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Influence of high temperature on the mechanical behaviour of Australian Strathbogie granites with different grain sizes

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ABSTRACT: Mechanical properties of Strathbogie granites were studied through compressive testing. This study focuses on the influence of temperature on peak strength, elastic modulus and total stain development. Rock samples include medium and coarse grained granites. Rock specimens were heated to various temperatures (from room temperature to 800 °C). It was observed the compressive strength of both medium and coarse granites increased as the temperature was increased up to 200 °C, but decreased sharply above this temperature. Stress-strain curves at 800 °C showed plasticity behaviour in which brittle-plastic transition was observed. The results indicated that the fracture initiation stress was more sensitive to the influence of grain size due to the length of initial cracks, and was inversely related to both porosity and mean grain size. Stress-strain data were incorporated into a finite element (FE) model (ABAQUS 6.7.1), so that both elastic and plastic behaviour could be predicted over a wide range of temperatures.

1. INTRODUCTION

Geothermal resource is now considered renewable on the time-scales of both technological and societal systems, with cost, reliability and environmental advantage over conventional energy resource. In the meantime, there is a new challenge for rock mechanics to deal with rock engineering problems at high temperature. The effect of temperature on the mechanical properties of rocks has been an important study in rock mechanics especially for high-level radioactive disposal, productions of geothermal energy and underground coal gasification projects. Granite is a very common rock type in the Earth's crust. It is rich in elements with heat-producing radioactive isotopes (K, Th, U) and is thus commonly associated with temperature anomalies within the crust and elevated geothermal gradients. These qualities make granite an important reservoir material for enhanced geothermal systems (EGSs), which reach temperatures up to 300 °C [1], and an important rock type for conventional underground nuclear storage (up to 250 °C)[2, 3] and nuclear self-storage (up to 1300 °C)[4, 5].

2. MATERIAL AND METHODOLOGY

2.1 Specimen preparation

Specimens are cored from granite rock block and prepared following the International Society for Rock Mechanics (ISRM) recommendations for compressive strength, and elastic modulus. Cored samples with visible cracks were discarded. A total of 20 Strathbogie granite specimens were used. Cylindrical specimens 22.5 mm in diameter and 45 mm in length (shape factor of 2) were prepared. The two ends of the specimens were ground to produce two parallel surfaces perpendicular to axial direction of the cylindrical specimen. The parallel surfaces were checked by using both a dial test indicator (DTI) and a micron meter. Rock specimens were placed on a flat plate for DTI checking which showed that the ends of the specimens were within ± 10 μm.

2.2 Physical property

Granites are medium- to coarse-grained igneous crystalline rocks that form by crystallisation of certain slow-cooling magma. The minerals that form granite are, primarily, quartz, plagioclase feldspars and alkali feldspar, in addition to biotite, muscovite and/or hornblende. Strathbogie granite is collected from the region surrounding the Strathbogie batholith which is a large, discordant, composite body more than 1500 km^2 in area situated 150 km north-northeast of Melbourne in central Victoria (Fig. 1) [6].

