

Lump System Analysis Modelling for Enhanced Ballistic Performance of Clay Box Doped with Different Types of Additives

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Abstract

The temperature of clay box used in the ballistic testing of body armour drops sharply upon removal from the oven. This implies that the clay has to be reinserted into the oven for another heating, which slows down the ballistic testing procedure. This paper attempts to solve the problem by studying the effect of addition of different percentages of rubber cuttings, saw dust and berley reeds additives on the cooling rate of clay used in clay box construction. The cooling rate is a measure of the ballistic performance of the clay box. The properties of the clay box such as the density, thermal conductivity and specific heat capacity are factored into the lump system analysis model. Minimum cooling rate of about 2.04×10^{-03} and $1.89 \times 10^{-03} \text{C/s}$ were obtained when 0% and 10% rubber cuttings were used as dopants respectively. Rubber cuttings also proved to be the best additives that can be used to enhance the ballistic performance of clay box used in the ballistic testing of body armour.

Keywords: Ballistic Testing, Body Armor, Additives, Lump System Analysis, Cooling Rate

1. Introduction

The evaluation of the performance of hard and soft body armor is done by placing clay at the back of the armor and firing the clay used with bullets or any other ballistic material. The depth to which the bullets penetrates the clay is chosen as scale of performance of the body armour. Therefore, to evaluate the performances of body armours, the first step is to place a clay box behind a material to be tested (Dale et al., 2011). Canonically, the clay box is molded into a block shape by a Roma Plastilina or modelling clay with 610mm by 610mm by 140mm dimension and has a 19mm thick backing made of either aluminium or steel frame. It also has 3.175mm thick U-channel according to the Law Enforcement Standards Office (LESO) at the National Institute of Standards and Technology (NIST) (Dale et al., 2011; NIJ Standard-0101.06., 2008; Garcia-avila, Portanova, & Rabiei, 2014).

Though clay has many favourable thermal and mechanical properties as demonstrated in reports (Silva & Perera, 2018; Rahman, 2014) where clay pots were confirmed to have a good heat retention ability. However, the incessant changing properties of the plastilina (modeling clay) makes it vulnerable to frequent pre-conditioning to a temperature of about 40°C in order to perform a ballistic test. Consequently, the performance of the clay box has to be validated by a series of calibration drop test upon removal from the oven after which the clay box will only be used for the actual ballistics test if it passed the calibration drop test i.e. if the indentations produced are within the acceptable limits. Despite all these, the National Institute of Justice (NIJ), still demands the calibration drop tests be repeated after every ballistic test according to its 0101.06 standard (Dale et al., 2011; Garcia-avila, Portanova, & Rabiei, 2014; Mukasey, Sedgwick, & Hagy, n. d.). However, this is not the case for other testing protocols. Hence, the integrity of the ballistic test result is at bleak courtesy of the unavoidable cooling the clay box usually encounters immediately upon removal from the oven. The unavoidable cooling of the thus actually affects the ballistic performance. The main material used in the construction of the clay box is the clay and the main properties that determine the rate of cooling of the clay are the thermal conductivity, the heat capacity and the density of the clay.

Clay is a type of soil that is commonly most finely grained. It has a unique property of being malleable when it is wet and becomes very hard when it is dry and at high temperature. Its formation is usually through natural process involving weathering, deposition and sedimentation of rocks over some geological period of time. The major

composition of clay are oxides of iron, alumina (Al_2O_3), silica (SiO_2), oxides of alkali and alkaline earth metals and water (H_2O). Minerals such as mica, feldspar, quartz are also available in the clay (Aramide, 2012; Johari, Said, Hisham, Bakar, & Ahmad, 2010).

