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PLUGGING METHOD FOR HDR RESERVOIR USING HYDROTHERMAL PROCESSING OF SMECTITE CLAYS TO IMPROVE RECOVERRY EFFICIENT

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ABSTRACT

Recent progress in geothermal technology enables us to explore the hot dry rock (HDR) as a promising massive energy source. Viscous gelation through hydrothermal processing of the smectite clays has proved to facilitate water control of flowing and plugging in the HDR fracture network. Utility of the hectorite and saponite agents prepared to comprise the individual smectite raw components in low concentrated slurry has been confirmed by water control test with the simulator of a flow type autoclave equipment. The flow path between the granite fragments in the reactor tube is successfully plugged with in situ formed hectorite gel when the low concentrated (more than 2%) slurry is consecutively injected ino the reactor heated at 200 and 250˚C. Effective plugging is adequately endurable for more than 30 days when the relatively higher concentrated 6% slurry is processed. The saponite agent also reveals endurable plugging for more than 10 days when the 3% slurry is processed at 300˚C. The montmorllonite agent is not useful for effective plugging because of its lesser viscous gelation when hydrothermally processed. Among them the hectorite agent is so functional in quality of plugging and endurance that it could make easier fundamental design of the HDR system, e.g., temporary or eterrnal blocking of the minute fractures in the HDR reservoir could prevent water leakage and therefore improve the recovery of the circulating water.

1. INTRODUCTION

Recently geothermal technolgy has advanced to extract the underground huge geothermal energy, in particular, targetting the hot dry rock (HDR) as a massive energy source (Takahashi and Hashida, 1992; Takahashi et al., 1995). There has been designed of creating artificial fracture network in the HDR allowing to inject water from a injection well to recover hot water through a production well. Presently several HDR plant testing fields have been developed to establish this HDR system. However, some serious problems remain unresolved. When the artificial fractures are made in the HDR body, many fine cracks are also produced over the entire body, so that the injected water may leak out through these fine cracks not part a main path, lowering a recovery of the circulating water (Hayashi et al., 1995). As a result, the overall efficiency of the heat extracting system decreases. According to Kitano and Hori (1995), for example, the final recovery of the circulating water is lowered to be less than 10% at the Ogachi HDR plant testing field in Japan. Under these circumstances, there has been an increasisng desire to develop a water control agent useful for plugging such undesirable artificial fractures that was produced in the HDR reservoir.

Smectite clays are well known gelling nature owing to their excellent hydration in water. If they can be hydrothermally synthesized in the HDR fractures, in situ formation and gelation of the smectite may be able to take advantage of plugging the fractures. Among the smectites, hectorite is considered to be preferable because its rheologial properties are extremely excellent in a colloidal dispersion system (Newmann, 1965; Torii and Iwasaki, 1987) and it has practically used as a mud water for deep drilling in many countries (Koga, 1993).

The present study aims to develop useful plugging agents for the HDR fractures by using hydrothermal processing of smectite clays such as hectorite, saponite and montmorillonite and to inspect their functional utility by water control test using the flow type autoclave equipment.

2. SYNTHESIS OF SMECTITE

Smectite is a clay mineral constructed of alternating silicate layer and hydrated interlayer with exchangeable cations. Referring to the method of Torii and Iwasaki (1987), the starting raw materials are prepared to comprise the smectite components in low concentrated slurry. Here are presented the procedures for the hectorite slurry. Water glass is solved with sulfuric acid and then mixed with $MgCl_2$ aqueous solution. This mixed solution is dropped into NaOH aqueous solution and stirred to produce homogeneous Si/Mg precipitate. After filtration and subsequent washing with distilled water for many times to remove excess cations, the precipitate is mixed with NaOH and LiOH aqueous solutions so that the resultant slurry comprises approximately 10 % of hectorite components in weight ratio. Partial dissolution of the Mg/Si precipitate during the washing procedure causes deviation to some extent from the ideal composition. As for saponite and montmorillonite, the slurry is prepared by mixing additional $AlCl_3$ aqueous solution with $MgCl_2$ aqueous solution according to their ideal compositions. Thus prepared slurry has been hyrothermally treated to examine the optimum conditions of the individual smectite formation in terms of viscous behavior of the gel product. Hydrothermal synthesis was carried out with an autoclave that is made of hastelloy material (inner volume of 20ml): 10ml of the starting slurry, diluted in lower concentration of 1-3 %, was put into the vessel at a filling ratio of 50%, and then reacted at 150-300˚C range for 1 to 72 hours under autogeous pressure with agitation by turning the vessel in an oven. When the 2% slurry is treated, hectorite is poorly crystallized at 150-200˚C range and rather well crystallized at 250-300˚C range for an excessively short reaction of 1-2 hours. Saponite and montmorillonite are sythesized under different conditions: their formation is optimized at higher temperature condition above 250˚C and a longer reaction of 24-48 hours particularly for montmorillonite.