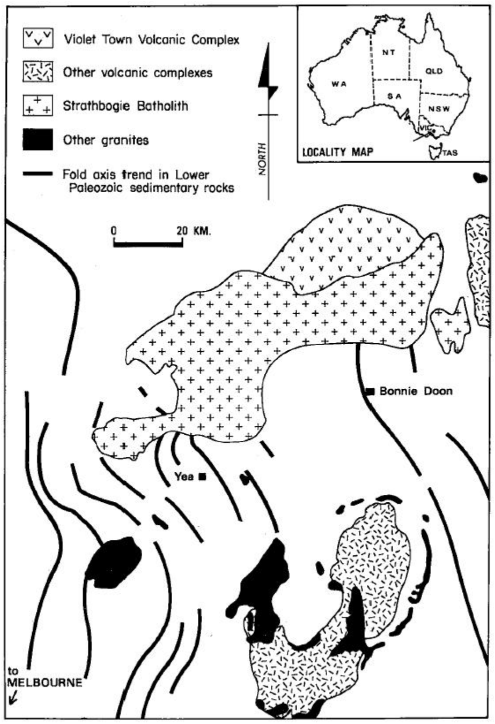
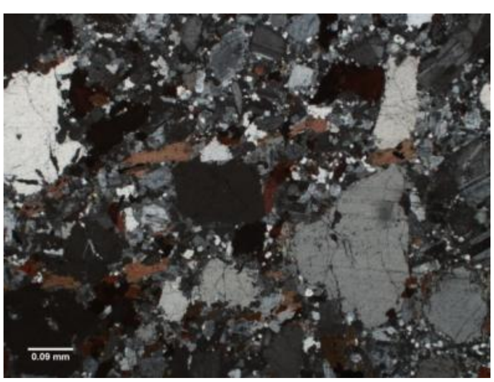
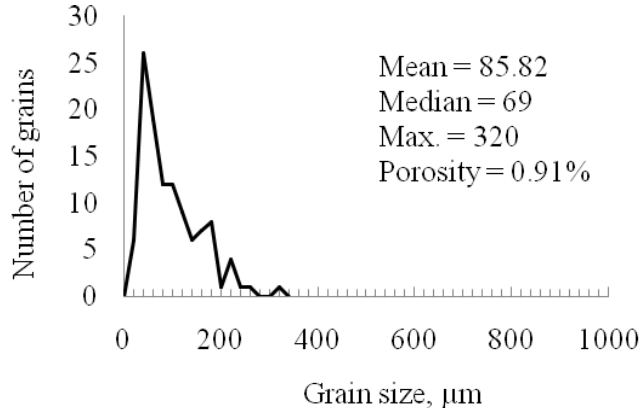


Fig. 1. Regional geological setting of the Strathbogie batholith and other felsic igneous complexes of central Victoria [6]

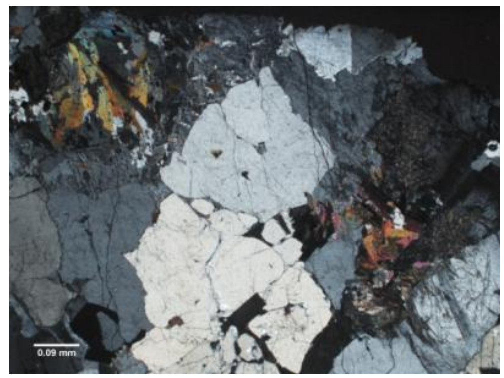
Two types of Strathbogie granite were selected for this study: medium-grained granite (MG) and coarse-grained granite (CG). MG granite has relatively broad grain size distribution varying from 15 μm to 320 μm (Fig. 2 (a), (b)), while the grain sizes of CG granite are distributed evenly from 70 μm to 600 μm (Fig. 2 (c), (d)), with a few larger grains over 800 μm. The porosity measurements are presented in Fig. 3, which shows that MG granite (0.914%) is less porous than CG granite (1.156%).



