corrosion free and its lightness. However, the initial cost of this material is quite high and the material is not fully utilised prior to concrete crushing.

Mortazavi and Pilakoutas (2001) have introduced a lateral pre-tensioning to the FRP jackets in order to have a better utilization of the confining material. The results have shown that pre-tensioned FRP materials can increase slightly the load bearing capacity of the column. The technique use expansive materials to apply pressure on the jacket reacting against the concrete. The degree of applied pre-tension force depends on the amount and type of expansive material used; hence it may only suitable for small concrete members.

3. EXPERIMENTAL WORK AND RESULTS

3.1 Materials and Mix Proportion

The HSC used in this study was produced from commercially available materials and the mix proportion was carried out based on local experience as well as references taken from existing literature. The cement used was ordinary Portland cement of type 1 satisfying BS 12:1978 (ASTM-C150). Normal weight river sand from local source (Johore River at southern Malaysia), consisting mainly of quartz and with fineness modulus of 2.8 was used. Normal weight crushed and rounded granite aggregate from local quarry, with a maximum size of 10 mm was used. The characteristics of fine and coarse aggregates complied according to either ASTM or British Standards as appropriate. For HSC, it was necessary to use a low water-cement ratio and a high cement content to achieve the desired strength level. The water-cement ratio of 0.3 was used. In order to minimise the adverse effects of the high content of cement to hardened characteristics of the concrete, cement content was limited to 500 kg/m^3. The silica fume of MB-SF was used for cement replacement. The superplastiser used was Glenium C380, supplied by the Master Builders Technologies. Besides the materials quality, the technique and process of mixing also affected the workability and strength of the concrete. Table 1 provides the mix proportion and other properties of the concrete. The average concrete cylinder compressive strength attained was 80.9 MPa for all cylinders at the time of tests.

Table 1. Concrete Mix Proportion

Materials	Cement	Silica Fume	Coarse Aggregate	Fine Aggregate	Plasticiser	Water
Type	OPC	Dry Powder MB-SF	Crushed granite	River sand	Glenium C380	
Proportion	480 kg	30 kg	1011 kg	757 kg	5100 mL	153 kg

3.2 Properties of Steel Confinements

Three types of steel straps with tensile strengths in a range of 420 and 1000 MPa were used as external lateral confinement reinforcement. The cross-section of all straps was 0.4 mm width and 10 mm thickness. These types of straps are similar to the type usually used in the box packaging industries. Stress-strain relationships for all types of steel, established by tensile tests, are shown in Figure 3. Each relationship represents the average result from at least three specimens of steel straps.

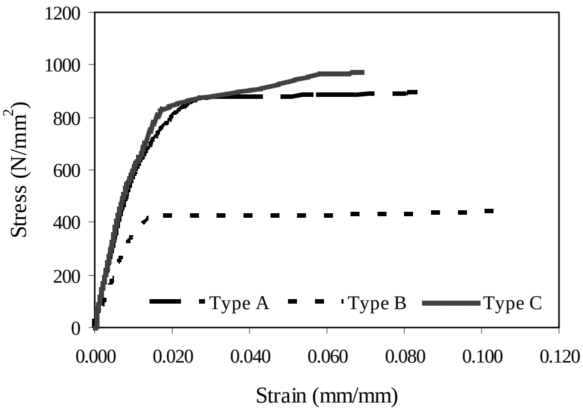

Figure 3. Stress-Strain Relationships of Steel Straps

As shown in the figure, the steel straps type A and C are products of high-strength black steel with ultimate stress of 900 and 1000 MPa respectively. Both of them have ultimate strain in a range of 0.07 to 0.082. Whereas type C is zinc plated steel with an ultimate strength of 420 MPa and has high elongation with a strain of 0.12. Type A and C has also slightly higher modulus of elasticity compared with type B steel straps.

3.3 Test Specimens

Thirty cylindrical specimens with a diameter of 85 mm and a height of 170 mm were cast. The size of the cylinder was designed to suit with the capacity of the testing machine that is available in the laboratory. It was estimated that the confined concrete cylinder capacity would reach up to more than twice of the unconfined cylinder. The specimens were cast in PVC's moulds. In order to ensure the stability and to obtain perfectly horizontal top and bottom surfaces of the cylinder, moulds were placed in specially designed plywood bracings as shown in Figure 4. All test specimens were water cured until the age of 28 days.