3. VISCOUS OF SYNTHESIZED SMECTITE GEL

Hydrothermally synthesized smectites are of viscous nature in association with gelation. The mass viscosity of these smectite products are considered to play an important role to plug the geothermal reservoir fractures. Such high temperature viscous behavior in terms of hectorite formation and gelation was demonstrated by Higashi et al. (1997), in which the mass viscosity of the hectorite product could be in situ measured by means of a torque meter attached to the screw axis of a mixing type autoclave. Figure 1 shows the result of torque measured when the 0.5-2% of hectorite slurry was treated from room temperature up to 300˚C in comparison with the result of a control sample consisting of water alone (concentration; 0%). As evident in Figure 1, the torque value of the 2% hectorite slurry product shows a rapid increasement at the 150-200˚C range, indicating an outstanding rise in the mass viscosity of the product as compared to the control sample (water). This temperature is reasonably consistent with the initial crystallization stage of hectorite. The torque value is maximized around 200˚C and thereafter overcomes the control sample although it gently decreases towards 300˚C. It is noted that the differencial torque ascribed to the mass viscosity of the hectorite gel product is almost unvaried throughout the temperature range of 200-300˚C. Hydrothermal treatment of the 0.5 and 1% hectorite slurry also yields a similar behavior, in which the mass viscosity is lowered a little but reasonably proportional to the concentration of the slurry treated: namely, the higher concentrated slurry is treated, the higher mass viscosity developed (Higashi et al., 1997). This fact that the viscous nature of the hectorite product depends upon the starting slurry concentration is of great importance in its practical usage for a plugging agent as mentioned later. The mass viscosity of the saponite and montmorillonite products has not measured yet. Like the hectorite product, the saponite product has an aspect of fairly intensive gelling: it is likely to serve as a plugging agent. But gelling nature of the montmorillonite product is less developed as compared to the hectorite and saponite products.

4. WATER CONTROL TEST USING SYNTHESIS SMECTITE

In order to establish utility of the smectite plugging agents, water control tests in a supposed HDR reservoir environments have been performed with a simulator of the flow type autoclave (Hirano and Higashi, 1994; Hirano, 1995). As outlined in Figure 2, this equipment consists mainly of a tube reactor (autoclave) and a circulation loop of slurry and water. In a tube reactor, the granite fragments of 1-4 mm in size are charged after glass wool is packed in the bottom. To the periphery of the middle portion of the reactor, a heater is provided to control reaction temperature. Two pressure gauses attached to the lowermost and uppermost portions are to measure inflow and outflow pressures, respectively. A pressure regulator on the lowerend of the reactor is used to adjust the inner pressures. A water pump in combination with a feed tank enables concecutive injection of the slurry. A bypass parallel to the feed tank is used for direct injection of water. The feed tank with inner volume of 200 cm^3 is divided into two portions by a diaphragm: a starting slurry is charged up in the upper portion; water is contained in the lower portion. The water pump serves water to feed into the tank to push out the slurry via the diaphragm, therby injecting the slurry into the tube reactor.

Firstly water must be injected into the tube reactor for many hours so that the flow path between the granite fragments is completely filled with water. After allowing both the inflow and outflow innner pressures to stand around 100 kg/cm^2, the reactor is heated. Once the reaction temperature is attained, the circulation system is turned to supply the slurry at a flow rate of 1 ml/min. During the reaction procedure, the both inner pressures are recorded at a interval of 5-10 minutes in order to inspect how fast is the flow path plugged or not. Figure 3 shows the result of a successful plugging test for the 8% hectorite slurry processed at 250˚C. In the figure, both the inflow and the outflow pressures are plotted against the reaction duration time when smectite slurry supplied. The slurry injection commences immediately the reactor temperature is attained to 250˚C. The flow path in the reactor is still flowing during erarly reaction procedure; namely, the both inner pressurees are not differentiated. When the reaction proceeds around the duration time of 20 minutes, however, the both pressures are gradually differentiated as the inflow pressure increases and the outflow pressure decreases to the contrary, which means the flow path is partially blocked by insufficient hectorite gel product. At the duration time of 53 minutes, the inflow pressure jumps over 300Kg/cm^2 (instantly the injection ceases because the water pump stops by means of a limiter), indicating that the flow path is completely blocked by sufficient hectorite gel formed.

