HOLMESSOLUTIONS

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PREPARED FOR ROYAL COMMISSION

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INVESTIGATION INTO THE INFLUENCE OF STRAIN-AGING ON THE SEISMIC PERFORMANCE OF THE REINFORCING STEEL FROM THE CTV BUILDING

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1.0 EXECUTIVE SUMMARY

The CTV building suffered a catastrophic collapse in the February 2011 earthquake. A series of extensive investigations have been undertaken in an attempt to learn from the collapse.

The CTV building was subjected to server ground shaking during the September 2010 earthquakes and was reported to have undergone a degree of inelastic behaviour. Site inspections completed on the building following the September earthquake noted minor concrete cracking in a number of structural elements. Additional damage may also have occurred in regions not readily accessible for visual inspections. The building was then subjected to more severe ground shaking in February 2011 which resulted in the collapse of the structure.

Numerous research projects have been completed that indicate reinforcing steel bars can suffer from the effects of strain aging. This is whereby the mechanical properties of the steel that are subjected to an initial level of inelastic strain, and then unloaded for a period of time before being restrained, is different to that of an identical steel sample that are not subjected to the initial inelastic loading cycles. The results reported by previous researchers are often contradictory and appear to be heavily related to the specific chemical composition of the steel tested; however, it is generally reported that strain aged steels achieve a greater peak stress, and a reduced level of uniform elongation. Uniform elongation is defined as the strain value corresponding to the attainment of peak stress in the steel, before the onset of localised necking.

Holmes Solutions was commissioned to investigate the strain-aging potential of the reinforcing steel used in the construction of the CTV building. All testing was completed on undamaged steel samples salvaged from the debris of the building. Samples of 12 mm diameter, deformed reinforcing steel were collected from salvaged from both columns and from within sections of the suspended floors.

All recovered steel samples were subjected to uniaxial tensile testing, in accordance with ASTM E8/E8M-11 using a EN ISO 7500-1:2004 Class 1 calibrated Shimazu Universal test machine. Elongation was measured by a 50 mm gauge length digital extensometer during each test. Testing was completed to the specifications and grouping, as detailed in Table 1 below.

Table 1 Strain aged tested samples

Aged Period	1.5% pre-strain		2.5% pre-strain		5.0% pre-strain	
	Unstrained samples	**Strained samples**	**Unstrained samples**	**Strained samples**	**Unstrained samples**	**Strained samples**
1 Month	3	3	3	3	3	3
2 Month	3	3	3	3	3	3

Each grouping of strain age tests was completed in match pairs extracted from a single length of salvaged reinforcing steel, to reduce the influence of material variation in the test results. One of the samples were subjected to the initial level of pre-strain and then immediately tested to destruction, where the remaining sample was pre-strained and then left to age for the desired period prior to undergoing destructive testing

For each grouping of strain-aged samples, a minimum of three samples were tested to achieve a degree of statistical robustness to the testing programme.

It was determined that two grades of 12 mm reinforcing bars were used in the construction of the recovered elements of the CTV building; with 30 samples obtained from a material with a derived lower characteristic yield strength of 517 MPa and 6 samples from a material with an average yield strength of 380 MPa. Due to a low sample population, the samples with the lower grade steel were excluded from analysis on the basis of statistical robustness.

The results obtained for the strain-aging testing indicated the following trends;

- The ultimate strength (f_u) of the aged steel samples was lower than the un-aged samples. On average, the decrease in capacity was found to be 5% of the capacity, equivalent to 33 MPa.

- The decrease in ultimate strength of the material with strain-aging showed no specific trends with regards to the level of pre-strain applied to the steel, or the length of aging period.

- The uniform strain capacity (ε_u) of the strain-aged material was found to decrease when compared to the un-aged samples. Uniform strain is defined as the strain corresponding with the attainment of peak stress. On average the decrease in strain capacity was found to be 9% of the capacity.

- The decrease in uniform strain capacity of the material show no specific trends with regards to the level of pre-strain applied or the length of the aging period.

Overall, the 12 mm diameter deformed reinforcing steel used in the construction of the CTV building was found to be influenced by the effects of strain aging, resulting in lower elongation potential and a decreased ultimate stress. However, the changes observed did not appear to follow any specific trends with regards to the level of pre-strain applied, or length of aging.

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2.0 INTRODUCTION

The CTV building suffered a catastrophic collapse in the February 2011 earthquake. A series of extensive investigations have been undertaken in an attempt to learn from the collapse, the results of which are reported elsewhere.

The CTV building was subjected to server ground shaking during the September 2010 earthquakes and was found to undergo a degree of inelastic behaviour. Site inspections completed on the building following the September earthquake noted minor cracking in a number of concrete elements. The building was then subjected to more sever ground shaking in February 2011 which results in the collapse of the structure.

Numerous research projects have been completed that indicate reinforcing steel bars can suffer from the effects of strain aging. This is whereby the mechanical properties of the steel that are subjected to an initial level of inelastic strain, and then unloaded for a period of time before being restrained, is different to that of an identical steel samples that are not subjected to the initial inelastic loading cycles.