Figure 4. Concrete Cast in PVC Moulds

The test specimens were grouped into three groups. The first group was for the unconfined cylinders. There were five cylinders tested under compression loads without confinement reinforcements. The second group that contained 15 cylinders was wrapped laterally with steel straps type B along the cylinder length. The variables of confined cylinders were the spacing between the successive straps, i.e., 5 mm, 10 mm and 15 mm. The straps were wrapped on the cylinder surface using special tensioner and then sealed with steel clips. They were slightly pulled to ensure that they were fully grips to the concrete before applying the load. The confined concrete cylinders are shown in Figure 5. The third group of the cylinders was wrapped with different steel straps, namely type A and type C. The spacing of straps was fixed to 10 mm. All cylinder specimens used in this programme had no longitudinal bars.

Thin layers of a high-strength composite material were used as capping over the top and bottom ends of each specimen. HSC columns were more susceptible to end imperfections than NSC due to the higher stresses in the concrete. Therefore, to ensure that the failure would occur in the instrumented region of the tested specimens, the ends have to be smooth, parallel to each other and perpendicular to the axis of the cylinder.

Figure 5. Confined Concrete Cylinders with Steel Straps of Type A (Right) and Type B (Left).

3.4 Experimental Set-up

Tests were conducted in a stiff loading frame using a Universal Testing Machine of 1200 kN capacity in the displacement-controlled mode with a velocity of 0.1 mm/min. All specimens were adequately instrumented at the middle of their height to measure the axial and radial deformations. Linear variable displacement transducers (LVDTs) and strain gauge were used to measure the average deformations. However, due to some errors while measuring radial deformation, the results could not be presented in this paper.

Test progress was monitored on a computer screen, and all load and deformation data were captured and stored in a diskette via a data logger.

3.5 Test Results and Discussion

Failure Modes: Some of the typical modes of failure of unconfined and confined concrete cylinders are shown in Figure 6. It was observed that the fracture surface of high-strength concrete was smoother and the cracks propagated through both the matrix and aggregates without any discontinuity. This observation could not be seen in an ordinary concrete that the fracture only occurs along the aggregate-matrix interface; the aggregates are not broken. This results in rough failure surface of the NSC.

Figure 6. Concrete specimens after failure

For the confined concrete cylinders subjected to compressive load, in this preliminary study, it was observed that the failure occurred mainly at the top face of the concrete. In general, the whole length of concrete cylinders remained intact except for only few small cracks of concrete between the steel confinements. However, the failure at the top should be avoided, in order to ensure that the actual effects of the confinement materials were achieved. It was noticed that the failure was due to the insufficient of confinement at the top ends of cylinders. As a result, a substantially more confinement at the top and bottom to avoid the end effects will be used in the subsequence works. Failure at the top may also be due to segregation of the concrete. To avoid segregation, more sand is required in the mix, in a way to offer support to the aggregates.

It was also observed that the confinement materials were not failed until the concrete crushed in cylinders confined with steel straps type A and C. Most of the steel straps were failed at the connections before the ultimate capacity of the confined cylinders was achieved. It was noticed that the failure of the joint was due to the breaking of the clips and the slipping of the steel ends. An attempt was made to improve the connection efficiency for the next experimental work. For the cylinders with the steel type B, the straps were broken while the concrete crushed. The tensioning force applied to the steel straps facilitated in initiating the confining pressure to the concrete. Such type of force was observed very significant due to the lateral dilation of high-strength concrete occurred in a slow pace especially at the initial stage of loading to induce lateral pressure to the confining materials.

Stress-Strain Responses: Figure 7 and 8 show the stress-strain diagrams for the unconfined and confined specimens tested under axial compression loads. Figure 7 shows results for concrete wrapped with different types of steel straps. Strength comparison between the different types of steel straps is as shown in Figure 3. Figure 8 shows a variation of strength and ductility achievement with different spacings of steel straps type B. Strain measurements shown, are the average values from longitudinal LVDTs and strain gauges.

From Figure 8 it can be seen that, the strength has increased by about twice of that the unconfined concrete whilst the strains in longitudinal direction increased by almost three times. However, in contrast, the highest stress and strain increments were occurred in concrete confined by the steel with less tensile strength and slightly high elongation. This implies that the concrete confined by such type of steel is more effective in term of improving the ductility of concrete. The ductility of concrete was indicated by the descending or softening portion of the axial-stress–axial-strain curve. However, the performance of the concrete confined with steel straps of types A and C were under estimated due to connections failure. Their strength and strain capacities are expected will be much higher if the joints are improved. The stress-strain curve of the confined concrete remains linear at a higher axial stress. This may due to that the internal microcracking that occurs in concrete as load was applied was delayed, and therefore the elastic response to compression was extended. This linear portion of the curve of confined concrete is also remained the same as the unconfined behaves. This means that the key material parameters such as the modulus of elasticity were not affected by the steel confinement.