Plugging tests have been also made on the hectorite slurry for variable concentrations at different reaction temperatures and flow rate. The results are given in Table 1. In the tests for the 2% concentration slurry, plugging is completely successful at a lower temperature of 250˚C, whileas effective plugging does not take place at the lowermost temperature of 200˚C since the hectorite formed at this temperature is poorly crystallized and therefore gelation is not sufficient as to complete plugging. On the other hand, the higher concentrated 4% slurry treated at 250˚C results in plugging within a considerably shorter reaction of 80 minutes. This is explainable: the higher concentreated hectorite slurry causes enhancement of the mass viscosity of the hectorite gel product, which may facilitate not only initial blocking developed point to point in the narrow flow path but also subsequent linking of the blocking points by accelerated accumulation of hectorite.

Considering its practical usage under high temperature conditions, durability of plugging is a more critical quality as a plugging agent. The present simulator equipment enables endurance test after plugging has been successfully achieved. Upon further prolonged heating at the reaction temperature, water injection and reading of the inner pressures are repeated at an interval of 24 hours to inspect how long endurable is effective plugging. The higher concentrated hectorite slurry has the advantage of desirable durability for effective plugging. Figure 4 is an interesting result when tested the 6% hectorite agent, in which the pressure difference between the inflow and the outflow is plotted against the reaction duration time divided into the plugging test (in minute) and the endurance test (in hour). In the preceding plugging test, the pressure difference is maximized when plugging has been successfully completed. In the following endurance test, it goes down a little in 48 hours and thereafter it lasts invariably for more than 30 days (720 hours). Although a little down of the pressure difference means subtle decrease of the mass viscosity of the gel product, there is no indication of reopening of the minute flow path during the prolonged heating run. In contrast, the endurance tests for the lower concentrated hectorite slurry of 1% and 2% result in considerably less endurable plugging within 2 and 6 days, respectively. Probably slight breakdown of the hectorite gel strength damaged through the prolonged heating may cause reopening of very minute flow path. From these results, the higher concentrated hectorite agent is adequately endurable and therefore preferable in practical usage.

Plugging and endurance tests have been also made on the saponite and montmorillonite slurry agents. The results are summarized in Table 2 and Table 3 in comparison with those of the hectorite agent. The runs at 250˚C when tested the saponite and montmorillonite individual 3% slurry have partly successed to achieve plugging. Optimum conditions for effective plugging by hydrothermal processing of the both smectite slurry agents are determined to elevated temperature of 300˚C. In particular, thus processed saponite gel product is adequately endurable during the prolonged heating for more than 10 days, of which excellent endurance can be correlated to that of the hectroite agent (Figure 5). On the other hand, the montmorillonite agent is hard to accomplish plugging because of its low viscous nature and probably slow crystallization, and therefore it is practically useless as compared to the hectorite and saponite agents (Figure 6).

5. CONLUSIONS

The geothermal energy extracting system has been advanced to target the relatively shallow and small HDR with the temperature range of 200-250˚C presently and will be extended to the deeper and gigantic HDR with the higher temperature of 300˚C in future. In this study developped ar smectite plugging agents are useful for such high temperature geothermal reservoirs. When the starting raw materials prepared to comprise smectite raw components in low concentrated slurry are hydrothermally treated at the temperature range of 200-300˚C, viscous smectite gel are formed in a few hours. This hydrothermal processing takes advantages of plugging the HDR fractures by the steps of allowing the starting slurry to inject into the HDR fractures, and allowing the smectite to be in situ synthesized hydrothemally under such circumstances of the underground.

