SEWAGE SLUDGE MELTING PROCESS
BY COKE-BED FURNACE: SYSTEM
DEVELOPMENT AND APPLICATION

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ABSTRACT

A sewage sludge melting process by coke-bed furnace, which is an application of
cupola melting technology, was developed. The outline of the course of the
development from the bench-scale experiment to the construction of a
commercial plant is described. The process is a more sophisticated one which
enables high volume reduction, stabilization and utilization of sewage sludge.
The slag produced by the process has a volume reduction ratio of 1/9 to 1/40
compared with dewatered sludge, and potential to be utilized as road
subbase material and concrete aggregate. The operational cost of the process
is estimated to be comparable to that of the conventional ones.

KEYWORDS

Sludge; melting; slag; coke; coke-bed; road subbase; concrete aggregate.

INTRODUCTION

With the spread of sewage systems in Japan, the amount of waste sludge
discharged from sewage treatment plants has been steadily increasing. In a
country like Japan with its limited land area, it is very difficult to find
landfill sites to bury sludge. Volume reduction, stabilization and, if
possible, utilization is most important in the sewage sludge disposal process in
Japan. With this in mind, the authors launched the development of a new sewage
sludge melting process in which coke instead of petroleum is burned as an
auxiliary fuel. Through the course of bench-scale experiment, pilot-plant
experiment and demonstration-plant experiment, the process was improved, and
the design criteria and operating know-how were established (Hiraoka et
al., 1983, 1984). A commercial plant was constructed on the basis of the
results and is now in operation. Slag utilization was also studied. Road
subbase material and concrete aggregate are the most realistic utilization of
slag now considered.

PRINCIPLES OF THE MELTING PROCESS

The core of the process, the melting furnace, is an application of the cupola
melting technology which has been used to manufacture cast metal. The cupola
is a furnace in which ore and cokes are melted with air. It is a cylindrical
and vertical furnace of quite simple structure, having tuyeres for feeding air
and a tapping hole at the bottom for discharging molten slag. Figure 1 shows
a schematic diagram of the melting process when sewage sludge is fed upon the coke bed in the cupola. To treat sewage sludge in the furnace, only ore should be replaced by sludge. Fixed carbon of coke is burnt inside the coke bed with primary air, generating high temperature exhaust gas. The exhaust gas gives part of its enthalpy to sewage sludge, and drying and pyrolysis process of sewage sludge proceeds on the coke bed. The pyrolysis process converts the organic portion of sewage sludge into combustible gases such as methane, ethane etc. The combustible gases are, at the next stage, burnt out in the secondary combustion zone with secondary air. The inorganic portion of the sludge is melted in the high-temperature atmosphere of the coke bed, forming molten slag, which flows down through the coke particles to be discharged continuously from a tapping hole.

![Diagram of melting process](image)

**Fig. 1** Schematic diagram of melting process

**PROCESS DEVELOPMENT**

**Bench-scale Experiment**

The hypothetical principles of the sludge melting process mentioned above were confirmed through the laboratory experiment using a small size cupola. After that, a melting furnace with a capacity of 10 tons of dewatered sludge/day (assuming dewatered sludge having a moisture content of 80%) was constructed and the basic data concerning the operating conditions for the furnace were collected. In this bench-scale experiment, conditions for stable operation of the main stream of the process, that is, sludge and coke feeding, drying, pyrolysis, combustion, melting and molten slag discharge were the major items of investigation. The authors got basic data from the bench-scale experiment. The amount of slag production was so small, less than 50 kg/hr, that the slag could not be discharged continuously. In such case, the slag should be discharged intermittently. For stable operation, it became clear that dewatered sludge was better to be preliminarily dried up to 40 to 50 percent moisture content before being fed into the furnace. A higher moisture content above 50 percent results in a decrease in processing capacity, and a lower moisture content below 40 percent results in an increase in dust concentration of exhaust gas from the furnace.
Pilot Plant Experiment

