:DVWH LPPRELOL]DWLRQ DQG HQYLURQPHQWDO VX
JOD]HV GHYHORSPHQW

0 5HEHQ 0 .RVPDO 1 3DÅF]\ VND[D DQG 3 3LFKQDUF]\N

$*+ 8QLYHUVLW\ RI 6FLHQFH DQG 7HFKQRORJ\ )DFXOW\ RI 0DWHULDOV 6FLHQFH DQG &H
,QVWLWXWH RI &HUDPLFV DQG %XLOGLQJ 0DWHULDOV 'LYLVLRQ RI *ODVS LQ &UDFRZ /

$EVWU7DKHWFXUUHQW ZRUN LQYHVWLJDWHG WKH IRUPXODWLRQ RI JOD]HV X
JODVV SRZGHU PL[HG ZLWK EDVDOW NDROLQ DQG RWKHU DGGLWLYHV 1HZ
LPSUYH WKH PHFKDQLFDO DQG FKHPLFDO SURSHUWLHV RI IDVW ILUHG JO
UHVLVWDQFH WR DEUDVLRQ

,QWURGXFWLRQ

*OD]HV FDQ EH GHILQHG DV D VWDQ
WR FHUDPLF HDUWKHQZDUH DQG
R[LGHV RU PLQHUDOV DSSOLHG
RI FHUDPLF REMHFWV 7KH ODUJHU
ZLWK LPSUYHG DQG DGYDQFHG
UHVLVWDQFH WR DEUDVLRQ KL
SRURVLW\ DQG LPSUYHG FKHPL
> @ JODVV FHUDPLF JOD]H PXVW
ZKLFK LV WHFKQLFDOO\ DQG FR
WKH IDEULFDWLRQ FRQGLWLRQVW
SURGXFWLRQ ZKHUH JOD]HV VK
ILULQJ SURFHVV 'HQVLILFDWLRQ
LQ WKH SUHVHQFH RI D YLVFRXV
KLJKHU WKDQ WKH JODVV WUDQ
UHVXOWLQJ LQ D FRPSDFW OD\HU
'XULQJ IDVW ILULQJ SURFHVV
RFFXUV ,W UHVXOWHG LQ WKH
LQ JOD]H REWDLQHG > @ 0RUH
DQG VWUXFWXUH GHYHORSPHQW
DUH YHU\ LPSRUWDQW VDWXUL
LQ WKH OLQHDU H[SDQVLRQ
7KH JUHDWHU WKH GLIIHUHQFH
RI WKH FHUDPLF VXSSRUW DQG
ZLOO DSSHDU> @XVSHQVLRQV
RI GLIIHUHQW PDWHULDOV DZ
QRQ SODVWLF GLWLYHV 3ODVW
FOD\V H J NDROLQ DQG EHQWR
PDWHULDOV RI EHQ VLSWJ HQW
7KH DGGLWLYHV DUH XVHG DV
DUH GLVSHUVLQJ DQG GHIORF
DQG GHIRDPLQJ DJHQWV &RW
QDWXUDO FRPSRQHQWV LQ FHUDPLFV
ZLWK ZDVWHV LV ZHOO GRFXPHQWHG
5HSODFLQJ IOX[HV ZLWK FXOOHW
DQG 7DUYRUQSDQLFK > @

3 .HWERRQUXDQJ VWXGLHG WKH SRW
VROLG ZDVWH 06: VRGD OLPH VLG
*OD]HV FDQ EH GHILQHG DV D VWDQ
WR FHUDPLF HDUWKHQZDUH DQG
R[LGHV RU PLQHUDOV DSSOLHG
RI FHUDPLF REMHFWV 7KH ODUJHU
ZLWK LPSUYHG DQG DGYDQFHG
UHVLVWDQFH WR DEUDVLRQ KL
SRURVLW\ DQG LPSUYHG FKHPL
> @ JODVV FHUDPLF JOD]H PXVW
ZKLFK LV WHFKQLFDOO\ DQG FR
WKH IDEULFDWLRQ FRQGLWLRQVW
SURGXFWLRQ ZKHUH JOD]HV VK
ILULQJ SURFHVV 'HQVLILFDWLRQ
LQ WKH SUHVHQFH RI D YLVFRXV
KLJKHU WKDQ WKH JODVV WUDQ
UHVXOWLQJ LQ D FRPSDFW OD\HU
'XULQJ IDVW ILULQJ SURFHVV
RFFXUV ,W UHVXOWHG LQ WKH
LQ JOD]H REWDLQHG > @ 0RUH
DQG VWUXFWXUH GHYHORSPHQW
DUH YHU\ LPSRUWDQW VDWXUL
LQ WKH OLQHDU H[SDQVLRQ
7KH JUHDWHU WKH GLIIHUHQFH
RI WKH FHUDPLF VXSSRUW DQG
ZLOO DSSHDU> @XVSHQVLRQV
RI GLIIHUHQW PDWHULDOV DZ
QRQ SODVWLF GLWLYHV 3ODVW
FOD\V H J NDROLQ DQG EHQWR
PDWHULDOV RI EHQ VLSWJ HQW
7KH DGGLWLYHV DUH XVHG DV
DUH GLVSHUVLQJ DQG GHIORF
DQG GHIRDPLQJ DJHQWV &RW
QDWXUDO FRPSRQHQWV LQ FHUDPLFV
ZLWK ZDVWHV LV ZHOO GRFXPHQWHG
5HSODFLQJ IOX[HV ZLWK FXOOHW
DQG 7DUYRUQSDQLFK > @