Water control tests by the simulator of a flow type autoclave reveal functional ulitity of the present smectite plugging agents. The results of plugging test and endurance test for each smectite agent are summarized in Table 1 along with the individual starting slurry concentration and the reaction temperature data. The hectorite and saponite agents serve well to plug the miniaturized HDR fractures in the reactor for more than 30 and 10 days, respectively. The hectorite agent is preferable to the saponite agent because the former is more functional in the quality of plugging, which could realize artificial water control of flowing and/or plugging in the HDR fractures depending on the reservoir circumstances. When the higher concentrated hectorite slurry is injected into the HDR, for example, the resulting highly viscous gel product could be helpful to prevent leakage of the circulating water through the minute fractures distributed in the entire HDR and hence to approve greately the recovery of the hot circulating water. Otherwisely less endurable hectorite gel product processed from the lower concentrared slurry could be helpful for temporary blocking in such case that tentative water circulation tests are repeated many times especially in early stage of fundamental design to predict the growth behavior of the artificial fracture network in the HDR. As compared to the hectorite agent, the saponite agent is rather functional at the elevated temperature condition approaching to 300˚C. It may be helpful to plug the more deeper HDR fracures or the surrounding minute fractaures distant from the shallow HDR.

Aside from the functional quality of the present smectite plugging agents mentioned above, their economical preparation must be taken into consideration when a great mass of these slurry agents will be used in the real geothermal fields. The hectorite agent is costly because lithim is an essential component in it. Saponite agent has a advantage over hectorite agent because it, compositionaly free from litium, can be prepared at conpitent prices.

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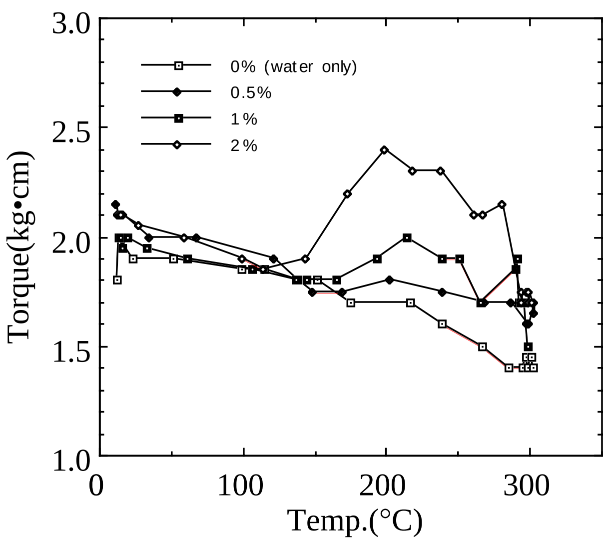

Figure 1 Torque variation during hydrothermal processing of 0.5 - 2% of hectorite slurry.

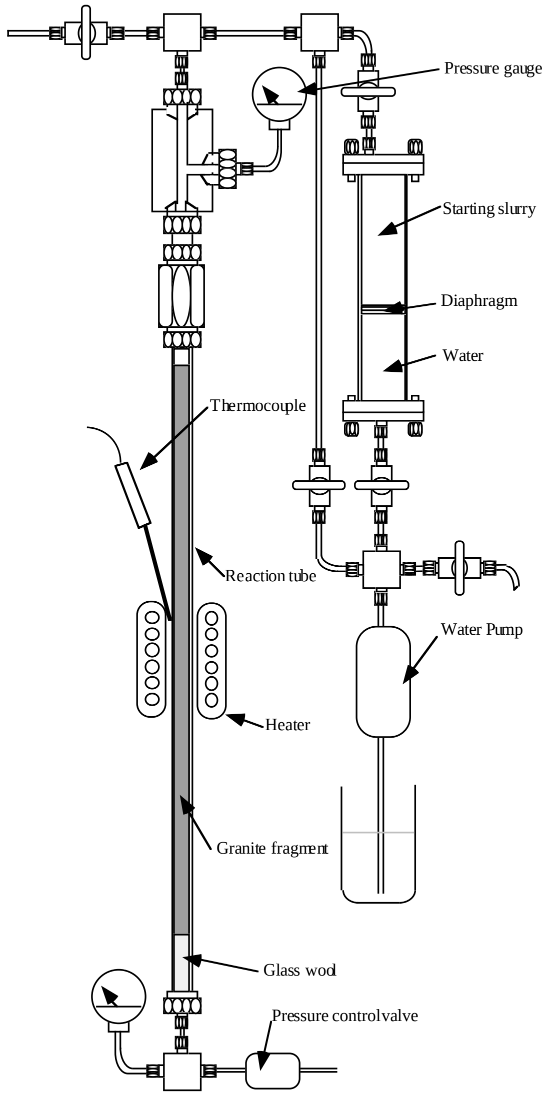

Figure 2 Illustration of the flow type autoclave used for water control test.