Many research works have been conducted on the effect additives on clay properties such as thermal conductivity, density, porosity, thermal diffusivity, dry shrinkage and heat capacity of the clay by addition of various types of additives such as ashes, saw dust, rice husks, berley reed, rubber cuttings etc. to make the clay better refractory or for other suitable applications (Silva & Perera, 2018; Rahman, 2014; Aramide, 2012; Folaranmi, 2009; Qatta, 2012; Ahmad, Iqbal, & Muhammad, 2017; Silva & Mallwattha, 2018; Velasco, Ortíz, Giró, & Velasco, 2014; Journal & Scientific, 2011). Meanwhile, to the best of our notice, no research work has investigated the effect of additives on the cooling rate of clay in an attempt to improve the ballistic performance of the clay box. The coupling of thermal conductivity, heat capacity and density all combine to affect the cooling rate of a body. These quantities however vary with the types and the quantity of additives on the clay (Silva & Mallwattha, 2018; Velasco, Ortíz, Giró, & Velasco, 2014; Oskouei, Afzali, & Madadipour, 2017; Kazmi, Abbas, Saleem, Munir, & Khitab, 2016; Toure, Sambou, Faye, & Thiam, 2017). In fact, literature showed that the thermal conductivity of the clay decreases as the percentage by mass of the additives increases. If the thermal conductivity of clay can be affected by the addition of additives, then, there should be an effect of adding these additives on the ballistic performance of the clay used in clay box construction since the rate of cooling of the plastilina is affected by the thermal conductivity of the clay used in the modeling. Also, literatures (Silva & Perera, 2018; Rahman, 2014; Aramide, 2012; Johari, Said, Hisham, Bakar, & Ahmad, 2010; Folaranmi, 2009; Qatta, 2012; Ahmad, Iqbal, & Muhammad, 2017; Velasco, Ortíz, Giró, & Velasco, 2014; Oskouei, Afzali, & Madadipour, 2017; Chen & Ahmad, 2017; Olgun, 2013) have proved that other thermo-physical properties of clay such as density and heat capacity are affected by the percentage by mass of additives in the clay.

This paper is therefore aimed at investigating the effects of additives on the ballistic performance of the clay box when various proportions of berley reeds, saw dust and rubber cuttings additives are used dopants in clay. The intrinsic properties of clay such as: density, thermal conductivity and thermal conductivity are integrated into the lump system analysis model. The Lump system analysis was then used to compute the cooling rate of clay with various percentages of additives using a code written c++ and compiled with devcpp 4.9.9.2. This computational modelling was based on the results of experimental measurements of density, heat capacity and thermal conductivity of clay as reported by (Silva & Perera, 2018; Rahman, 2014; Folaranmi, 2009; Ahmad, Iqbal, & Muhammad, 2017; Journal & Scientific, 2011).

2. Methodology

To apply the lump system analysis model, one needs to obtain the value the biot number. The biot number gives a measure but in form of ratio of heat resistance inside of a body to the heat resistance at the surface of the body. It can be used to check the applicability of the lump system analysis since it determine whether temperature will vary much in space (i.e it checks the extent to which the temperature remains a function of position) when heat is applied. Generally, to apply the lump system analysis model, the evaluated biot number must be greater or equal to 1. While biot number of 0.001 indicates the exactness of lump system applicability, the model only gives an approximate result for biot number above 0.001. If accuracy is not of major concern, then the model may even be applied for biot number greater than one. In this case, investigating the effect of dopands on the cooling rate of clay does not call for stringent accuracy. Hence, the lump system modelling can be applied (Subramanian, n. d.; Rickards, 2013).

2.1 The Calculation of Biot Number

The dimension of the clay box conventionally is given by 610mm by 610mm by 140 mm (Dale et al., 2011). The coefficient of heat transfer, h is given by

$$h = 1.42 \left(\frac{\Delta T}{L} \right)^{\frac{1}{4}} \quad (1)$$

Where ΔT is the change in temperature and L is the length of the box (Velasco, Ortíz, Giró, & Velasco, 2014), at a very small change in temperature, say 0.5°C , between the clay box and its surrounding upon removal from the oven, then the Biot number is given as

$$Bi = \frac{hL_c}{K} \quad (2)$$

Where h is the coefficient of heat transfer, L_c is characteristic length, K is thermal conductivity (Ahmad, Iqbal, & Muhammad, 2017)

Evaluating h from eqn. 1 gives, coefficient of heat transfer, $h = 1.95Wm^{-2}K^{-1}$

The biot number evaluated from Equation 2 is $Bi = 1.09$ which is approximately equal to 1. Even though, this result does not look much favorable because the condition is $Bi \geq 0$ but out of this, $Bi > 0$ is only an approximate. If $Bi < 0.1$, it implies heat conduction rates in the body is faster than heat convection rates away from the surface of the body. The type of body is said to be “thermally thin” and temperature can be assumed to be uniform through the volume of the body. However, when $Bi > 0$, this assumption made earlier cannot be made. In this case, the application of lump system analysis to the modeling is only a matter of approximation. The approximation is however convenient for us just to demonstrate the effect of additive on the ballistic performance of the clay box (Subramanian, n. d.; Rickards, 2013; Glen, 1971).