[D] &RUUHVSRQGLQJ DXWKRU QDWDOLD SDOF]\QVND#ZS SO

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

([SHULPHQWDO

7KH FKHPLFDO FRPSRVLWLRQV RI ... EDVDOW ERURVLOLFDWH JODVV ... LQ WDEOH &KHPLFDO FRPSRVLWLRQ ... LQ WKLV H[SHULPHQW ZDV DQDO\]HG E\ ;5) ZLWK XVH RI VSHFWURPHWHU ... 3$1DO\WLFDO 7KH WKHUPDO OLQHDU H[SDQVLRQ FRHIILFLHQW ZDV PHDVXUHG RQ WKH EORFNV SUHSDUHG IURP WKH SRZGHU\ JOD]HV DQG IULWV MXVW DV VKRZQ LQ WDEOH 7KH GLODWDWLRQ RI WKH PDWHULDOV ZDV PHDVXUHG XVLQJ GLODWRPHWHU %DKU 7KHUPR $QDO\VH ',/ / *HUPDQ\ ZLWK D KHDWLQJ UDWH . PLQ 7KH NLQG RI FU\VWDOOLQH SKDVHV ZKLFK ZHUH IRUPHG YLD WKH WKHUPDO WUHDWPHQW DW WKH WHPSHUDWXUH H[DPLQHG E\ ;5' PHWKRG ZLWK XVH RI 3KLOLSV ; 3HUW ZLWK α&X UDGLDWLRQ VRXUFH 7KH PRUSKRORJ\ RI FU\VWDOOLQH SKDVHV GHYHORSHG ZHUH H[DPLQHG E\ VFDQQLQJ 6(0 1RYD 1DQR 6(0)(, &RPSDQ\ ZHUH SHUIRUPHG ZLWK DQ DWWDFKPHQW RI VSHFLPHQV LQ PLFUR DUHDV ZLWK VSHFWURVFRS\ ('$; 7KH REVHUYDWLRQV ZHUH FDUULHG RXW LQ ORZ YDFXXP FRQGLWLRQV PRGH 7KH VDPSOHV ZHUH FRYHUHG ZLWK FDUERQ OD\HU 7KH DEUDVLRQ UHVLVWDQFH ZDV GHWHUPLQHG DFFRUGLQJ WR WKH (1 ,62 VWDQGDUG 7KH WHVW ZDV EDVHG RQ D YLVXDO DVVHVVPHQW RI FKDQJHV LQ WKH JOD]HG VXUIDFH DQG PRYHPHQW PRYLQJ WKH VKHDULQJ ORDG RI WLPHV LQ FRPSDULVRQ ZLWK WKH VXUIDFH RI WKH WLOH

'HWHUPLQDWLRQ RI ZDWHU DEVRUSWLRQ ... RI WKH WRWDO S :DWHU VDWXUDWLRQ ... $IWHU &RROLQJ IRU GU\LQJ ... WKH ... ZDWHU DEVRUSWLRQ ... $IWHU ... ZHLJKHG ... 3$1DO\WLFDO