The results reported by previous researchers are often contradictory with regards to the extent of the influence of strain-aging. The majority of previous research reports indicate that the effect of strain-aging is heavily dominated by the specific chemical composition of the steel, with steel that have a high carbon content generally displaying a greater potential for strain-aging effects.

The most commonly noted effects of strain-aging on the mechanical properties of a steel are an increase in the peak stress of the steel and an associated reduction of uniform elongation capacity. Uniform elongation is defined as the strain value corresponding to the attainment of peak stress in the steel, occurring prior to the onset of localised necking. Some of the reported research indicates changes of up to 25% increase in peak stress and 30% reduction in uniform elongation capacity.

3.0 TEST METHODOLOGY

Strain-aging has been shown in research, to affect the mechanical properties of reinforcing steel. As such, the influence of strain-aging is best investigated by undertaken mechanical tension load testing on steel samples.

In a reinforced concrete structure like that of the CTV building, the concrete elements are typically under-reinforced in an attempt to make sure that during overload conditions, the structural members' deform in a ductile tension-based mode. In under-reinforced concrete members, the critical section of reinforcing steel is likely to have been located at or near the extreme fibres of the reinforced concrete element. Given that the neutral axis of the element is expected to have been located near the location of the reinforcing steel during the compression load cycle, the steel is likely to have been subjected to small induced compressive strains. During the reverse loading cycle the steel located at or near a crack in the concrete section is likely to have been subjected to disproportionately larger tensile strains, thereby significantly skewing the strain profile into the tension domain. Due to the skewed strain profile of the in-situ reinforcing element, it is believed that the unidirectional cyclic tensile test provides an adequate representation of the strains induced in the steel during a seismic event. All testing was completed with the steel samples subjected to uniaxial tension testing on this basis.

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Testing was undertaken by creating matched samples of reinforcing steel from the collected samples. Each pair of matched samples were cut from the sample length of reinforcing steel and were therefore assumed to have identical material properties.

For each of the matched samples, the steel section was initially subjected to a level of pre-straining of either 1.5%, 2.5% or 5% strain. The control sample from each of the matched samples was then immediately tested until tensile failure was achieved. The remaining sample from the matched pair was aged for the desired period of time and then subjected to re-testing as per the initial methodology until tensile failure was achieved.

All tensile testing was completed using the test equipment detailed in Section 4.0 and testing was undertaken in accordance with the requirements of ASTM E8/E8M-11.

This testing methodology was adopted to ensure that the only difference between the two matched samples was the length of time between the application of the initial strain and the final testing to failure. As such, any variations in the results between the two samples can be attributed to the effect of strain-aging.

4.0 TEST EQUIPMENT

4.1. UNIVERSAL TEST MACHINE

A EN ISO 7500-1:2004 Class 1 calibrated UH600 Shimazu servo-controlled Universal Test Machine (UTM) with a 600 kN capacity was used to undertake all laboratory based materials testing. The UTM has a maximum stroke of 250 mm and a maximum table velocity of 150 mm/min. Applied loads to the test specimen were recorded directly using the internal measurement transducer of the Shimazu control system.

Steel Elongation was recorded using a strain gauge based digital extensometer with a gauge length of 50 mm. The extensometer is calibrated to ISO 9513-1999, with a reported Class 1 accuracy.

5.0 COLLECTION OF TEST SAMPLES

All steel samples were collected from the stock-piled debris of the CTV building. The primary elements of interest were the suspended concrete floor slab sections and the perimeter concrete columns, both reinforced with 12 mm diameter deformed longitudinal reinforcing steel. Care was required when collecting the steel samples to ensure the samples had not been subjected to previous cycles of inelastic loading that could influence the recorded results.

For all tested steel samples, it was necessary to collect samples with a minimum length of 600 mm to allow a minimum of 2 steel samples to be obtained from a single length of steel. One of the samples was to be used for completing the strain-aging testing with the other required to provide a baseline sample of the material property, thereby allowing the influence of variations in the baseline material properties to be removed from the analysis.

Reinforcing from the suspended floor samples was difficult to obtain. The majority of the floor slab sections had been extensively damaged in the building collapse and subsequent rescue and demolition activities.

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Reinforcing bar samples were obtained from an intact column element. Care was taken to collect the samples from zones in the column that had no visually apparent cracks.

In total, 60 test samples were obtained for testing, the majority obtained from the column element and remaining samples from the suspended floor. All samples were a minimum of 600 mm long and cut into two sections to form the pair of matched samples prior to testing.

Figure 1 Example of Column element suitable for sample extraction.

Figure 2 Unprepared 12 mm diameter reinforcing bar samples.

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Figure 3 Prepared 12mm diameter control bars from a column element

Figure 4 Testing of 12 mm diameter control bar from a column element

6.0 TEST RESULTS

6.1. DERIVED LOWER 5TH PERCENTILE MATERIAL PROPERTIES

A total of 34 reinforcing bar samples were tested across the testing programme. Six of the reinforcing bars were found to be of a different grade material than the remained 28 samples, and were therefore excluded from the remainder of the analysis.

