

Higher corrosion resistance of old cast iron pipes installed for early stage of water supply network in Yokohama City

Yuuki Kuwahara, Yoshikazu Miyata, Shukuji Asakura, Tadashi Shinohara, Takao Yakou, Keiichi Shiimoto, Keiji Inoue and Junichi Hatano

ABSTRACT

The old gray cast iron for water supply pipes in Yokohama City which was made in the UK in 1887 is highly corrosion resistant. The corrosion behavior of the old gray cast iron in soils was studied. For comparison, a gray cast iron used for modern pipes, a spheroidal graphite cast iron, and a carbon steel were tested. The corrosion potentials and corrosion rates were measured. The corrosion products and the base metals were analyzed by X-ray diffractometry and energy dispersion spectroscopy. The corrosion rate of the gray cast iron made in the UK in 1887 was lower than those of the others. The gray cast iron contains a large amount of steadite, which is a ternary eutectic (γ -Fe, Fe₃C, and Fe₃P). The network structure of steadite enclosed the corrosion products and decreased the corrosion rate.

Key words | cast iron, corrosion, steadite, water pipe

Yuuki Kuwahara (corresponding author)
Yoshikazu Miyata
Shukuji Asakura
Takao Yakou
 Graduate School of Engineering,
 Yokohama National University,
 79-5, Tokiwadai, Hodogaya-ku,
 Yokohama 240-8501,
 Japan
 E-mail: kuwahara-yuuki-ty@ynu.ac.jp

Tadashi Shinohara
 National Institute for Materials Science,
 1-2-1, Sengen, Tsukuba 305-0047,
 Japan

Keiichi Shiimoto
Keiji Inoue
 Hinode Suido Kiki K.K.,
 Iwasaki, Aza, Harukoga,
 Miyaki-chou, Miyaki-gun, Saga-pref 849-0101,
 Japan

Junichi Hatano
 Yokohama Waterworks Bureau,
 1-1, Minato-cho, Naka-ku, Yokohama, 231-0017,
 Japan

ABBREVIATIONS

a coefficient of experimental constant
b power of experimental constant
t corrosion time
Y average corrosion loss

INTRODUCTION

Cast iron has been used for water pipes for a long time. The corrosion of cast iron in soils has been reported by many authors (Sugita 1958; Gerhold 1976; Lawrence 1987; Japan Ductile Iron Pipe Association 2010). However, the corrosion mechanism is not always obvious.

Yokohama Waterworks Bureau empirically knows that the cast iron pipes made in the UK in 1887 are highly corrosion resistant. These pipes (hereinafter referred to as 'old water pipe') were used for 110 years in the early water

doi: 10.2166/aqua.2013.225

supply system in Yokohama City. The outside surface of the old water pipe is shown in Figure 1. No red rusts (ferric oxides) are observed. The corrosion behaviors of the old water pipes were studied. For comparison, a modern water pipe made of gray cast iron buried for about 50 years, spheroidal graphite cast iron, and carbon steel were also examined.

METHODS

Specimens

- Gray-1: old water pipe (390 mm in diameter) made of gray cast iron.
- Gray-2: old water pipe (100 mm in diameter) made of gray cast iron.



Figure 1 | The outside surface of cast iron for water supply pipe constructed in 1887 in Yokohama City.

- Gray-3: modern water pipe made of gray cast iron.
- Ductile: spheroidal graphite cast iron.
- Carbon steel: carbon steel.

Gray-1, gray-2, and gray-3 are water pipes that had been used in the field. Chemical compositions of these metals are

Table 1 | Chemical composition of specimens

Name	C	Si	Mn	P	S	Material
Gray-1	3.32	1.76	0.63	1.590	0.053	Gray cast iron
Gray-2	3.37	2.24	0.43	1.740	0.083	Gray cast iron
Gray-3	3.54	2.02	0.49	0.069	0.099	Gray cast iron
Ductile	3.67	1.99	0.42	0.013	0.008	Spheroidal graphite cast iron
Carbon steel	0.11	9.24	0.61	0.024	0.020	Carbon steel

shown in Table 1. Microscopic photographs of the base metals appear in Figure 2. Cast iron is used for water pipes more widely than steel. The casting performance of cast iron with a high carbon content is advantageous for practical application because of the low melting point. The graphite in gray cast iron is flaky, while spheroidal graphite is formed by the addition of magnesium. Spheroidal graphite cast iron has higher mechanical strength than gray cast iron.