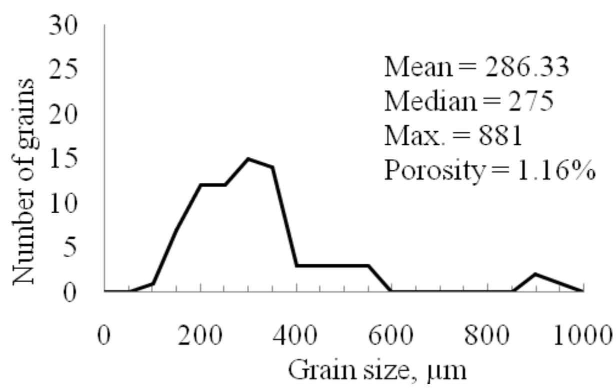
(a) Microscopic image of MG granite



(b) MG gain size distribution



(c)Microscopic image of CG granite



(d) CG grain size distribution

Fig. 2. Grain sizes of MG and CG granites

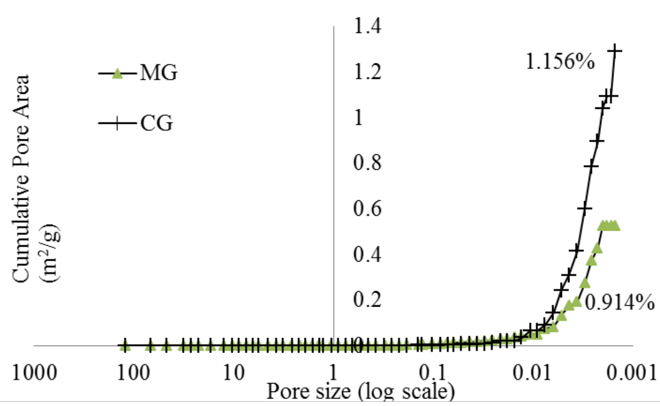


Fig. 3. Cumulative pore area vs pore size

2.3 Experimental methodology

Compressive strength testing was carried out to study the mechanical behaviour of granite samples at room temperature (23 °C) and at high temperatures (200 °C, 400 °C, 600 °C 800 °C). Specimens were heated inside a high-temperature furnace, using a heating rate of 5 °C/min to reach the selected testing temperatures. This heating rate was adopted in order to avoid thermal shock and the development of stress fracture. The temperature was kept constant for an adequate duration (> 1 hr) in the furnace after it reached the assigned temperature, to ensure uniformity in temperature across the specimen. The specimens were loaded in compression with a constant displacement rate of 0.1 mm/min at the appointed temperature (Fig. 4). Stress-strain behaviour was obtained and mechanical characteristics such as load and deformation were also measured during axial compression at various temperatures until the specimens failed.

Fig. 4. Servo-controlled Instron machine with a loading capacity of 10 tonnes and environmental furnace

3. RESULTS AND DISCUSSION

3.1 Strength of Strathbogie granite at various temperatures

The axial stress-strain plots for representative tests at each temperature investigated are given in Fig. 5. The test results (bulk density, peak load, compressive strength, axial strain and elastic modulus) at each of the temperatures investigated are given in Tables 1 and 2. The stress-strain curves of MG and CG granites (Fig. 5 (a) and (b)) display concave up curves from initial loading to peak strength followed by brittle failure when tested between 23 °C and 600 °C. At 800 °C, both MG and CG granites displayed more pronounced plastic behaviour after reaching the peak strength and greater strain at failure compared to those deformed at 600 °C and below.

The brittle fracture of polycrystalline rocks may correspond to general axial splitting by macroscopic cracks (pre-existing joints and faults) extending in the direction of axial compression at low confining pressure [7-9]. When the temperature increases, the crystal particles of rock fractures will form new microscopic cracks (pre-existing grain boundaries) between mineral grains, as a result of differential thermal expansion between grains with different thermoelastic moduli and thermal conductivities [10-12]. Especially in crystalline rock, the amount of quartz has a significant effect on thermally-induced micro-cracks because of its complexity in thermal expansivity. It is reasonable to state that when the temperature increases to 400 °C or higher, the influence of temperature becomes greater on the mechanical behaviour of granite, due to the significant thermal response at the higher temperature. The brittle-plastic transition for Strathbogie granite was found to occur between 600 and 800 °C under uniaxial conditions (Fig. 5).

Figures 6 (a) – (c) present the influence of temperature on the mechanical properties (compressive strength, elastic modulus and strain to failure) of the granite which can be considered over two temperature ranges, i.e. from 400 °C to 600 °C and from 600 °C to 800 °C.

<u>Compressive strength</u>

In both MG and CG granites there is a greater reduction in peak compressive strength of when the deformation temperature is increased from 400 °C to 600 °C compared to when the temperature is increased from 600 °C to 800 °C. Figure 6(a) also shows that MG granite continued to weaken at temperatures above 600 °C. Whereas CG granite only weakens a little between 600 °C and 800 °C. Rock strength weakening at high temperature can be caused by the combination of micro-cracks, inter-granular cracks and intra-granular cracks. Micro-cracks is highly depending on the pre-existing fault and the grain boundary of crystalline rock, which is also defined as the grain size [13]. Inter-granular cracks occur in some of the weaker mineral constituents such as feldspar and biotite grains [14]. Intra-granular cracks may relate to the passage of the material through the brittle-plastic transition with temperature increase, which is a transition from dominantly micro-cracking to dominantly dislocation [15]. Therefore, the longer grain boundaries and larger inter-granular cracks resulting from increased grain size which provide longer paths of weakness, along which growing cracks propagate. This suggests the degradation of rock strength of CG granite was greater than MG granite at relatively low temperature (below 600 °C). When temperature increases close to the suggested brittle-plastic temperature region (above 600 °C) intra-granular cracking, took place. The results showed that MG granite was more sensitive to intra-granular cracking at brittle-plastic temperature range compared with brittle temperature range.