The results obtained from the 28 recorded samples were statically analysed and the lower 5th percentile material property values derived. All of the 28 samples were used when deriving the stress and strain values corresponding to the yield and on-set of strain hardening. However, only results obtained from the un-aged test specimen were used (totalling 14 records) to derive the ultimate stress and corresponding strain to exclude the effects of strain aging on material base data.

The derived lower 5th percentile material properties are presented in Table 2. The derivation of results was obtained assuming a normal distribution. A representative stress-strain response from the material is presented in Figure 5.

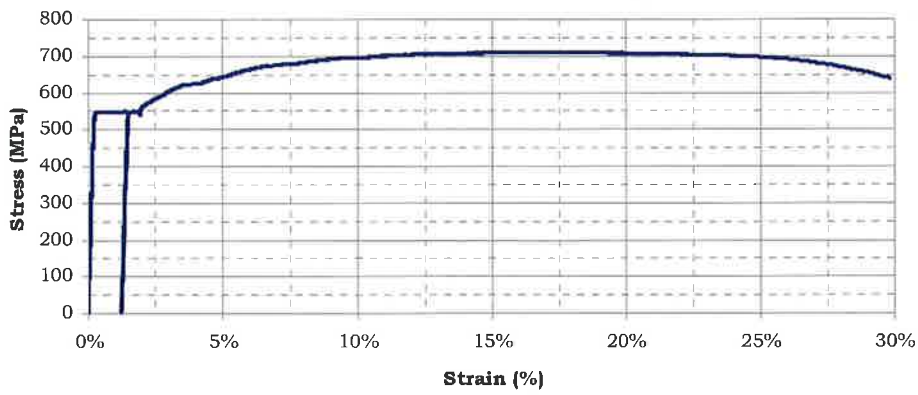

Figure 5 Representative Materials Stress-strain response

Table 2 Derived Lower 5th Percentile Material Properties from Test Sample

Yield Stress, f_y:	518	(MPa)
Strain Hardening Stress, f_{sh}:	519	(MPa)
Ultimate Stress, f_u:	652	(MPa)
Stress Ratio, f_u/f_y:	1.10	
Yield Strain, ε_y:	0.3	(%)
Strain Hardening Strain, ε_{sh}:	1.13	(%)
Peak Uniform Strain, ε_u:	10.6	(%)

6.2. STRAIN-AGED RESULTS

The results obtained from the tensile testing completed on the steel samples collected from the CTV building are presented below. All results are reported in matched sample groups, with a direct comparison of the ultimate stress and uniform elongation characteristics.

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Table 3 Tabulated mechanical test results

Conditioning		Material Properties			Un-Aged Sample		Aged Sample		Variance		Average Variance	
Aged Period (days)	Pre-strain (%)	f_y (MPa)	f_{sh} (MPa)	e_{sh} (%)	f_u (MPa)	e_u (%)	$f_{u(aged)}$ (MPa)	$e_{sh(aged)}$ (%)	$f_u/f_{u(aged)}$	$e_{sh}/e_{sh(aged)}$	$f_u/f_{u(aged)}$	$e_{sh}/e_{sh(aged)}$
30 day	1.5	543	536	1.38	703	15	670	15	1.05	1.00	1.05	1.14
30 days	1.5	526	532	1.32	695	15.1	654	10.5	1.06	1.44		
30 days	1.5	596	602	1.34	790	14	751	14.3	1.05	0.98		
60 days	1.5	590	599	1.25	772	15.2	725	12.9	1.06	1.18	1.06	1.20
60 days	1.5	545	530	1.5	708	15.3	669	15.2	1.06	1.01		
60 days	1.5	546	552	1.94	708	18.3	667	12.9	1.06	1.42		
30 days	2.5	586	591	1.38	781	12.7	740	11.7	1.06	1.09	1.06	1.09
60 days	2.5	536	541	1.45	712	12.7	666	15.2	1.07	0.84	1.06	1.05
60 days	2.5	538	554	1.87	710	15.1	668	12.6	1.06	1.20		
60 days	2.5	547	552	1.68	710	14.88	686	13.3	1.03	1.12		
30 day	5	543	545	1.15	620	12.7	686	10.5	0.90	1.21	1.01	1.07
30 days	5	571	583	1.34	767	13.8	728	12.4	1.05	1.11		
30 days	5	569	575	1.39	767	12	725	13.7	1.06	0.88		
60 days	5	548	550	1.6	714	15.2	673	12.7	1.06	1.20	1.07	0.94
60 days	5	534	554	1.5	722	9.86	675	14.5	1.07	0.68		
Min		526	530	1.15	620	9.9	654	10.5				
Max		596	602	1.94	790	18.3	751	15.2				
Average		555	560	1.47	725	14.1	692	13.2				
Standard deviation		22.1	24.1	0.22	43.8	1.95	32.0	1.53				
Lower 5th Percentile		518	519	1.11	652	10.9	639	10.6				

6.3. RESULTS SUMMARY

A series of key trends were noted in the obtained results;

- Two varieties of 12 mm reinforcing steel were utilised in the CTV building. The majority of samples obtained were from a steel with a lower characteristic yield strength of 517 MPa. A total of 6 samples of the second variety were tested achieving an average yield strength of 380 MPa.