There are other approaches to measuring the ballistic performance of the clay box but the lumped system analysis provides the simplest approach for this measurement (Dale et al., 2011; Glen, 1971). The assumptions used by this approach is that the heat transfer to the environment by a body is controlled by the convection heat transfer coefficients and thermal capacities of the material provide these two are high enough (Glen, 1971). This approach however may be too simple to be valid practically but can still be used to demonstrate the effect of additive on the ballistic performance of the clay box. The limitation of this approach is that it assumes temperature is only a function of time and not a function of distance. This assumption is not likely to be achieved since clay itself is not a very good conductor and also the thickness of the clay box is about 140mm.

2.2 The Model

The lump system analysis model is written after a slight modification as;

$$\frac{(T - T_\infty)}{(T_o - T_\infty)} = \exp\left[\frac{-hA\tau}{\rho cV}\right] \quad (3)$$

Where T_∞ is the ambient (environment) temperature, T_o is the initial temperature of the clay box, A is the exposed surface area, τ is the elapsed time, ρ is the density of the clay box, c is the heat capacity of the box and V is the volume (Dale et al., 2011). It is important to note that eqn (3) is a modification of the equation below though applied in a very different perspective, all stem from the same basis (the lump system analysis)

$$t = \frac{mc_p}{hA_s} \ln\left[\frac{T_m - T(t)}{T_m - T_i}\right] \quad (4)$$

m is the mass of the body, h is the convection heat transfer coefficient, c_p is the heat capacity, A_s is the surface area of the body, T_m is the temperature of the surrounding medium, T_i is the initial temperature of the body and $T(t)$ is the temperature at time, t (Dale et al., 2011; Subramanian, n. d.; Glen, 1971).

Even though, there are many materials that make up the clay box, but we will be concerned with the clay since it forms the greater percentage of the clay box for the purpose of demonstration. From the above model, the only intrinsic properties of the clay are density, thermal conductivity and heat capacity; all others are extrinsic properties (they can be regarded as constants for the plastilina). In order to include the effect of varying thermal conductivity on the ballistic performance of the clay box, we modify Equation 3 as shown below

$$Bi = \frac{hL_c}{K} \cong 1 \quad (5)$$

Factoring Equation 5 into Equation 4:

$$T = (T_o - T_\infty) \exp\left[\frac{-hK\tau}{\rho cL_c^2}\right] + T_\infty \quad (6)$$

Also, the relation $L_c = A/V$ was factored into Equation (3) to obtain the above equation. Where K , L_c , A and V are thermal conductivity, characteristic length, area and volume respectively (Dale et al., 2011; Mukasey, Sedgwick, & Hagy, n. d.). We shall now use the above model to evaluate the ballistic performance of the clay box by varying

the values of ρ , c and K due to different percentages of additives (sawdust, berley reeds and rubber cuttings) on the clay used in the construction of the clay box.

3. Result and Analysis

The graphs shown below were obtained from the output of the code written in c++ which has been compiled by devcpp version 4.9.9.2 software. In Figures 1a, 2a and 3a, the cooling curves decreases downward towards the room temperature as time increases. As observed in Figure 1a, after about 1.5 hours, the clay with rubber cutting additives has only cooled to 33.51°C, 30.41°C, 33.70°C, 32.68°C and 31.60°C for 0%, 5%, 10%, 15% and 20% rubber cuttings additives respectively, which indicates different cooling for each of the samples. Thus, heat retention ability of the clay samples is very good. As shown in Figures 1a, 1b and 1c, temperature of the clay samples decay exponentially with time, which is the characteristic of a typical cooling curve. Also from these Figures, the role additives generally play on the cooling rate of clay is explicit. It is shown that different samples of clay doped with percentages of additives have different cooling curve slopes, which is a direct measure of their cooling rate. It is important to state that the ballistic performance has an inverse relationship with the cooling rate. Thus, for an improved ballistic performance, lower cooling rate is essential. As the percentage by mass of additives increases from 10% upwards, the rate of cooling also increases as shown in Figures 1d, 1e, 1f and 3. This may seem counter intuitive since thermal conductivity decreases as the percentage by mass of additives increases (Silva & Perera, 2018; Folaranmi, 2009; Ahmad, Iqbal, & Muhammad, 2017; Journal & Scientific, 2011) and thermal conductivity has a direct relationship with cooling rate as shown in Fourier's law. One might therefore expect that as the percentage by mass of the additives increases, the cooling rate should reduce since thermal conductivity reduces. However, this cannot always be true since thermal conductivity alone does not determine the cooling rate. The cooling rate also depends on density and heat capacity of the clay. For example, heat capacity and density have inverse and direct proportionality with cooling rate respectively. Thus, the higher heat capacity and lower density are essential for lower cooling rate. We can then infer that different properties dominate the cooling rate at different percentages by mass of additives. Cooling rate increases between 0 and 5%, decreases from 5% till 10% where it is minimum, then increases afterward. This behavior of cooling rate in response to varying percentage by mass of additives is still not fully understood. Therefore, open to further investigation.