Axial strain

The maximum axial failure strain is greater in MG granite compared to CG granite (Fig. 6(b)) over the entire range of tested temperatures and is consistent with smaller grain displaying greater plasticity. In both MG and CG granites the failure axial strain is relatively unchanged until the deformation temperature exceeds 600 °C. The transition temperatures for quartz and feldspar to change from dominantly micro-cracking to dominantly dislocation have been reported to be between approximately 300-400 °C and 550-650 °C, respectively [16]. Therefore, the increase in axial strain of CG granite when temperatures exceed 600 °C is possibly due to the dislocation of quartz composition.

Table 1. Medium-grained granite (MG)

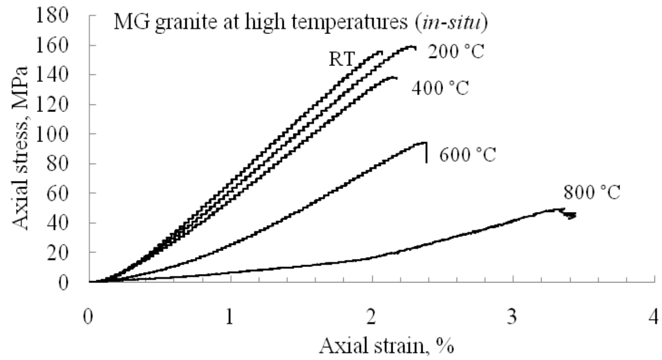
T, °C	Peak load, kN	Compressive strength, MPa	Failure strain, %	Elastic modulus, GPa
RT*	57.52	154.97	2.07	8.57
200	74.31	161.58	2.22	8.61
400	51.79	138.63	2.16	7.59
600	34.29	91.32	2.45	5.39
800	19.76	53.32	3.07	2.94

*RT = Room Temperature, 23 ° - 25 °C, bulk density of 2650.75 kg/m^3

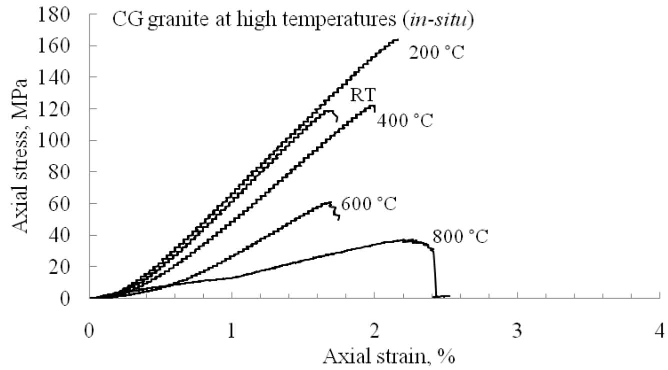
Table 2. Coarse-grained granite (CG)

T, °C	Peak load, kN	Compressive strength, MPa	Failure strain, %	Elastic modulus, GPa
RT*	41.16	112.94	1.57	8.87
200	50.05	137.77	1.91	8.57
400	39.69	108.38	1.68	7.58
600	20.89	56.26	1.69	4.87
800	15.12	40.64	2.40	2.53

*RT = Room Temperature, 23 ° - 25 °C, bulk density of 2650.75 kg/m^3



(a)



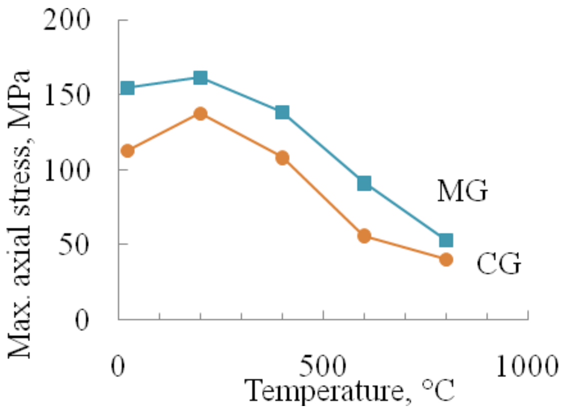
(b)