5HVXOWV DQG GLVFXVVLRQ

7KH GLODWRPHWULF ... &57 JODVV FXUYHV ... LQ ... FRPSRVLWLRQ ... DV VXEVWLWXWH ... WR IULW DQG ... GHVLJQHG DQG DV D SDUWLDO ... FRPSRQHQWV LQ FDVH RI ... JOD]H ... LQ >PRO@ &57 SDQHO JODVV LV D ... FRQWDLQLQJ KHDY\ PHWDO ... DQG LWV LQFRUSRUDWLRQ ... WR FU\VWDOOL]DWLRQ ... DQG WUDQVLWLRQ ... &KHPLFDO ... FRHIILFLHQW ... RI WKH WKHUPDO H[SDQVLRQ FRHIILFLHQW ... GRHV QRW DOORZ WR XVH WKLV ... SURGXFWLRQ ... FDUERQ ... JOD]H ... DW GLIIHUHQW VKRZHG ... KDG ... EHWZHHQ ... WKH ... RI NDROLQ ... D GXH ... WR REWDLQ D EHWWHU DJUHHPHQW ... EOG\ GLODWRPHWULF FRHIILFLHQW ... GLIIHUHQW IRUPXODWLRQV XVLQJ &57 ... UDQJLQJ LQ ± DQG ± ZW ... SUHSDUHG ,W SHUPLWWHG WR ... FKDUDFWHUL]HG E\ WKH E\ D ORZHU ... FRHIILFLHQW)LJ

)LJXUH 70$ H[SDQVLRQ FXUYHV RI VWXGLHG JOD]HV

5DZ PDWHULDOV IRU WKH SURGXFWLRQ RI JOD]HV ZHUH VKUHGGHG DQG PL[HG WKHQ PLOOHG LQ D SRUFHODLQ EDOO PLOO 7KH UDZ PDWHULDOV ZHUH ZHW PLOOHG IRU PLQXWHV DQG WKH PLOOLQJ WLPH ZDV FKRVHQ H[SHULPHQWDOO\ WR REWDLQ H[SHFWHG VLHYH UHVLGXH RI OHVV WKDQ 7KH UHVXOWLQJ PL[WXUH ZDV DSSOLHG WR D FHUDPLF WLOH E\ KDQG DQG KHDWHG DW D UDWH RI PLQ XS WR WKH ILULQJ WHPSHUDWXUH 7KH HQWLUH ILULQJ F\FOH ODVWHG ZHUH FRROHG ZLWK WKH IXUQDFH ... H[DPLQHG YLVXDOO\ LQ WHUPV RI VXUIDFH ... VPRRWKQHVV DQG JORVV)RU WKH ... SK\VLFDO DQG FKHPLFDO SURSHUWLHV RI ... WKH ZDWHU DEVRUSWLRQ DQG DEUDVLRQ ... 'HWHUPLQDWLRQ RI ZDWHU DEVRUSWLRQ ... DFFRUGLQJ WR WKH PHWKRG GHVFULEHG ... >31 (1 ,62 &HUDPLF WLOHV

)LJXUH 0$ H[SDQVLRQ FXUYHV RI VWXGLHG ... 7KH JOD]H SUHSDUHG FRQWDLQV ... VXEVWLWXWHG ... E\ &57 JODVV ... WR EH PDWW ... 7LOH ... DIWHU ILULQJ ... VXUIDFH ... RI JOD]H FRPSRVLWLRQ ZDV ... 7KH JOD]H SUHSDUHG FRQWDLQV ... IUDFWLRQ VXEVWLWXWHG WKH EDVLF ... RI 0 ERURVLOLFDWH JODVV ... DQG DEUDVLRQ UHVLVWDQFH ZHUH ... 7KH WKHUPDO H[SDQVLRQ FRHIILFLHQW ... UHGXFHG E\ WKH DGGLWLRQ RI ... RI 0 ERURVLOLFDWH JODVV)LJ

7DEOH &KHPLFDO FRPSRVLWLRQ RI JD]HV FRPSRQHQWV >ZW @

&RPSRQHQW &57 JODVV FXOOHW	)HOGVSDU	)ORDW %DVDOW FXOOHW
6L2		
&D2		
0J2		
$O2		
)H2		
1D2		
. 2		
%D2		
%2		

7DEOH 7KH FRPSRVLWLRQV RI JOD]HV GHVLJQHG

6\PERO RI &57 JOD]HV	7KH FRPSRVLWLRQV RI GHVLJQHG JOD]HV >ZW @						
	JODVV FXOOHW	*ODVV	0)HOGVSDU	)ORDW JODVV FXOOHW	%DVDOW	&RPSRQHQW SDUDPHWHUV DQG DSSHDUDQFH	
							°&K 0DWW JOD]HV
							°&K *OD]HV ZLWK JORVV