Figure 8 shows the strength enhancement improved as the concrete confined by the close spacing of steel. The steel spacing is related to the concrete volume and core area confined by steel, and is defined as volumetric ratio. And the results imply that the volumetric ratio of steel is an important parameter in enhancing strength and improving ductility. The concrete confined with higher volumetric ratio can resist the larger stress due to the improved confinement, and they can resist the high axial loads and high lateral pressure. This will result a considerable improvement of the confinement degree.

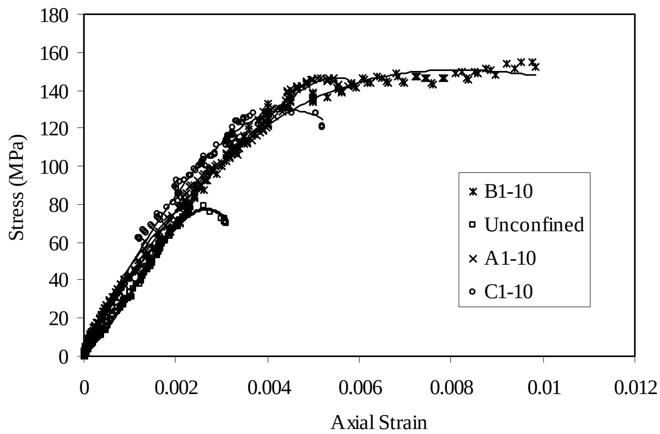

Figure 7. Stress vs. Axial Strain (Different Types of Steel)

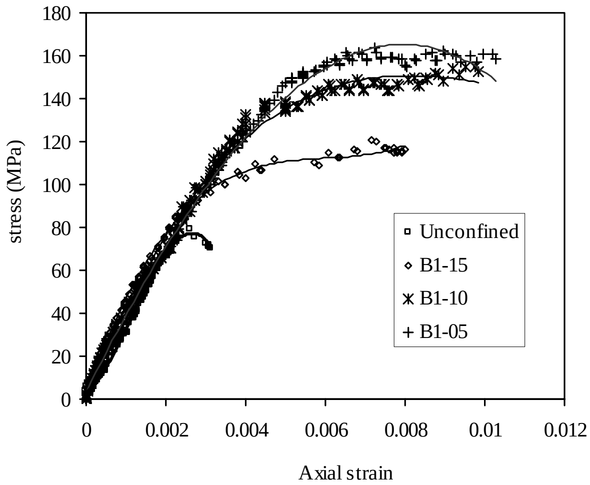

Figure 8. Stress vs. Axial Strain (Different Spacings of Steel Type B)

Confinement effects: The confinement effects in term of the effective volumetric index were analysed by calculating and comparing the strength and ductility enhancements of the confined concrete. Table 2 provides the summary of the present experimental results and some other results from Mei et al. (2001) and Campione and Miraglia (2003). Mei et al. used steel sleeve with different thickness to confine HSC, whilst Campione and Miraglia (2003) investigated the confined HSC using FRP materials (i.e. aramid and carbon). It is clear that the low cost steel straps are a comparable material for confining HSC in order to improve its ductility. It shows that steel straps with a lateral pre-tensioned relatively have a great effect on the increase in strength and ductility, especially for the specimen B1-05 with an effective volumetric index of 0.065. That specimen has better enhancement in strength and ductility with a ratio of 2.0 and 2.573 respectively, compared with specimens tested by Mei at el and Campione and Miraglia which have an equivalent value of volumetric index. However, the comparison shows in the table should not regard as an explicit comparison since the experiments were done by different researchers and the value of volumetric index have been calculated using different approaches for different confinement materials. In general the strength and ductility of a column depends greatly on the volumetric ratio of confinement of the core concrete.

Table 2. Summary of Results from Present Study and Other Researchers

Specimen	f_{co}	f_{cc}	ρ_s	$K_s = f_{cc}/f_{co}$	$\mu_\varepsilon = \varepsilon_{0.85}/0.004$
A1-10	80.9	146.4	0.105	1.810	1.438
B1-05	80.9	162.0	0.065	2.000	2.573
B1-10	80.9	154.6	0.049	1.911	2.463
B1-15	80.9	120.9	0.039	1.494	2.000
C1-10	80.9	130.8	0.117	1.617	1.303
Mei et al. (2001)	71.0	150.0	0.391	2.113	2.125
	71.0	125.0	0.196	1.761	1.500
	71.0	100.0	0.095	1.408	1.050
[a] Campione and Miraglia (2001)	43.0	71.0	0.551	1.650	4.225
	43.0	58.9	0.365	1.370	3.675
	43.0	47.3	0.210	1.100	2.775
[b] Campione and Miraglia (2001)	44.0	48.0	0.161	1.090	2.425
	44.0	75.0	0.483	1.700	4.550