- The ultimate strength (f_u) of the aged steel samples decreased from the matched un-aged samples. On average, the decrease in capacity was found to be 5%, equivalent to 33 MPa.

- The decrease in ultimate strength of the material with strain-aging showed no specific trends with regards to the level of pre-strain applied to the steel or the length of aging period.

- The peak uniform strain capacity of the strain aged material was found to decrease. On average the decrease in strain capacity was found to be 9%.

- The decrease in uniform strain capacity of the material show no specific trends with regards to the level of pre-strain applied or the length of the aging period.

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APPENDIX A

EXPERIMENTAL TEST RESULTS

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1.5% PRE-STRAIN RESULTS

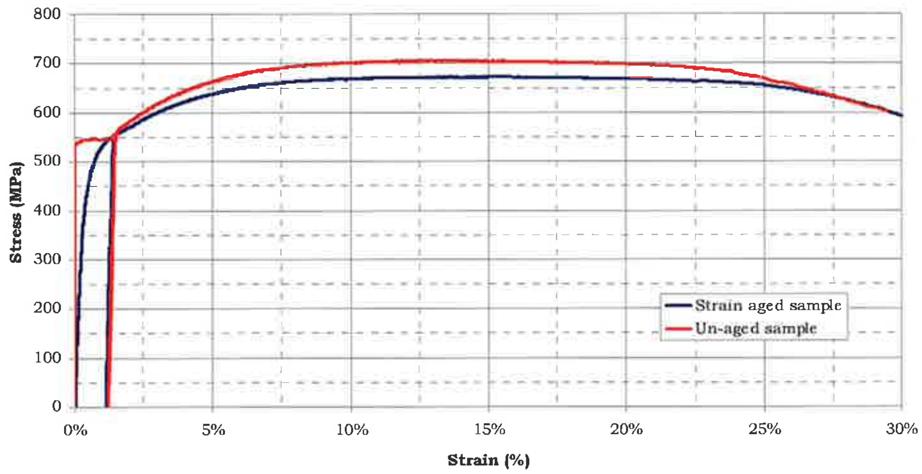

Figure 6 Materials Stress-strain response for 1.5% pre-strain and 30 days aging

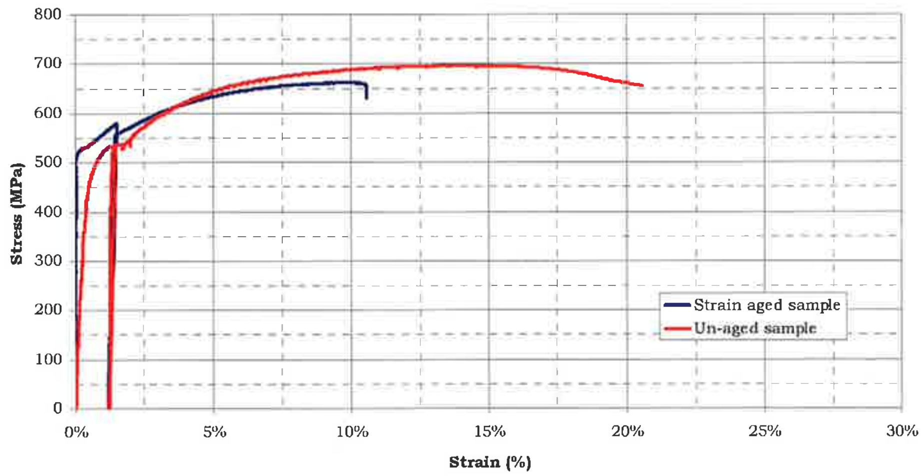

Figure 7 Materials Stress-strain response for 1.5% pre-strain and 30 days aging

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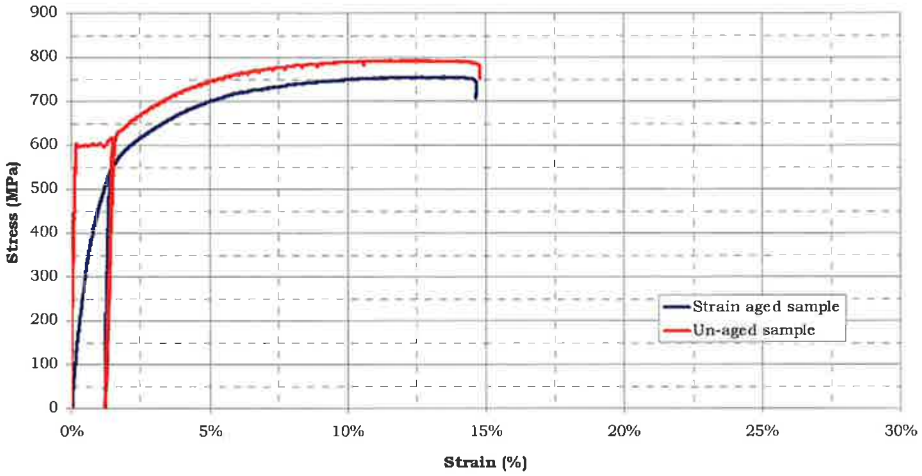