In the next stage, a melting furnace with a capacity of 20 tons of dewatered sludge/day (assuming dewatered sludge having a moisture content of 80%) was constructed to examine the scale-up factor and continuous discharge of slag. Thermal property of molten slag is one of the important factors governing the stable discharge of slag out of the furnace. The authors examined the softening point, melting point and pouring point against the basicity of the inorganic portion of the sludge. Here, basicity means the weight ratio of calcium oxide to silicon dioxide. The results are shown in Figure 2. Acid slag has a glass-forming tendency which is peculiar to silicon dioxide. It can be easily melted, for its melting point is lower than 1250 deg.C. However, its fluidity is not good (Streeter et al., 1984), and it is very difficult to discharge molten slag continuously from the tapping hole. On the other hand, basic slag has such a high melting point, above 1300 deg.C, that it immediately crystallizes and blocks the tapping hole when the temperature goes down a little. The authors concluded that a basicity around 1.0 should be the best condition for discharge, and tried adjusting basicity of molten slag to lower the pouring point while maintaining good fluidity. Limestone (basicity=53.6) was added to increase basicity when the sewage sludge was dewatered with a polymer coagulating agent. Crushed stone (basicity=0.05) was added to decrease basicity of the sewage sludge cake which was dewatered with calcium hydroxide. Continuous discharge of slag was kept by this adjustment. This adjustment guaranteed not only the continuous discharge of slag but also increased the strength of slag.

![Graph showing the relationship between melting properties and basicity](image)

**Fig. 2** Relationship between melting properties and basicity

There was concern for the durability of the fire bricks used on the inside wall of the melting furnace. The wall of the melting portion of the furnace was replaced by a water-cooling jacket to improve the durability for long-term continuous operation. The authors obtained all the basic design data concerning the melting furnace through this pilot experiment.

**Demonstration**

To complete the development of the sludge melting system by coke-bed furnace, a demonstration plant was constructed at Chuo Sewage Treatment Plant Site of the Sewage Union of the River Ai Basin, Osaka Prefecture. The nominal
capacity of the plant is 36 tons of dewatered sludge cake/day, and a maximum of 50 tons of dewatered sludge cake/day. The plant consists of mainly indirect heating type steam dryer, coke-bed furnace, waste heat boiler and air pollution control units. The two years demonstrative operation was conducted under supervision of the Researching Committee for Sewage Sludge Disposal of Osaka Prefectural Government. The committee examined mainly the following items:
1. Energy and material balance of the sewage sludge melting system.
2. Utilization of slag.
3. Economics of the system.
The authors faced two problems at the beginning of the experiment. One was the high NOx concentration in the exhaust gas as shown in Figure 3 (a). This problem was solved by improving the distribution of recycled exhaust gas and secondary combustion air. Before the improvement, exhaust gas, after scrubbing, was recycled only to the upper part of the furnace, and the secondary air was supplied exclusively at the lower part of the secondary combustion area. A circulation port for exhaust gas was set up at the lower part of the furnace, just above the coke bed, to decrease the temperature at that site. Also, three ports for secondary air supply were set up at the upper part of the secondary combustion area of the furnace to conduct a two-step combustion of combustible gases in this area (Hiraoka et al., 1976, 1978). The improvement is shown in Figure 4. The first improvement was effective to reduce thermal-NOx production in the high temperature zone, and the

![Figure 3 Reduction of NOx concentration](image)

![Figure 4 Improvement in distribution of circulating gas and air](image)
Sewage sludge melting process

second to reduce fuel-NOx production at the area where reductive atmosphere changes into oxidative atmosphere. The NOx concentration observed after the improvement is shown in Figure 3(b).

The second problem was too large a heat loss from the system. The radiation loss of the overall plant accounted for 20-30 percent of the input heat. In order to reduce the radiation loss, the authors studied the breakdown of the radiation and remodelled the equipment as follows:

1. The water jacket in the lower portion of the furnace was replaced by a jacket boiler to generate steam.
2. To lower the temperature of the exhaust gas, boiler tubes were inserted in the upper portion of the furnace to absorb waste heat and generate steam.

The furnace temperature was controlled by introducing cooled waste gas into the furnace before the remodelling, so that too much enthalpy was lost with exhaust gas from the furnace. By this remodelling, the radiation loss was reduced to 9-16 percent of the heat input and the heat recovery ratio was enhanced from 60 percent to 80 percent. As the exhaust gas decreased, the electricity consumption was also reduced by approximately 20 percent.

The authors examined the influence of seasonal variation on sludge characteristics over a year of plant operation. The variations in heating value and moisture content were large. The variation in heating value could all be absorbed in the melting furnace. The moisture content of the sludge varied between 75 and 83 percent. The maximum moisture content of the sludge at dryer outlet reached 53 percent depending on the moisture content at the inlet of the dryer. Particularly when the moisture content of sludge at the dryer outlet was around 53 percent, the furnace temperature was lowered and, in some cases, the operation of the furnace became unstable. In order to absorb the variation in moisture content of the sludge to be received by the dryer, the authors decided to adopt a dried sludge returning method, in which a portion of the sludge coming out of the dryer was returned to the inlet of the dryer so that the moisture content of sludge to be received could be as constant as possible and the heat conduction area of the dryer could be effectively used. As a result, the moisture content of sludge at the dryer outlet could be kept at 45 ± 2 percent and the stability of the furnace was further increased. By the efforts to improve the process, mentioned above, various defects which the process had at the beginning were conquered. As a result of the analysis, the authors successfully established design criteria for the overall process and completed the process development.