Gray-1 and gray-2 contained larger amounts of phosphorus than gray-3. Specimens were machined from the host materials. Then, they were polished with emery paper up to #1000 and degreased by acetone. The rusts were completely removed by this process. The surface was adjusted to 20 mm × 20 mm.

Soils

- Black soil: commercially available for gardening. It is one of the typical soils in Japan.
- Marine soil: that was taken in Yokohama City. It is widely distributed there.

The corrosivity evaluation based on ANSI A21.5 was made by a third-party organization that specializes in the analysis of soil. The specimens were buried in these soils for 30, 60, and 120 days. The soil corrosion was tested in the laboratory from August 22, 2012 to December 20, 2012.

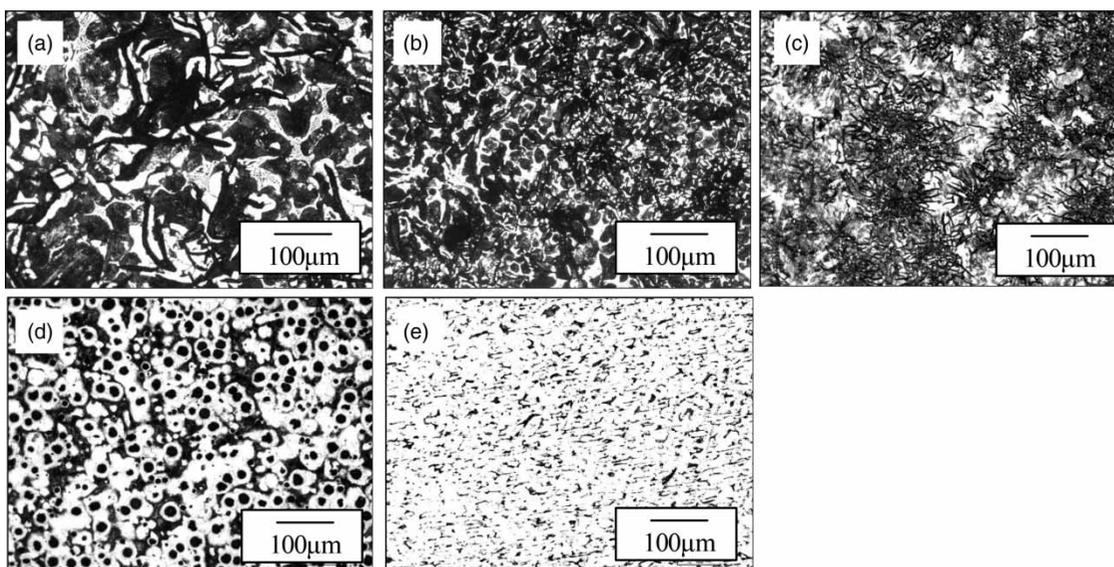


Figure 2 | Microscopic photographs of specimens: (a) gray-1, (b) gray-2, (c) gray-3, (d) ductile, (e) carbon steel.

Measurements

Corrosion potential

Corrosion potentials of specimens were measured periodically with a saturated silver–silver chloride reference electrode. The potential was expressed on the standard hydrogen electrode scale.

Corrosion loss

Corrosion products were removed chemically by immersing in 5.7 mol dm^{-3} aqueous hydrochloric acid which contained $0.025 \text{ mol dm}^{-3}$ hexamethylenetetramine for 10 minutes. The remaining corrosion products were removed by brushing. Corrosion rate was calculated from the weight loss.

Analyses of the corrosion products

The corrosion products were analyzed by X-ray diffractometry and energy dispersion spectroscopy (EDS). These corrosion products had formed on the surface of gray-1 for 110 years.

Analysis of the base metal structure

The base metal structure of gray-1 was analyzed by EDS.

RESULTS AND DISCUSSION

Corrosion test in soils

Corrosion potential

The corrosion potentials are shown in Figure 3. The corrosion potentials reached steady states in about 10 days in the black soil. In the marine soil, the corrosion potentials of all specimens stayed constant during the tests. The corrosion potentials of gray cast iron (gray-1, gray-2, and gray-3) were higher than those of ductile and carbon steel in both soils in the steady states. The steady corrosion potentials in black soil were higher than those in marine soil.