Figure 8 Materials Stress-strain response for 1.5 % strain and 30 days aging

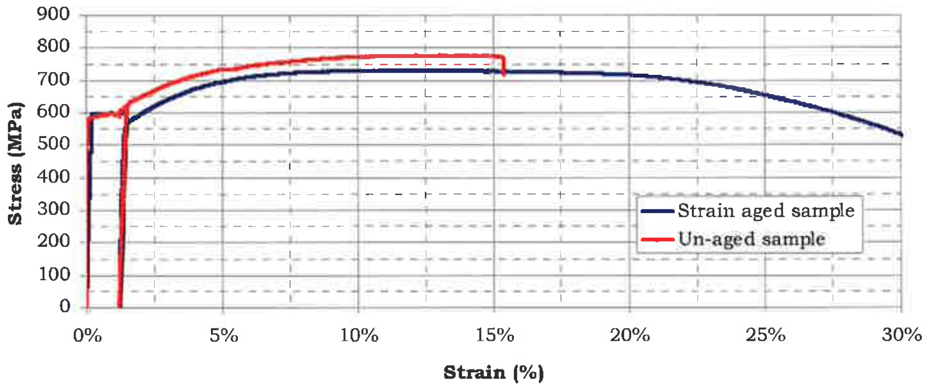

Figure 9 Materials Stress-strain response for 1.5% pre-strain and 60 days aging

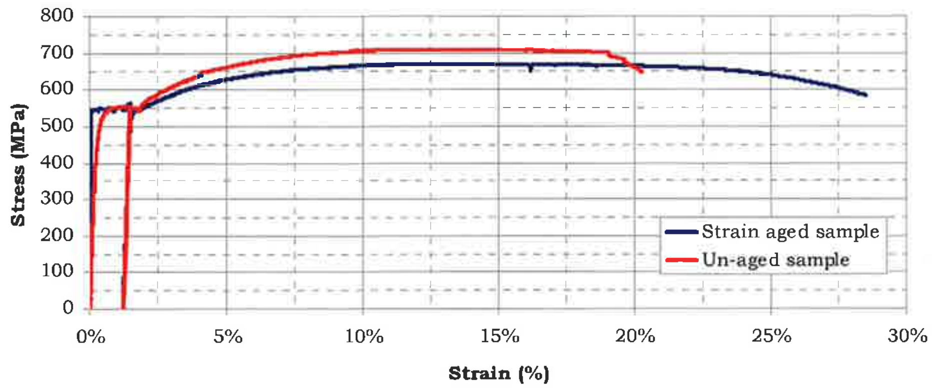

Figure 10 Materials Stress-strain response for 1.5% pre-strain and 60 days aging

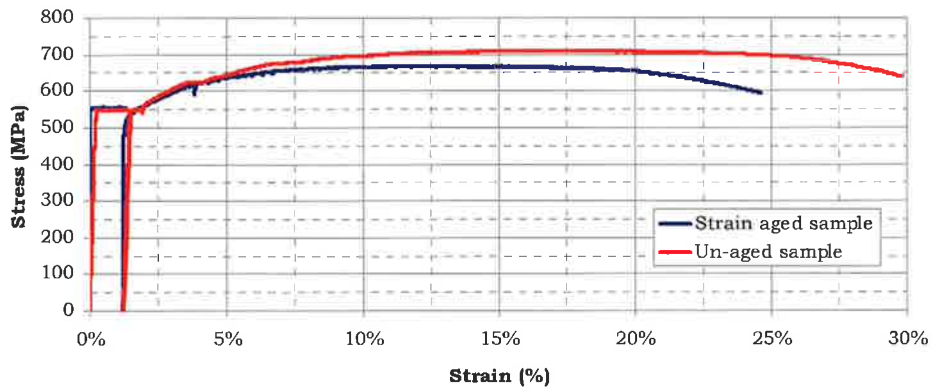

Figure 11 Materials Stress-strain response for 1.5% pre-strain and 60 days aging

2.5% PRE-STRAIN

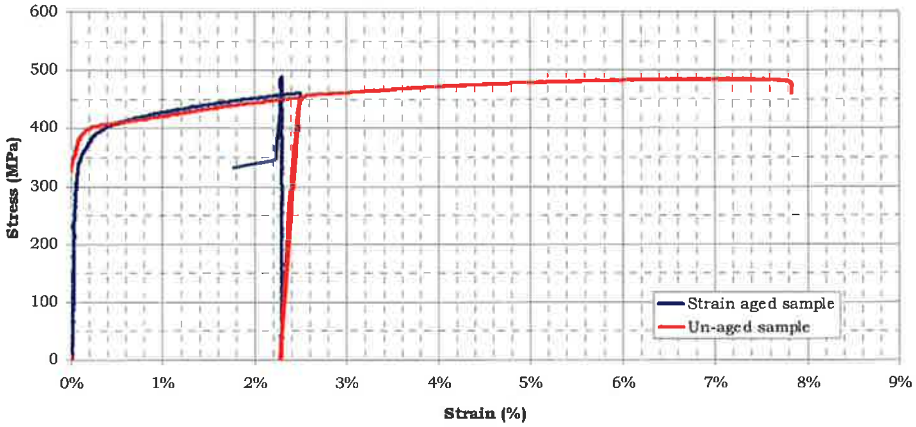