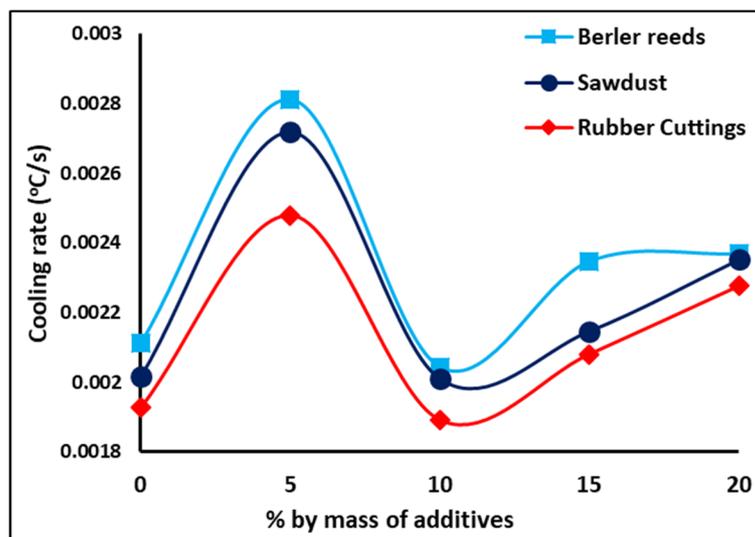


Figure 1. The graph of cooling rate versus % by mass of saw dust, berley reeds and rubber cuttings additives

The highest cooling rate was obtained for clay doped with 5% additives, which implies a bad ballistic performance at that level of dopands. From Figure 1 also, it is depicted that the rate of cooling of clay with 10% additives is comparable with that with 0% doping, though the minimum cooling rate is obtained at 10% doping. This observed two minimal levels of cooling rate is unique and evident for all the additive types as shown in Figures 1, 2d, 2e and 2f. This uniqueness instigates experimentalists to choose between perfect purity and an exact doping with 10% additives. However, clay is an earth element and therefore expected to have inherent impurity apart from its normal composition. While one is free to choose between 0% and 10% for ballistic testing, using clay box doped with 10% additives seem more practical since achieving a perfectly pure state for clay is definitely more tasking.