Fig. 5. Stress-strain curves of (a) MG granites and (b) CG granites

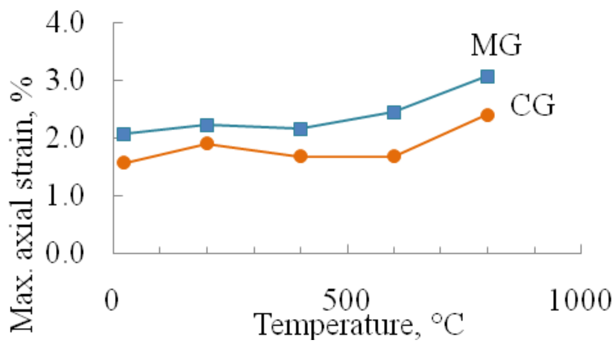
Elastic modulus

Figure 6(c) shows that the effect of deformation temperature on the elastic modulus of both MG and CG granites are similar with no obvious difference between the two temperature ranges, 400 °C – 600 °C and 600 °C – 800 °C. The elastic modulus is relatively consistent of both MG and CG granite up to 400 °C, above which the elastic modulus drops in a linear fashion. Therefore grain size has very little influence on elastic modulus.

Previous research has found that the fracture initiation stress is highly sensitive to grain size due to the length of initial cracks, and is inversely related to both porosity and mean grain size [17]. The experimental results in this study support this relationship, even at high temperatures (up to 800 °C). MG granite was observed to have smaller grain size and porosity than CG granite, and was found to have higher compressive strength and elastic modulus than CG granite at all tested temperatures.



(a)



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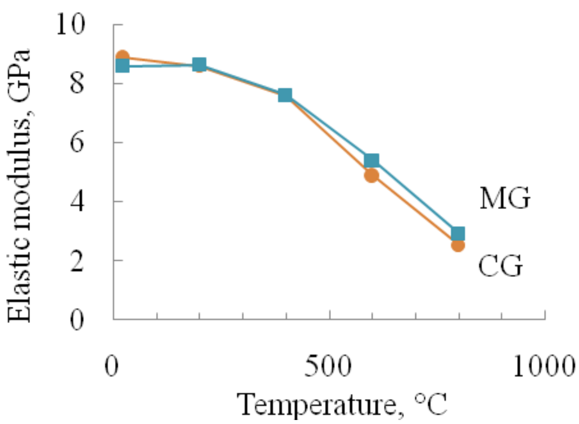
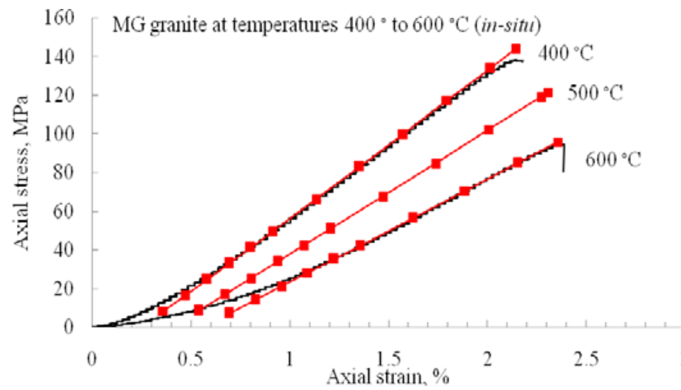


(c)

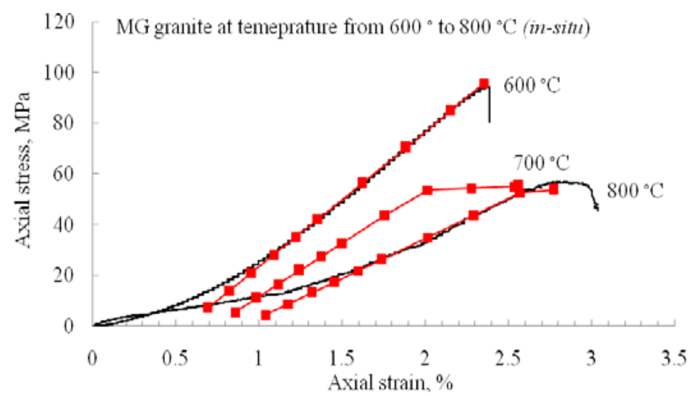
Fig. 6. (a) Axial stress vs temperature, (b) Axial strain vs temperature, and (c) Elastic modulus vs temperature.