Figure 12 Materials Stress-strain response for 2.5% pre-strain and 30 days aging

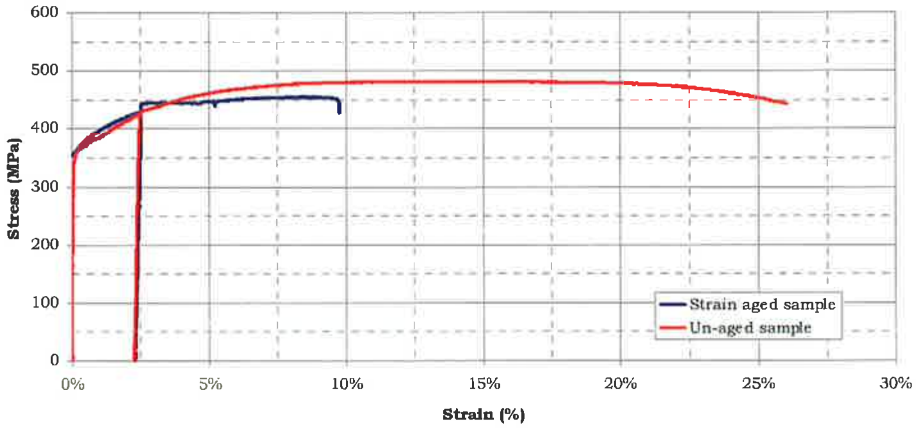

Figure 13 Materials Stress-strain response for 2.5% pre-strain and 30 days aging

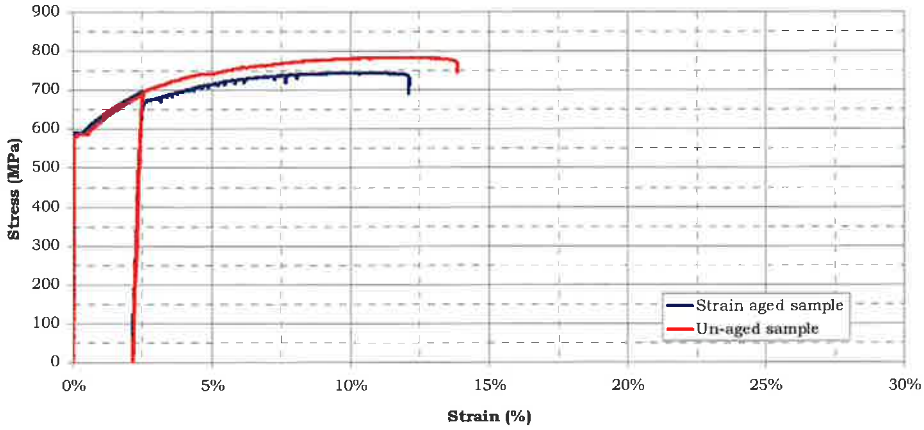

Figure 14 Materials Stress-strain response for 2.5% pre-strain and 30 days aging

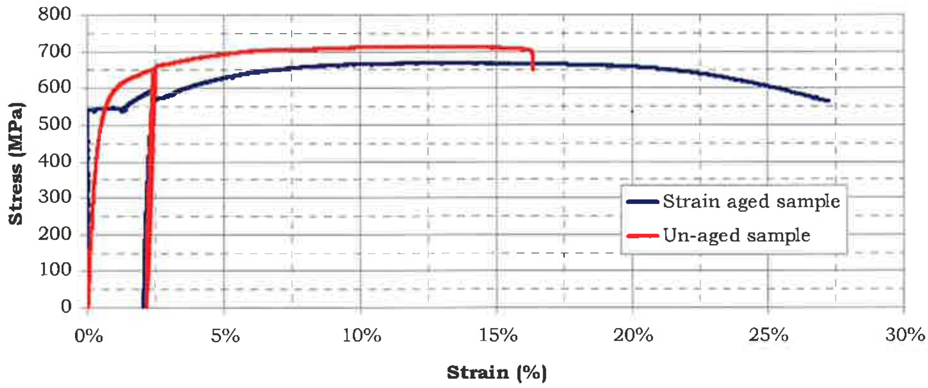

Figure 15 Materials Stress-strain response for 2.5% pre-strain and 60 days aging

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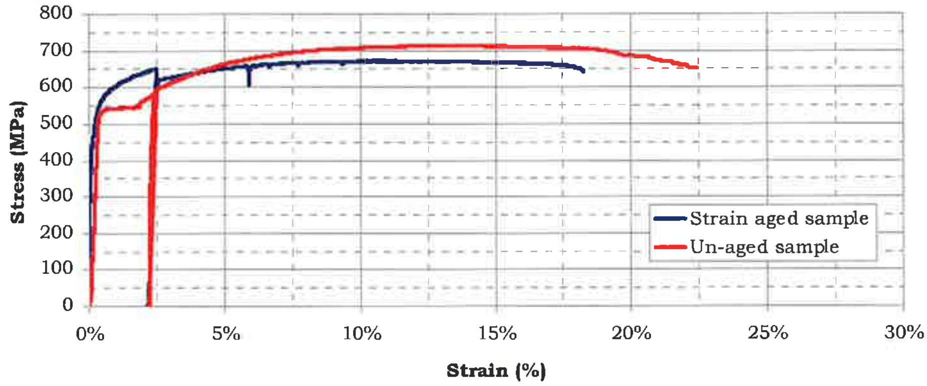