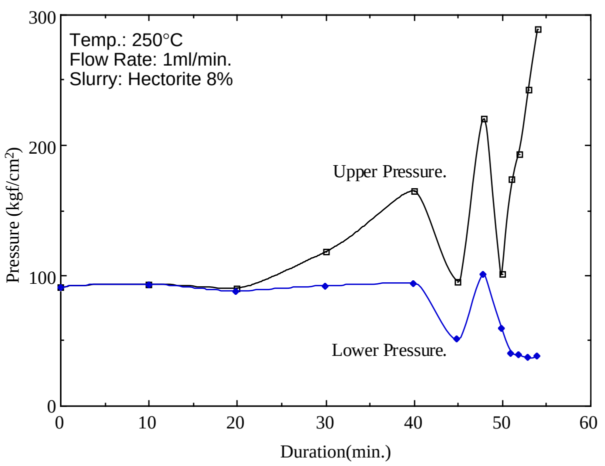

Figure 3 Plugging test for 4% hectorite slurry treated at 200˚C and 250˚C

Table 1 Summary of the water control tests with hectorite for various concentration, flow rate and temperature.

Slurry concentration (wt%)	Flow rate (ml/min.)	Temperature (°C) 150	200	250
2%	1	n.p.	n.p	180min*.
	2	n.p.	n.p.	n.p.
	4	n.p.	n.p.	n.p.
4%	1	n.p.	220min.*	100min.
	2	n.p.	n.p.	50min.
	4	n.p.	n.p.	n.p.
8%	1	n.p.	93min.	53min.
	2	n.p.	60min.	25min.
	4	n.p.	----	----

n.p.: not pluged
* : partly plugged
---- : no experiment

Table 2 Summary of the plugging temperature for various smectite slurry for various smectite slurry.

Slurry Clay mineral	Slurry concentration (wt%)	Temperature (°C) 150	200	250	300
Hectorite	4	n.p.	220min.*	100min.	30min.
Saponite	3	----	n.p.	100min.*	80min.
Montmorillonite	3	----	n.p.	150min.*	100min.

Flow rate: 1ml/min. n.p.: not plugged
* : partly plugged
---- : no experiment

Table 3 Summary of the plugging endurance time for various smectite slurry.

Slurry specimen	Slurry concentration (wt%)	Temperature (°C)	Plugged Time
Hectorite	3	250°C	< 1 week
	6		> 2 months
Saponite	4	300°C	< 1 week
Montmorillonite	4	300°C	> 10 days