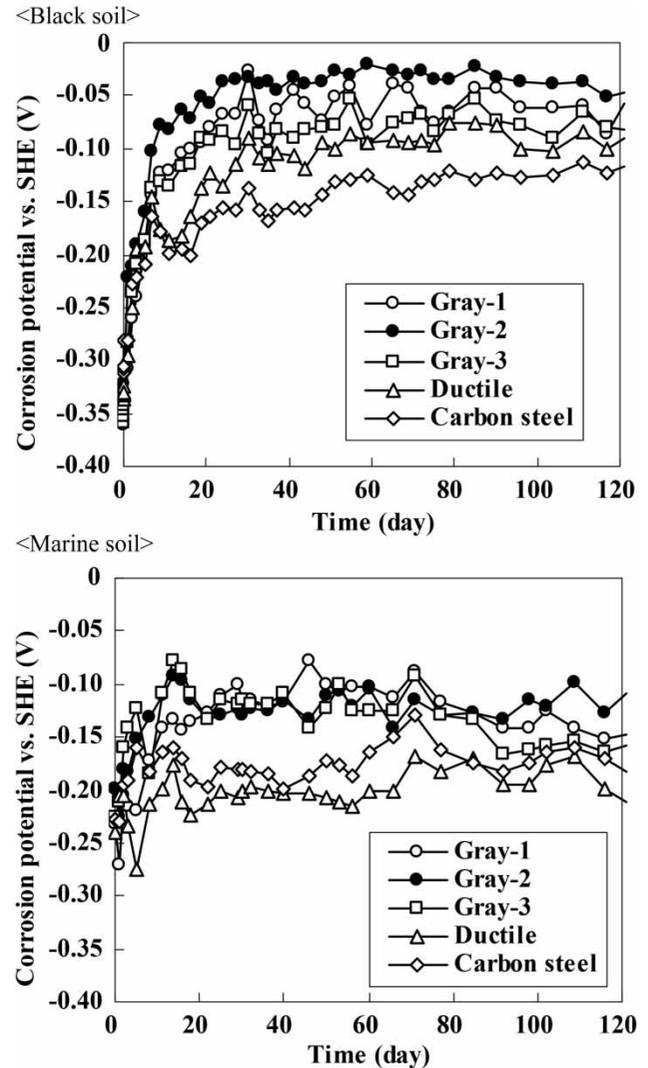


Figure 3 | Corrosion potentials of specimens.

Corrosion loss

In both black and marine soils, the corrosion losses of gray-1 and gray-2 were lower than those of gray-3, ductile and carbon steel as shown in Figure 4. Corrosion loss of metals in soils is usually expressed by a power law of Equation (1) (Ahmed & Melchers 1994).

$$Y = at^b \quad (1)$$

where Y is the average corrosion loss (mm), t is time (day), and coefficient a and power b are experimental constants. In this study, the values of coefficient a and power b are shown