Figure 16 Materials Stress-strain response for 2.5% pre-strain and 60 days aging

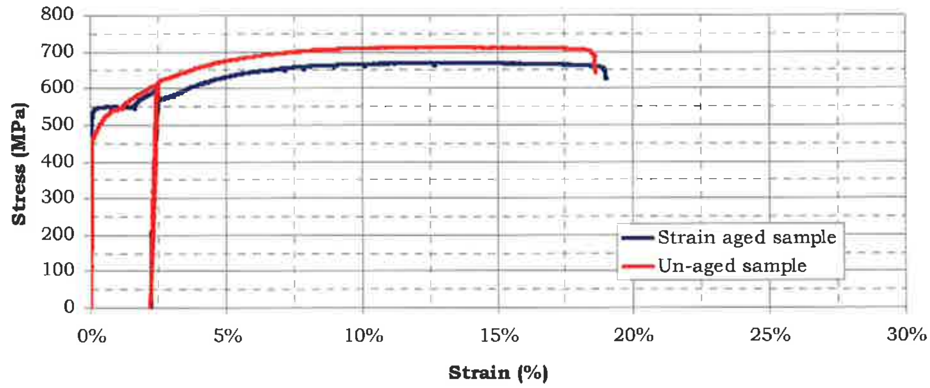

Figure 17 Materials Stress-strain response for 2.5% pre-strain and 60 days aging

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5% PRE-STRAIN

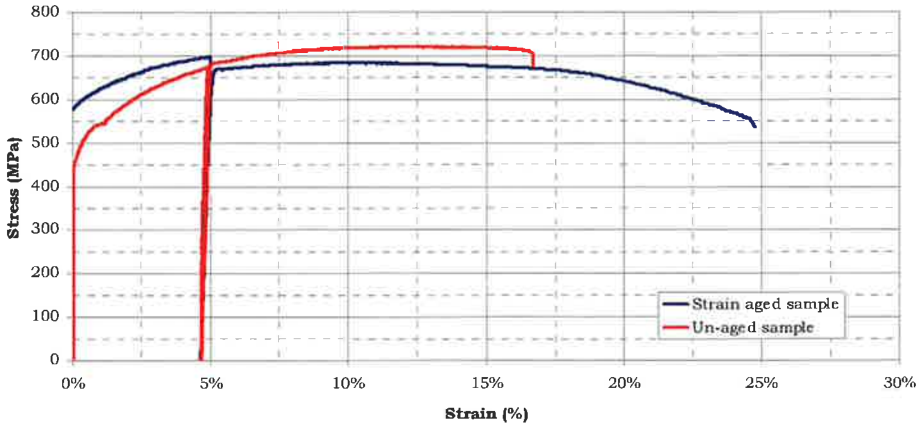

Figure 18 Materials Stress-strain response for 5.0% pre-strain and 30 days aging

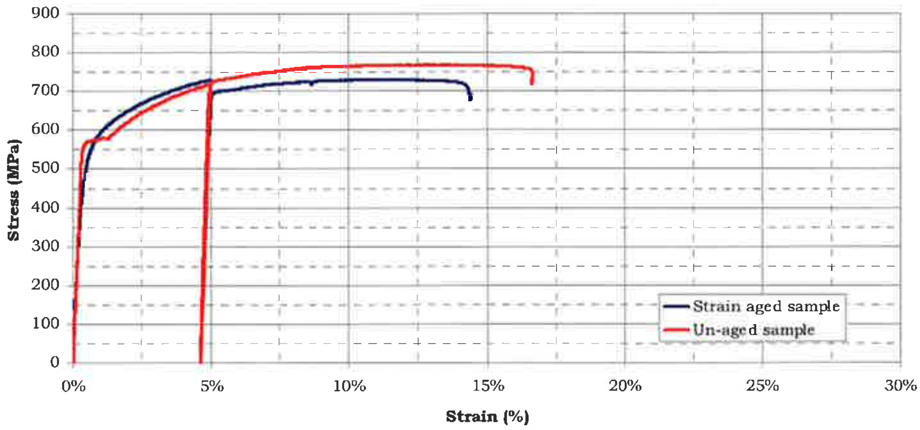

Figure 19 Materials Stress-strain response for 5.0% pre-strain and 30 days aging