%RURVLOLFDWH JODVVHV DUH NQRZQ WR RU WKH HYLQH FRPSRVLW
FRHIILFLHQWV RI WKH PRO W[SDQVLRQ &RQVHUTXHQWOO\ FU\VWDOOL]H HDVLO\ E
PDNLQJ WKHP UHVLVWDQW WR WKH HOHPHQWDO &RQWHQW &RQVHTXHQW
RWKHU FRPPRQ JODVV > @α %\ RUHWXHL QUDQGRPLVW WKH RI ILGHV RI EL
%2 FRQWULEXWHV WR WKH GHQVLWH VHQXFWXUH RI WKH PRO PDNLQJ WKHP PRUH FKHPLFDOO\ UHVLVWDQW)LQ WKH SUHVHQ
7KH WHQGHQF\ WR FU\VWDOOL]H WKH FU\VWDOOL]DWLRQ FDSDELOLW
7KH NLQG RI WKH FU\VWDOOL]LQ
E\ WKH ;5' WHFKQLTXH 7KH ;5' SDWV

ILUHG DW °& UHYHDOHG WKH SUHVHQFH RI D WKUHH FU\VWDOOLQH2SKDVH 6DQ6L2 6DQLGLQH -&3'6 1R 6L2 6LOOLPDQLWH -&3'6 1R DQG 6L2 %D$O 3DUDFHOVLDQ -&3'6 1R 7KH LQWHQVLW\ RI OLQHV FRUUHVSRQGLQJ WR 6L2 DQG 6L2 %D$O SKDVHV DUH QDUURZ LQGLFDWLQJ WKH H[LVWHQFH RI ZHOO GHYHORSHG FU\VWDOV)LJ

)LJXUH ;5' SDWWHUQ RI JOD]H QR KDIWHU ILULQJ DW

7KH DSSHDUDQFH RI QRW VLJQLILFDQW DPRXQW RI %D$O FDQ EH H[SODLQ E\ LWV DQ H[WHQVLYH SROLPRUSKLVP > @ 8QGHU ;5' WKH FU\VWDOOLQH SKDVHV LQ JOD]H ZHUH QRW GHWHFWHG HQDEOHV XV WR FRQFOXGH WKDW JOD]H PRVW SUREDEO\ EHLQJ DPRUSKRXV)LJ

)LJXUH ;5' SDWWHUQ JOD]H QR & DIWHU ILULQJ DW

0RUSKRORJ\ RI JOD]H VXUIDFH ILUHG DW °& E\ 6(0 VKRZV VPRRWK VXUIDFH ZLWK YHU\ ILQH FU\VWDOV RQ WKH VXUIDFH DV VKRZQ LQ)LJXUH WKH PDMRU HOHPHQWV DQDO\]HG E\ ('6 FRQVLVWHQW ZLWK WKH UHVXOWV RI SKDVH DQDO\VLV E\ ;5' WKDW VKRZV FU\VWDOOLQH2SKDVH DQG VLJQLILFDQW DPRXQW RI 6L2 %D$O JOD]H)LJ *OD]H DW °& VKRZV JODVV\ VXUIDFH)LJ

)LJXUH 6(0 SKRWRJUDSK DQG ('6 DQDO\VLV RI WKH DQDO\VLV SHUIRUPHG LQ SRLQW

6(0 DQDO\VLV GLG QRW VKRZ DQ\ FU UHYHDOHG PRUH &D DQG 1D FRQWHQ LQ WKH JOD]H FRPSRVLWLRQ 7KH UH WR PHFKDQLFDO GDPDJH UHVXOWL RI WKH DEUDVLYH IDFWRU ZDV WHVW LQWR DEUDVLRQ UHVLVWDQFH JUDG QXPEHU RI URWDWLRQV RI WKH GH RI WKH JOD]HG WLOHV DIWHU ZKLF RI DEUDVLRQ EHFRPH YLVLEOH %D WKH JOD]H LV DVVLJQHG WR WKH F DQG JOD]H QXPEHU RI UR WR WKH FODVV *OD]H FDQ EH IRU IORRULQJ LQ GRPHVWLF KRXVLQJ DQG QRUPDO IRRWZDUH ZKHUH VPD RFFDVLRQDOO\ EH FDUULHG RXW * IRU PRUH IUHTXHQW SHGHVWULDQ W DEVRUSWLRQ DUH SUHVHQWHG LQ 7D ZDV FDOFXODWHG E\ WKH IROORZLQJ