[a] results from aramid composite, and [b] from carbon composite material

5. COMPARISON OF EXPERIMENTAL RESULTS AND THEORETICAL MODELS

Figure 9 shows a general comparison of results from the experimental and confinement models by Eurocode 8 (2001), Mander et al. (1988) and Cusson and Paultre (1995). It is clear that lateral tensioning of steel straps lead to an enhancement in strength and this strength is conservatively predicted by the Eurocode 8, Mander et al and Cusson and Paultre equations. The Cusson and Paultre model, developed for HSC confinement, gives slightly better prediction for the lower ratio of low strength steel straps compared with other models.

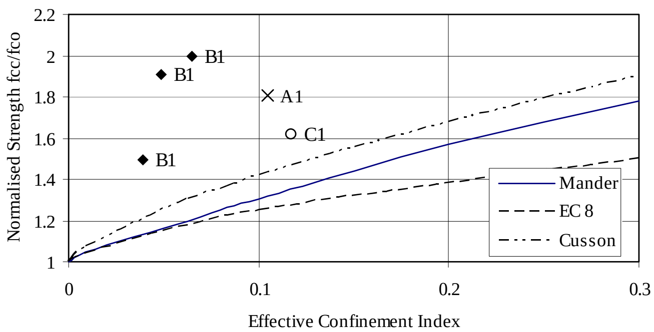

Figure 9. Strength Comparison Between Experimental and Theoretical Predictions

6. CONCLUSIONS

The lateral tensioning of steel straps confinement has been demonstrated to be effective in improving the ductility of HSC; it also produces a new ultra high strength concrete. The low cost of the materials used and the ease and speed of application make this technique very competitive for the new construction and repair of damaged HSC members.

A very important factor contributing to the good performance of this type confinement is the fact that a tensioning force can be applied at the time of installation. The initial stress from the strapping is beneficial in mobilising the lateral steel since the lateral expansion of HSC under axial compression loads is in a slow pace.

ACKNOWLEDGEMENTS

The research reported in this paper was financially supported by Universiti Teknologi Malaysia.

REFERENCES

ACI 363R-92. (1997). "*State-of-the-Art Report on High-Strength Concrete*." American Concrete Institute.

Bae, S., and Bayrak, O. (2003). "Early Cover Spalling in High-Strength Concrete Columns." *Journal of Structural Engineering*, 129(3), 314-323.

Campione, G., and Miraglia, N. (2003). "Strength and Strain Capacities of Concrete Compression Members Reinforced with FRP." *Cement & Concrete Composites*, 25, 31-41.

Chung, H.-S., Yang, K.-H., Lee, Y.-H., and Eun, H.-C. (2002). "Stress-Strain Curve of Laterally Confined Concrete." *Engineering Structures*, 24(9), 1153-1163.

Cusson, D., and Paultre, P. (1995). "Stress-Strain Model for Confined High-Strength Concrete." *Jounal of Structural Engineering, ASCE.*, 121(3), 468-477.

Eurocode 8. (2001). "*Design Provisions for Earthquake Resistance of Structures, Part 1-4, Strengthening and Repair of Buildings (Draft No 4)*." Commission of the European Communities, Brussels.

Forster, S. J., Liu, J., and Sheikh, S. A. (1998). "Cover Spalling in High Strength Concrete Columns Loaded in Concentric Compression." *Jounal of Structural Engineering*, 124(12), 1431-1437.

Mander, J. B., Priestley, M. J. N., and Park, R. (1988). "Theoretical Stress - Strain Model for Confined Concrete." *Jounal of Structural Engineering*, 114(8,), 1804-1826.

Mei, H., Kiousis, P. D., Ehsani, M. R., and Saadatmanesh, H. (2001). "Confinement Effects on High-Strength Concrete." *ACI Structural Journal*,, 98(4), 548-553.

Mortazavi, A. A., and Pilakoutas, K. (2001). "Pre-tensioning of Composites by Lateral Pressure." *FRP Composites in Civil Engineering*, 1, 345-354.

Persson, B. (1999). "Poisson's ratio of high-performance concrete." *Cement and Concrete Research*, 29(10), 1647-1653.

Razvi, S., and Saatcioglu, M. (1999). "Confinement Model for High-Strength Concrete." *Journal of Structural Engineering*, 125(3), 281 -289.

Saatcioglu, M., and Razvi, S. R. (1992). "Strength and Ductility of Confined Concrete." *Journal of Structural Engineering, ASCE*, 118(6), 1590-1607.