4. FINITE ELEMENT MODEL OF HIGH TEMPERATURE COMPRESSION TEST

A finite element (FE) model of the compression test of Strathbogie granite at an elevated temperature was developed using ABAQUS 6.7.1. A two dimensional (axis-symmetric) model of the compression test was set-up in two parts: top compression steel plate and the granite specimen. Based on the experimental results, the stress-strain behaviour under unconfined uniaxial compression was found to be strongly dependent on temperature and the elastic-plastic transition was found to take place between 600 ˚C and 800 ˚C. Therefore, for a temperature range of 25˚C to 600˚C, the material properties were assumed to be elastic up to the failure strain. For temperature range from 600 ˚ to 800˚C, an elastic-plastic model was assumed. There are several assumptions made in the FE model: (1) uniform temperature across the entire granite was predefined before the start of each analysis; (2) the Poisson ratio of the Strathbogie granite was assumed to be 0.25 at all temperatures; (3) the interaction between the platen and granite assumes a friction coefficient of 0.1. Vertical downward displacements were applied to the bottom surface of the platen and enabled the granite to be loaded in compression.



(a)

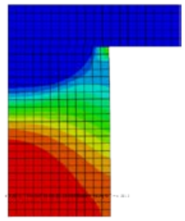
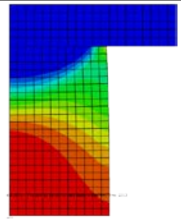
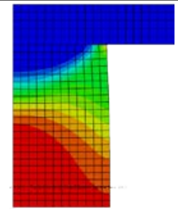
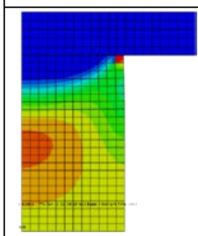
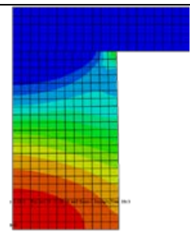
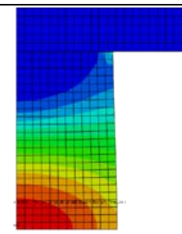


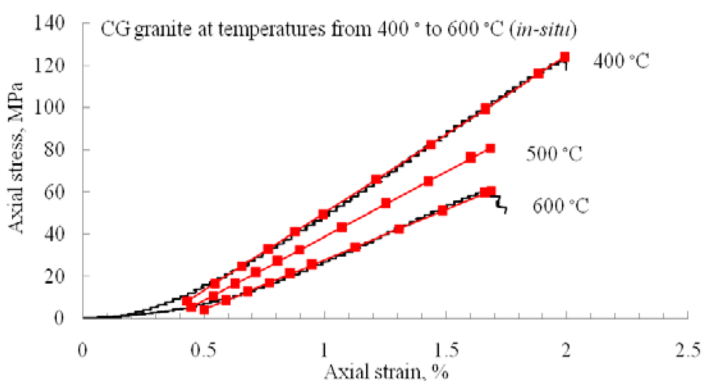
(b)

Fig. 7. Stress-strain curves of MG granite at high temperatures. Solid line: experimental results; solid line with square marker: finite element method results

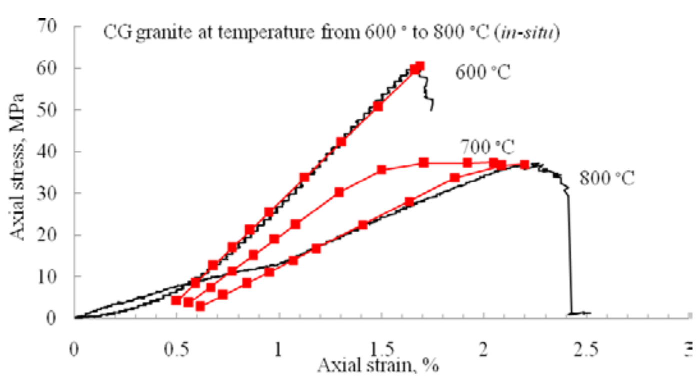
Figures 7 and 8 show axial stresses for compression strength of the MC and CG granites undertaken at 400, 600 and 800 °C which are plotted against the predicted values for the various test temperatures. Figures 7 (a) and 8 (a) show linear elastic behaviour for both experimental results and FE model results, which are aligned very well. The results predicted using the FE model show the decrease in elastic modulus with increase in temperature. As well as the elastic-plastic