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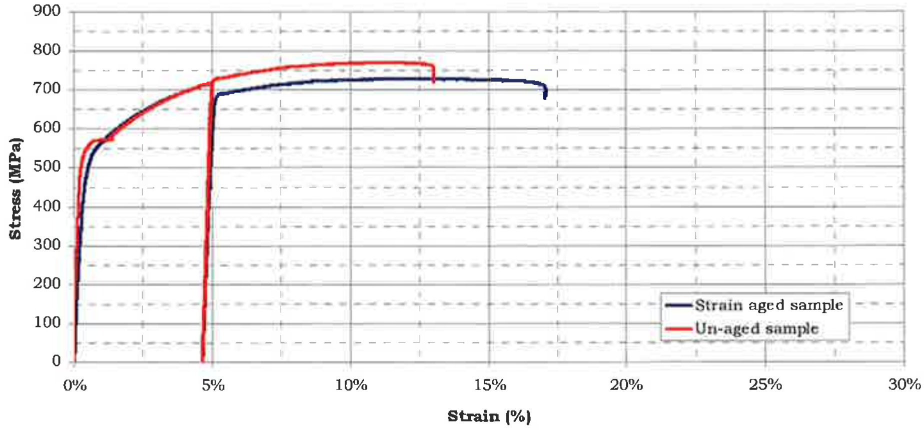

Figure 20 Materials Stress-strain response for 5.0% pre-strain and 30 days aging

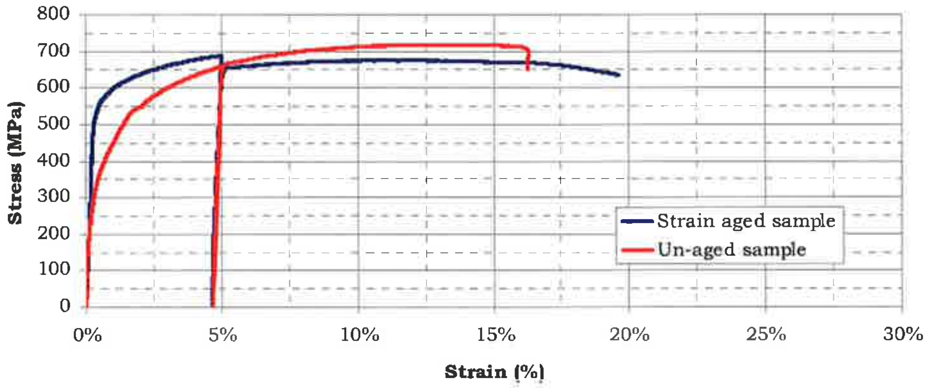

Figure 21 Materials Stress-strain response for 5.0% pre-strain and 60 days aging

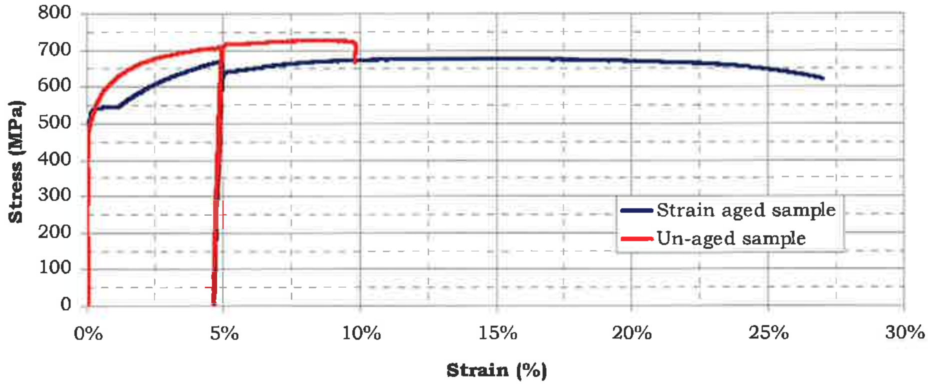

Figure 22 Materials Stress-strain response for 5.0% pre-strain and 60 days aging

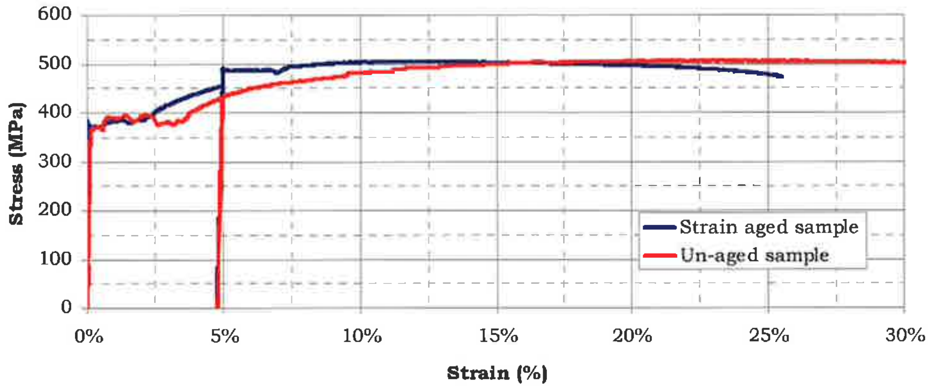

Figure 23 Materials Stress-strain response for 5.0% pre-strain and 60 days aging