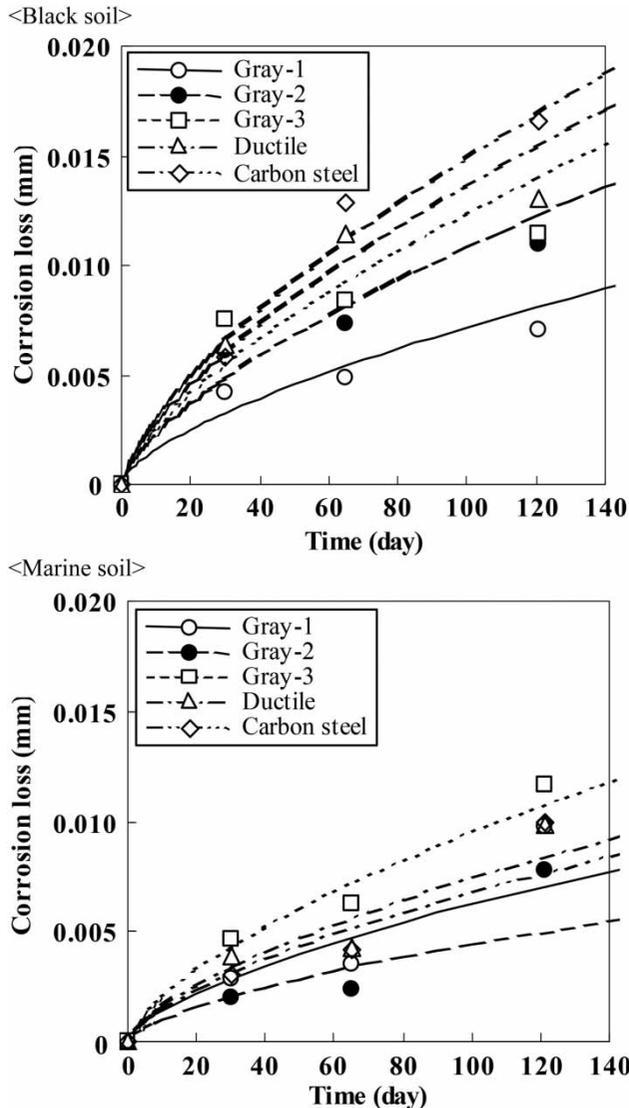


Figure 4 | Corrosion losses of specimens in soil.

in Table 2. Equation (1) is expressed as Equation (2) by taking the logarithm of both sides.

$$\log Y = b \log t + \log a \quad (2)$$

The values of coefficient a and power b are obtained by calculating the gradient b and the interception a on the straight line curve of Equation (2).

The power b was 0.64 to 0.68. The power b was not dependent on the materials. According to the Japan Society of Corrosion Engineering (2005), the power b is between 0.39 and 0.61. In addition, Kucera & Mattsson (1987)

Table 2 | Coefficient a and power b in Equation (1) calculated from corrosion loss

	$Y = at^b$		$Y = at^b$	
	Black soil		Marine soil	
	a	b	a	b
Gray-1	3.52×10^{-4}	0.664	3.14×10^{-4}	0.650
Gray-2	4.98×10^{-4}	0.669	2.38×10^{-4}	0.638
Gray-3	5.55×10^{-4}	0.674	4.48×10^{-4}	0.665
Ductile	6.01×10^{-4}	0.678	3.64×10^{-4}	0.656
Carbon steel	6.46×10^{-4}	0.681	3.38×10^{-4}	0.653

Y , corrosion loss (mm); t , time (day); coefficient a and power b , experimental constants.

reported that the power b lay between 0.4 and 1.2 for ferrous materials. The present results are in agreement with these reports.

On the other hand, coefficient a was a function of the materials. The values of coefficient a for gray-1 and gray-2 were smaller than those for other specimens. The coefficient a was more sensitive to the materials than the power b .

Corrosivity of the soil

The corrosion losses in black soil were larger than those in marine soil as shown in Figure 4. Soil test evaluation by ANSI A21.5 in Table 3 did not explain the results of corrosion losses. The discrepancy had been discussed by Matsushima (Matsushima 1976). Matsushima reported that the corrosion rate did not necessarily depend on the specific resistance. In the present study, organic acids in black soil for gardening are responsible for the higher corrosion rate. It is known that soil containing a large amount of organic acids is highly corrosive.