Table 3. FE models of plastic strain distribution and the visual images

MG granite at 800 °C			
Axial strain = 1.95%	Axial strain = 2.51%	Axial strain = 2.79%	Visual image
			
CG granite at 800°C			
Axial strain = 1.59%	Axial strain = 2.04%	Axial strain = 2.27%	Visual image
			



(a)



(b)

Fig. 8. Stress-strain curves of CG granite at high temperatures. Solid line: experimental results; solid line with square marker: finite element method results

behaviour at 800 °C and are in good agreement with experimental results. The constitutive equation is based on the temperature dependent modulus after a small correction is applied to the initial strain which allows the model to predict the axial stress up to the failure strain of the specimen with an acceptable measure of success.

At 800 ˚C, the predicted values also agreed adequately with the measured axial stress values in both the elastic and plastic regions. The finite element (FE) model was able to predict not only the elastic behaviour of the granite but also the plastic and ductile behaviour at higher temperatures.

The FE model can be used to predict the compressive stress-strain response of the two grain size granites at any given temperature between 23-800 ˚C. For example, although compression tests were not performed at temperatures of 500 and 700 ˚C, the axial stress can be predicted using the model and the results are shown in Figs. 7 and 8. The predicted stress-strain behaviour of MG and CG granites at 700 ˚C show both plasticity (Fig. 7 (b) and 8 (b)) from strain of 2.02% and 1.50%, respectively. The results show that the FE model has excellent capability for predicting the behaviour of the temperature dependent materials. The distribution of plastic strains in both MC and CG granites that were deformed at 800 ˚C at the onset of plastic strain, partway through the plastic deformation and just before final failure is shown in Table 3. Plastic strain initially develops at the corner and gradually extends through the specimen at an inclined angle of about 45˚ before failing roughly at that angle. Visual images of specimens after tested (Table 3) also confirmed that failure of compressed cylindrical granite specimens occurred in this fashion. However, by comparing the plastic strain distribution of MG and CG granite at the same axial strain stages, it has found that the deformation occurred more gradually than CG granite. Plastic deformation of CG granite is less evenly between 0.15% and 0.25%, possibly due to the larger grain size and micro-cracking compared to MG granite.

5. CONCLUSION

In this study, the mechanical properties of two types of Strathbogie granites were studied through compressive testing at room temperature and elevated temperature up to 800 ºC. Specimens were heated at the rate of 5 ºC/min. The conclusions are:

1. As expected medium-grained (MG) granite was found to have higher compressive strength than coarse-grained (CG) granite. Besides, it was observed the compressive strength of both medium and coarse granites were strengthened with increasing deformation temperature up to 200 °C, but decreased sharply above this temperature. The compressive strength decreased most significantly between 400 to 600 °C in coarse grained granite and between 600 to 800 °C in medium grained. Stress-strain curves at 800 °C showed plastic behaviour. The brittle-plastic transition temperature of both MC and CG granites under unconfined conditions were found to occur between 600 to 800 °C.

2. Depending on the quartz and feldspar content, the sudden strength change from 400 °C may be due to the dislocation of quartz during heat treatment. CG granite possibly has higher feldspar content, which causes the higher axial strain at high temperatures. The results indicate the fracture initiation stress is highly sensitive to the influence of grain size due to the length of initial cracks, and is inversely related to both porosity and mean grain size.

3. Unconfined compression testes were undertaken at different temperatures to determine the constitute behaviour of both MC and CG granites which were incorporated into a finite element (FE) model which is capable of predicting not only the elastic behaviour but also its plastic and ductile behaviour at high deformation temperature.

6. ACKNOWLEDGEMENT

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