Subsequently, a commercial plant with a sludge processing capacity of 40 tons/day (assuming dewatered sludge having a moisture content of 80 %) was constructed at the Chuo Sewage Treatment Plant in Osaka Prefecture, on the basis of the results obtained at the demonstration plant. This plant has been in operation since July 1985. The details of the commercial plant are described in the next section.

SLUDGE MELTING PROCESS BY A COKE-BED FURNACE

A schematic flow diagram of the sludge melting plant with coke-bed is shown in Figure 5. The plant was constructed at the Chuo Sewage Treatment Plant in Osaka Prefecture. The plant receives two kinds of dewatered sludge cakes; one from the Chuo Sewage Treatment Plant is dewatered with calcium hydroxide and ferric chloride; the other from the Takatsuki Sewage Treatment Plant is dewatered with polymer coagulating agent. These two kinds of sludge cakes meet on the conveyor and are supplied to the dryer after weight measurement. The sludge cakes are dried to around 45 percent moisture content by an indirect-heating type steam dryer. The dried sludge is supplied to the melting furnace along with coke and a basicity adjusting agent. These are fed onto the upper part of the coke-bed.

Combustion air for the sludge and coke is fed at multi-steps as primary and secondary air for the controlled combustion with nitrogen oxides reduction. The nitrogen oxides concentrations are reduced as a result of changing the upper burning zone of the coke-bed to a reductive atmosphere and accelerating ammonia-denitrification in the furnace. The primary air for burning coke is supplied after being preheated by exhaust gas in the heat exchanger.
The vaporization of the moisture contained in the sludge and the gasification of the combustible portion of sludge proceed in the upper part of the coke-bed by getting heat from the high temperature exhaust gas passing through the coke-bed. The combustible gases from the sludge are completely burnt out in the furnace with secondary air. The coke-bed plays the role of fire grate and forms the stable high temperature zone above 1600 deg.C required for melting. The ash in the sludge moves downward and melts in the coke-bed and flows down among the coke grains and finally reaches the slag outlet.

Meanwhile, the upper opening in the melting furnace is the secondary combustion zone for the combustible gas and also serves to prevent the scattering of dust. By inserting a water pipe unit, the temperature of this space is kept at a temperature lower than the softening point of sludge ash, and waste heat is recovered as steam. The exhaust gas temperature from the furnace is kept at around 900 deg.C. Molten slag discharged from the melting furnace is cooled with water or air and passes through a magnetic separation process. The slag is first stored in the slag bunker, then carried from the site by truck as scheduled.

As the exhaust gas coming out of the furnace is very hot, the heat is recovered by a waste heat boiler as steam, which is used for drying sludge. The flue gas is heat exchanged with combustion air for coke combustion. Dust in the exhaust gas is removed by the cyclone at the outlet side of the waste heat boiler. The collected dust along with the dust removed from the waste heat boiler is mixed with the sewage sludge to be fed into the furnace again for the melting process. Ten to thirty percent of the sulfur in the sludge and coke is fixed in the slag as sulfate in the melting process. As the rest becomes SOx and moves into the exhaust gas, it is removed by the desulfurizing equipment using caustic soda solution. After removing dust by an electrostatic precipitator in the final stage, the exhaust gas is discharged from a stack into the atmosphere.

Fig. 5 Schematic flow diagram of the commercial plant
RESULTS OF TEST OPERATION

Properties of Processed Sludge and Melting Characteristics

The properties of the sludge processed by this equipment and coke are shown in Table 1. Two kinds of sludge are processed here after being mixed.

<table>
<thead>
<tr>
<th>Additives</th>
<th>Sewage treatment plant</th>
<th>Coke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture(%)</td>
<td>79.9</td>
<td>80.8</td>
</tr>
<tr>
<td>Dry solid Heating value(MJ/kg) higher</td>
<td>18.1</td>
<td>10.5</td>
</tr>
<tr>
<td>lower</td>
<td>16.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Combustible(%)</td>
<td>79.1</td>
<td>55.7</td>
</tr>
<tr>
<td>Basicity(-)</td>
<td>0.28</td>
<td>2.45</td>
</tr>
<tr>
<td>Pouring point(deg.C)</td>
<td>1270</td>
<td>1390</td>
</tr>
</tbody>
</table>

Performance Test

The performance test was carried out at a load of 40 tons-WS/day which is the designed capacity, as well as at higher and lower loads. Table 2 shows the actual values of the operating conditions. For each operation condition, the calculated average values are shown for the averaging time of 8 hours of normal operation. One feature of this process is that as the processed sludge quantity increases, the amount of coke needed decreases. It becomes clear that for sludges with uniform properties the process has a large allowable load capacity.