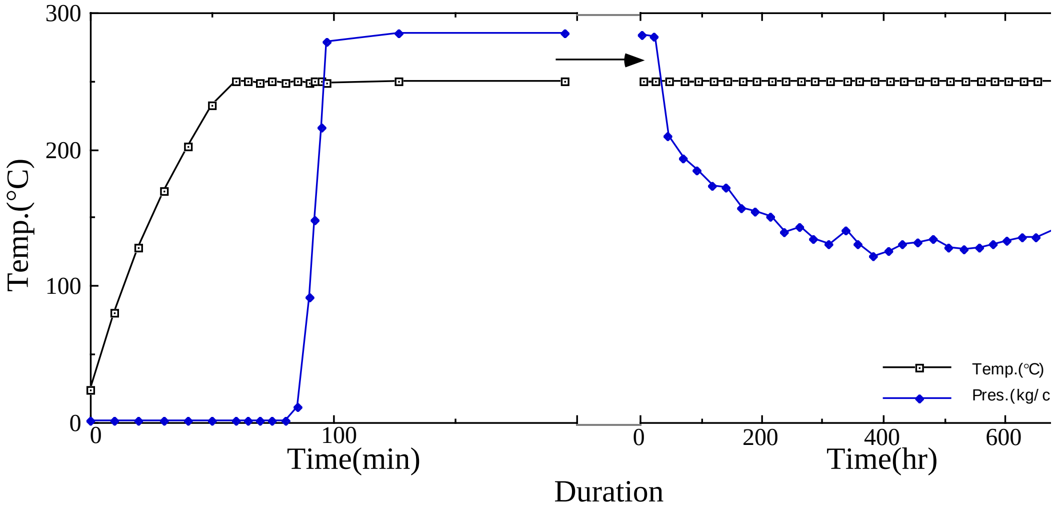

Figure 4 Plugging and endurance tests for 6% hectorite slurry treated at 250˚C

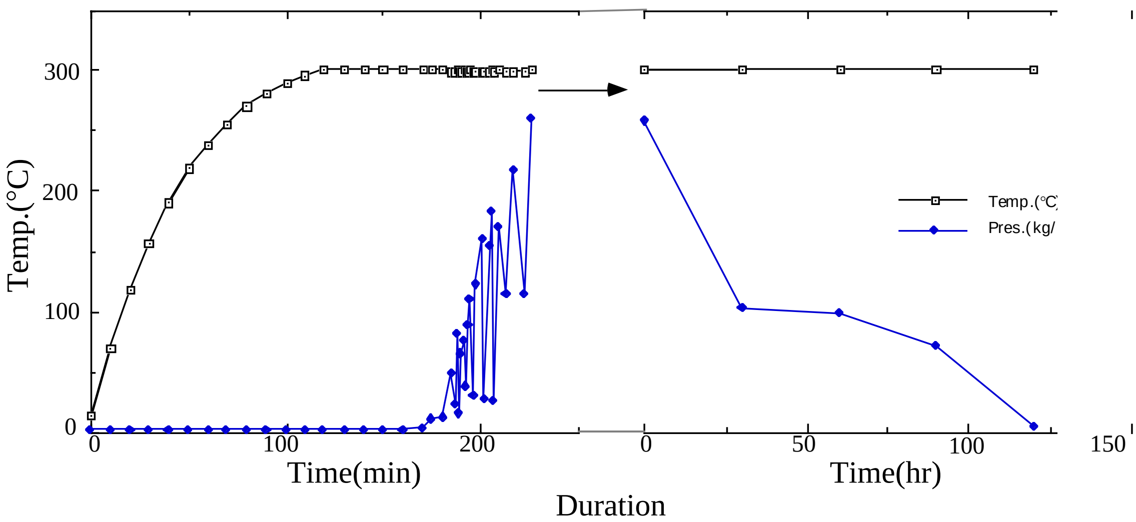

Figure 5 Plugging and endurance tests for 3% saponite slurry treated at 300˚C

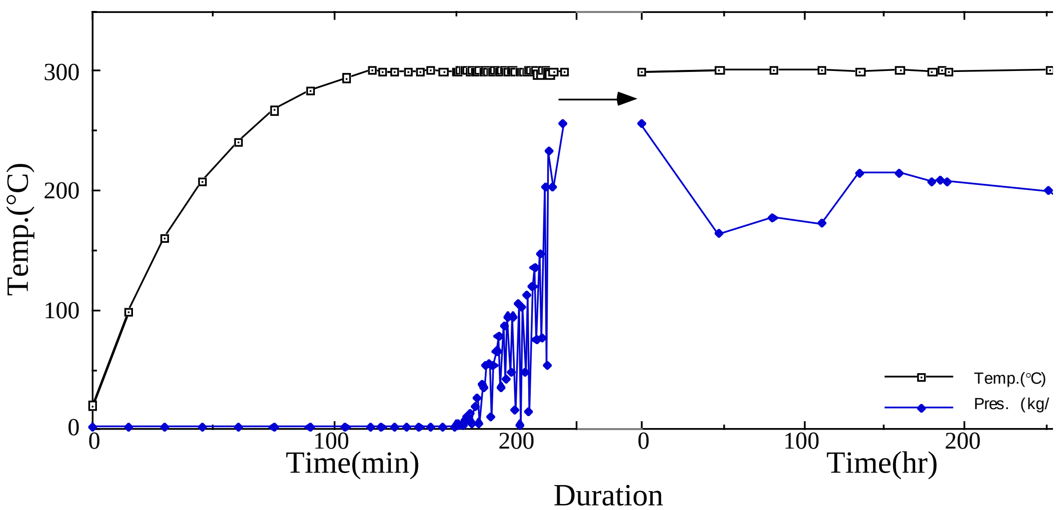

Figure 6 Plugging and endurance tests for 3% montmorillonite slurry treated at 300˚C