$$N = \frac{m - m}{m} \quad (1)$$

ZKHUH

P PDVV RI WKH GULHG VDPSOH > J@
P PDVV RI WKH VDPSOH VDWXUDWHG

7DEOH-DWHU DEVRUSWLRQ

7\SH RI VDPSOH	1XPEHU RI WLOHV	:DWHU DEVRUSWDQFH	:DWHU DEVRUSWLRQ DYHUDJH
*OD]H			
*OD]H			

&RQFOXVLRQ

7KH DLP RI WKH VWXG\ ZDV WR VXSSRUW WKH &57 SDQHO SRLQW RI YLHZ WKH UHF\FOLQJ VXFFHVVIXOO\ H[SHULPHQWHG LQ WKH &57 FHUDPLF LQGXVWU\ &57 FXOOHW XVHG DV D UDZ PDWHULDO LQ JOD]H IRU ORZ ILUHG SURGXFWV &57 JODVV UHF\FOLQJ *OD]HV IRU ORZ ILULQJ DUHD ZLWK ILULQJ WHPSHUDWXUH &57 SDQHO 7KH VWHQ RI WKH &57 SDQHO LV UHODWHG WR WKH EHQH ILW &57 FUDFNLQJ EXEEOLQJ 0RUHRYHU WKH DV‚QWLRQ ZL‚ ,QG

WRZDUG WKH WKHUPDO H[SDQVLRQ WR EH HOHYDWHG 7KH UH PRGXODW IRUPXODWLQJ WKH JOD]H FRP IXQGDPHQWDO WR REWDLQ DFFHSV SDUDPHWHU 7KH PDWW DQG DPRUSK YHU\ VLPLODU WR RULJLQDOV QRW F RQ WKH VXUIDFH DEUDVLRQ WHVW WKH LQWURGXFWLRQ RI &57 SDQHO J PHHWV WKH UHTXLUHPHQWV RI &57 SURG UHVHDUFK FRQGXFWHG KDYH EHHQ IRU WKH VWXG\ ZLWK WKH HQYL RI WHFKQRORJLHV IRU WKH SURGXF DQG &RQWULEXWH WR WKH UDWL RI &57 SURGXFW &RQWULEXWH &57 SURGXFW YDOXH &RQGXFW UDZ PDWHULDO

5HIHUHQFHV

0 * 5DVWHLUR 7 *DVVPDQ 5 6D &HUDP QW±
Q /OXVDU * 0RQURV &0 5RG /DEULQFK &HUDP ,QW
5 &DVDVROD - 0D 5LQFR•Q 0 5
6FL ±
: :HLDQG 5 0HU] . %RQN 7LOH ±
7 7DUYRUQSDQLFK 8QLYHUVLW\ R
1) <RXVVHI 0) $EDGLU 0 $ 2
3 .HWERRQUXDQJ 6 -LQDZDW '
:DVDQDSLDUQSRQJ 3 6XMDULG
%XJJDNXSWDY 1 7UDLSRO &RQ-LHF
6HULHV 0DWHULDOV 6FLHQFH DQG
/ $ 5 6LLNDPDNL 5HF DQG 5HXVH ±
$QGUHROD / %DUELHUL (.DUDP
0 3HOLQR &HUDP± ,QW
) $QGUHROD / %DUELHUL) %RQ
3 0LVHOOL $ 0)HUUDUL ,QW - ±
) 2 0pDU 3 * <RW $ 9 .RORERY
*XLPRQ ' *RQEHDX - 1RQ &U\VW ±
0 5HEHQ - :DV\ODN
3 :DOF]DN - 0DáROHSV]\ 0 5HEH
3UR (QJ
0 5HEHQ 0 .RVPDO 0 =L END 3
, *UHORZVND - 1RQ &U\¥W 6ROL
7ROXZDORSH ,QW ZDVKDV 7HFK
&DQQLOOR 7 0DQIUHGLQL 0 0RQ
$ 6ROD 0DWHU (QJ
) <HQ 3HL & &KLQ &KXQJ / &
7VXQJ 6KXQH &HUDP ,QW

)LJXUH &(0 SKRWRJUDSK DQG ('6 DQDO\VLV RI JOD]H WKH DQDO\VLV SHUIRUPHG LQ SRLQW