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>furnace boiler</th>
<th>waste heat boiler</th>
<th>steam consumption by dryer(kg/hr)</th>
<th>excess steam(kg/hr)</th>
<th>cokes feed rate(kg/hr)</th>
<th>water consumption(cu.m/hr)</th>
<th>electric power consumption(kW)</th>
<th>NaOH(48 %) (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate(kg-WS/hr)</td>
<td>1300</td>
<td>1700</td>
<td>1940</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content(%)</td>
<td>79.8</td>
<td>80.2</td>
<td>77.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slag production(kg/hr)</td>
<td>130</td>
<td>146</td>
<td>190</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary air(Ncu.m/hr)</td>
<td>1460</td>
<td>1450</td>
<td>1550</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature of primary air(deg.C)</td>
<td>454</td>
<td>511</td>
<td>491</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary air(Ncu.m/hr)</td>
<td>1440</td>
<td>1670</td>
<td>1610</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For an example of heat and material balance, the calculated results of the heat balance under the conditions of 40 tons/day are shown in Figure 6. If the excess steam energy currently put away is used as a heat source outside of the melting process, the overall heat efficiency will be greatly improved.

Properties of Materials Discharged from the Process

Some properties of exhaust gas and effluent are shown in Table 3. All of them meet the legal regulations. In particular, NOx concentration, is around 76 ppm at 02 12 percent conversion, due to the effect of two-step combustion with reductive atmosphere.
Fig. 6 Heat balance of the system

TABLE 3 Properties of Effluent and Exhaust Gas

<table>
<thead>
<tr>
<th>Sludge feed rate (kg/hr)</th>
<th>1700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent</td>
<td></td>
</tr>
<tr>
<td>pH (at 25 deg.C)</td>
<td>7.6</td>
</tr>
<tr>
<td>BOD (mg/l)</td>
<td>4.0</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>12</td>
</tr>
<tr>
<td>SS (mg/l)</td>
<td>10</td>
</tr>
<tr>
<td>Exhaust gas</td>
<td></td>
</tr>
<tr>
<td>Dust (g/Ncu.m)</td>
<td>0.003</td>
</tr>
<tr>
<td>SOx (ppm)</td>
<td>1.2</td>
</tr>
<tr>
<td>HCl (ppm)</td>
<td>0.9</td>
</tr>
<tr>
<td>HCN (ppm)</td>
<td>ND</td>
</tr>
<tr>
<td>NOx (ppm)</td>
<td>76</td>
</tr>
</tbody>
</table>

SLAG AS A RESOURCE

Properties of Slag

The inorganic portion of the sewage sludge was melted and then quenched by water or air, resulting in a sand-like or rock-like material. For either type, the volume can be reduced to 1/9-1/40 compared with the volume of dewatered cakes by converting it into slag. Table 4 shows the properties of air-cooled slag. As a result of the hazardous material extraction test in accordance with the methods of the Japanese Environment Agency Notice, no elution of toxic metals was found and it was confirmed that it is safe to use it.

Separation of Metals

Various metals contained in the sludge become isolated by the strong reductive atmosphere in the coke-bed and can be separated from the slag by gravity.
Magnetic separation yielded 5-20 percent iron with around 80 percent purity. In the process of making slag into a usable resource, magnetic separation is used both to prevent rust and to recover the value of the separated metal.

**TABLE 4 Properties of Slag**

<table>
<thead>
<tr>
<th>Composition (%)</th>
<th>36.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td></td>
</tr>
<tr>
<td>Al2O3</td>
<td>13.9</td>
</tr>
<tr>
<td>CaO</td>
<td>33.7</td>
</tr>
<tr>
<td>MgO</td>
<td>2.2</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>10.4</td>
</tr>
<tr>
<td>Others</td>
<td>3.6</td>
</tr>
<tr>
<td>Basicity(-)</td>
<td>0.93</td>
</tr>
<tr>
<td>Specific gravity(-)</td>
<td>2.72</td>
</tr>
<tr>
<td>Bulk density(kg/cu.m)</td>
<td>1490</td>
</tr>
</tbody>
</table>

**Utilization of Slag**

Some trials have been done for utilization of sludge as construction materials (Bryan, 1984 and Alleman *et al.*, 1984). In the process of converting slag into a usable resource, the authors have developed its application as an alternative to sand or rocks, and it is a promising material for road subbase or concrete aggregate. This paper presents two examples of the most advanced application.