Surface analyses

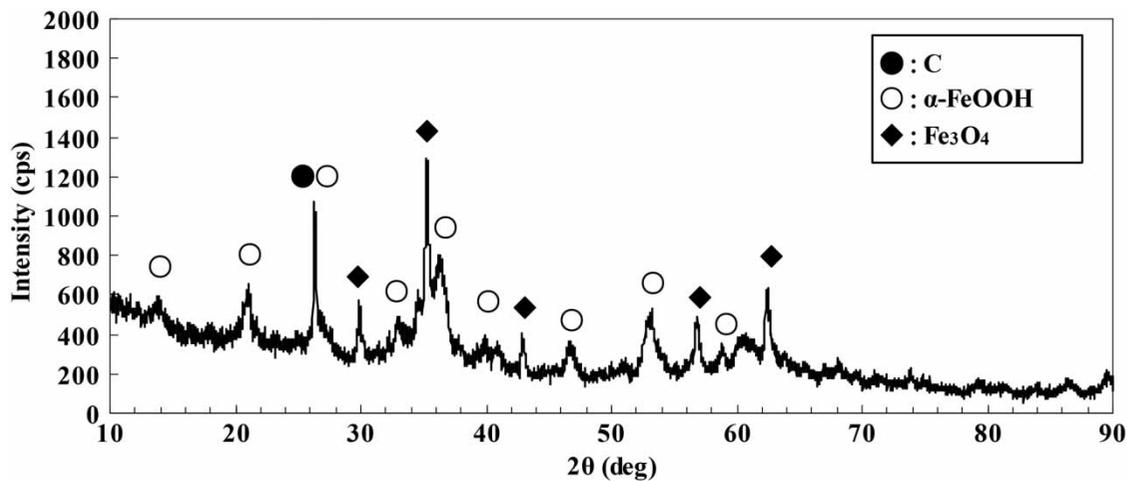
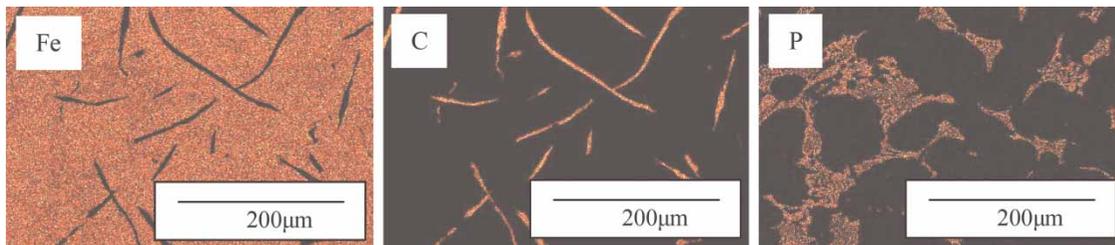
Figure 5 shows the X-ray diffraction pattern of the corrosion products for gray-1 buried for 110 years. Similar patterns were obtained for gray-2 and gray-3. The main components of corrosion products are carbon, α -FeOOH, and Fe_3O_4 .

Elemental analysis by EDS indicated that steadite was present in the base metal of gray-1. The elemental distribution in the base metal, in which phosphorus appears in the form of the mesh, is shown in Figure 6. This pattern seemed to be typical steadite structure. It is known that austenite (γ -Fe)

Table 3 | Soil test evaluation by ANSI 21.5

Soil		Specific resistance (Ω cm)	pH	Redox potential (mV)	Moisture content (%)	Sulfide	Total score
Black soil	Measurement value	104,814	5.5	520	90	None	–
	Score	0	0	0	2	0	2
Marine soil	Measurement value	1.057	8.3	556	23	None	–
	Score	5	0	0	2	0	7

Soil is evaluated to be corrosive when the total score is more than 10.

**Figure 5** | X-ray diffraction pattern of the corrosion product of gray-1 buried for 110 years.**Figure 6** | EDS images of the base metal of gray-1. The colored area indicates the presence of assigned element. Black area indicates the absence of assigned element. Please refer to the online version of this paper to see this figure in color: <http://www.iwaponline.com/jws/toc.htm>.

crystallizes out in the process of the solidification of iron. The presence of carbon produces cementite (Fe_3C). The added phosphorus forms the crystallized Fe_3P . A ternary eutectic of γ -Fe, Fe_3C , and Fe_3P is called steadite.

Corrosion resistance of the old pipe

Elemental distribution of the corrosion products formed on the surface of gray-1 buried for 110 years in the field is given in [Figure 7](#). Phosphorus in the corrosion products distributes

in a similar mesh form to that in the base metal. This suggested that steadite did not corrode and kept the network structure in the corrosion products.

[Figure 8](#) shows the cross-sectional scheme of gray-1 and gray-2. It is known that steadite itself is mechanically very hard and has high corrosion resistance ([Matsui *et al.* 1999](#); [Abbasi *et al.* 2007](#)). The network structure of steadite seems to constrain the corrosion products tightly. The stabilized corrosion products layer formed on the surface gradually could decrease the corrosion rate.

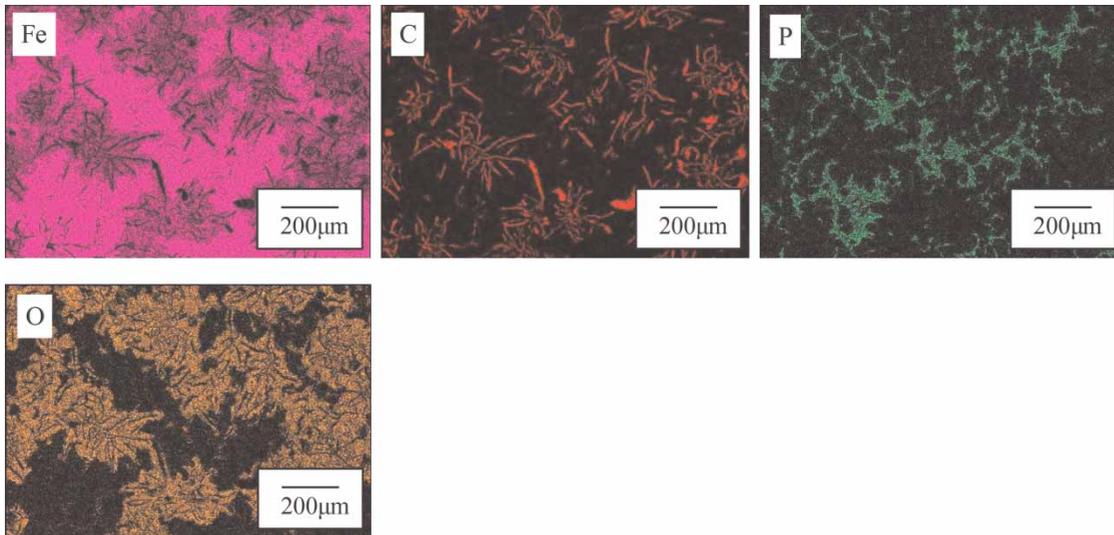


Figure 7 | Cross-sectional images of the corrosion product for gray-1 buried for 110 years. Colored area indicates the presence of assigned element. Black area indicates the absence of assigned element. Please refer to the online version of this paper to see this figure in color: <http://www.iwaponline.com/jws/toc.htm>.

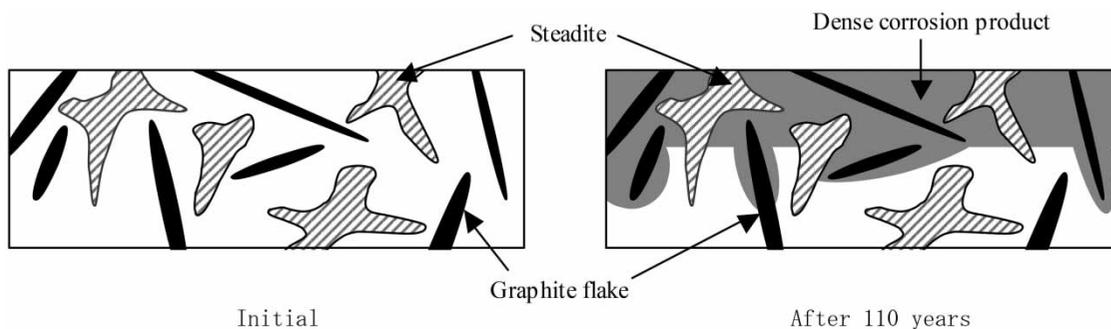


Figure 8 | Schematics of cross-section for the cast iron pipe (gray-1 and gray-2) and corrosion products.

In gray cast iron, the corrosion products are usually composed of iron oxides and graphite flakes. The graphite flakes enclose the iron oxides on the surface, stabilizing the corrosion products. The authors assumed that steadite enhanced the stability of the corrosion products further. As a result, the corrosion rates of gray-1 and gray-2 were lower than that of gray-3. From the view point of the corrosion resistance, the addition of phosphorus is favorable. However, phosphorus increases the brittleness of cast iron because steadite is very hard and not ductile.

CONCLUSIONS

Corrosion rates of cast iron for water supply pipes constructed in 1887 in Yokohama City were lower than those of gray cast iron for modern pipes, spheroidal graphite cast iron, and carbon steel in black soil and marine soil.

In Equation (1), coefficient a was a function of the metal, while power b was almost constant. The values of coefficient a of the old water pipes are smaller than those of the others.

The old water pipes contained a large amount of steadite which formed the network structure in the base metals. Steadite remained in the corrosion products since it did not corrode. The network structure constrained the corrosion products tightly and enhanced the corrosion resistance.

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First received 3 July 2013; accepted in revised form 24 October 2013. Available online 26 November 2013