**Subbase Material.** As an alternative to crushed stone, a test for its application as a base course material was made. Since the results of the laboratory test met the standard values as shown in Table 5, field tests were conducted. It had been installed in several places from parking lots to carriage ways and follow-up checks were being conducted. The results of the field tests show that it is almost equal to crushed stone, except that more compaction is required. This is considered to be the most promising application, particularly for using large volumes of slag.

**Concrete Product for Road Pavement.** Recently, water permeable pavement is attracting attention. Therefore, water permeable interlocking blocks were developed as a secondary product using air-cooled slag as a concrete aggregate. The results of quality tests on concrete aggregate made of slag and No.7 gravel are shown in Table 6. The results show that air-cooled slag can be utilized as a material for making interlocking blocks. The interlocking blocks are now being subjected to a field test.

**TABLE 5 Results of Road Material Tests (air-cooled slag)**

<table>
<thead>
<tr>
<th>Screen opening(mm)</th>
<th>Test Point</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parking lot</td>
<td>Carriage way</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>13</td>
<td>83</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>58</td>
<td>37</td>
</tr>
<tr>
<td>2.5</td>
<td>44</td>
<td>28</td>
</tr>
<tr>
<td>0.4</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>0.0074</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Abrasion loss(%)</td>
<td>32.1</td>
<td>32.7</td>
</tr>
<tr>
<td>Optimal moisture content(%)</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Maximum density(g/cu.cm)</td>
<td>2.38</td>
<td>2.32</td>
</tr>
<tr>
<td>Degree of compaction(%)</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Modified CBR(%)</td>
<td>106</td>
<td>83</td>
</tr>
</tbody>
</table>

Concrete Product for Road Pavement. Recently, water permeable pavement is attracting attention. Therefore, water permeable interlocking blocks were developed as a secondary product using air-cooled slag as a concrete aggregate. The results of quality tests on concrete aggregate made of slag and No.7 gravel are shown in Table 6. The results show that air-cooled slag can be utilized as a material for making interlocking blocks. The interlocking blocks are now being subjected to a field test.
TABLE 6 Results of Concrete Aggregate Material Tests

<table>
<thead>
<tr>
<th>Screen opening (mm)</th>
<th>Sample</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air-cooled slag</td>
<td>No.7 crushed stone</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>54</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
<td>87</td>
</tr>
<tr>
<td>2.5</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>1.2</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>0.6</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>0.3</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>0.15</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

Specific gravity (-) | 2.72 | 2.66 | more than 2.5
Bulk density (kg/l)  | 1.72 | 1.45 | -
Solid content (%)    | 63.5 | 55.2 | -
Soundness by use of | 1.6  | 0.1  | less than 12
sodium sulfate (%)   |      |      | -
Water absorption (%) | 0.36 | 1.29 | less than 3

OPERATIONAL COST ESTIMATED

Operational cost was estimated based on a conceptional design of the sludge melting system of 2 units of 50 tons of dewatered sludge/day. The operational cost includes electricity cost, utility cost, and repair cost. The operational cost is estimated as approximately 30,000 yen/ton of dry solids. This operational cost is almost comparable to that of conventional incineration treatment.

SUMMARY

The outline of the course of the development of the sewage sludge melting process using a coke-bed, the operating results of the commercial plant and some applications of the slag are described. At present, the commercial plant is working steadily at the Chuo Sewage Treatment Plant. As the process generates more steam than required for the plant operation, the heat efficiency will be improved if excess steam can be used outside of the plant. For this reason, electric power generation is planned at the plant for large scale treatment. The authors have just taken the first step toward converting slag into a usable resource, and are conducting research and development to discover highly effective applications. The integrated processing and utilization of sewage sludge as a construction material has been proposed and actually undertaken in Japan as "the Sewage Sludge Processing Work Project for Large Area (Ace Plan)". This project decided to adopt the melting process by coke-bed furnace for two areas; Osaka North-East Area (1st-term work = 2 units of 50 tons-WS/day) and Hyogo West Area (1st-term work = 2 units of 200 tons-WS/day). Both of these are currently under construction. Both plants will start operation from April 1988. The melting furnace in Hyogo West Area will be the largest in Japan and includes electric power generating units as well.

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