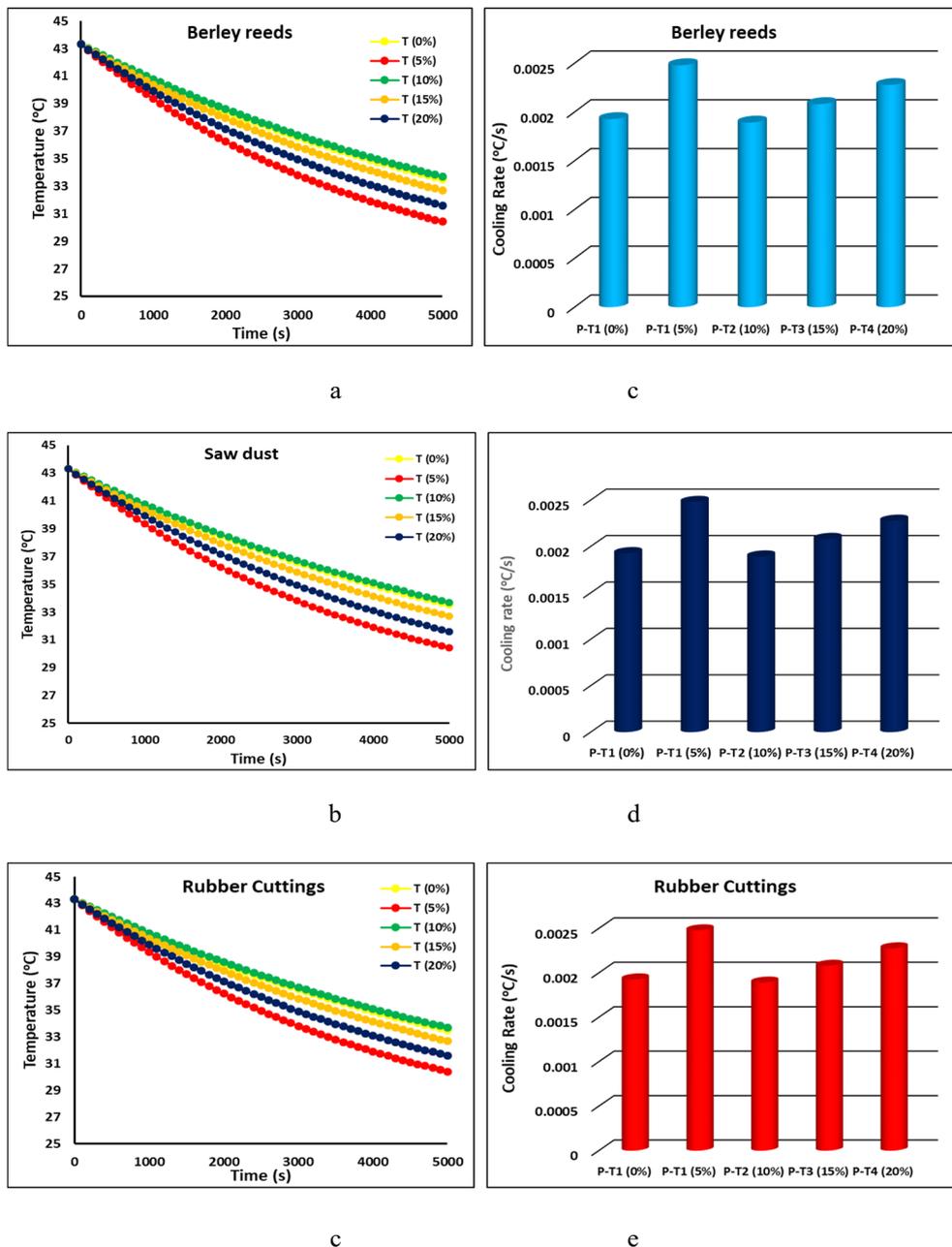


Figure 2. (a-c) The graph of cooling rate versus time (d-e) Bar chart representation for different percentages of saw dust, berley reeds and rubber cuttings additives, including bar chart representation

The effect of different additives (saw dust, berley reeds and rubber cuttings) on the ballistic performance of clay are shown in Figure 3. It is evident that the best additives to use as dopands for clay box construction is rubber cuttings, displaying the smallest minimum cooling rate of $1.89 \times 10^{-03} \text{C/s}$. The same behavior is repeated at different percentages of additives. This demonstrates further that at any percentages of additives, rubber cuttings will always have the lowest cooling rate. Therefore, rubber cuttings is the best additive out of all these three that can be used in the construction of clay box used in ballistic testing of body armour.

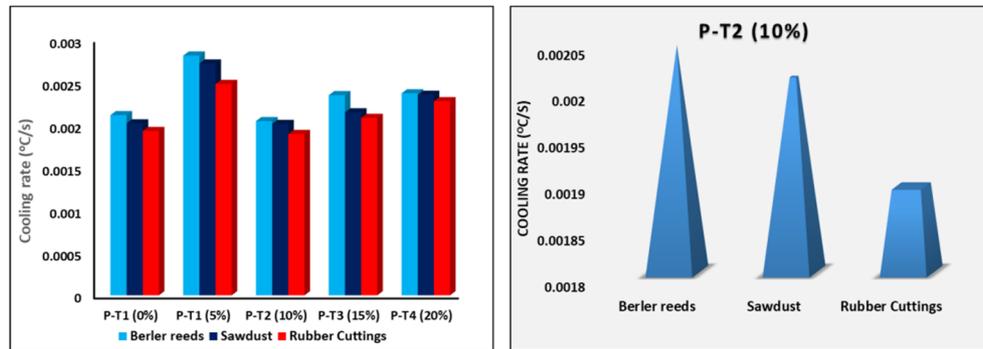


Figure 3. The graph of cooling rate versus time for different percentages of saw dust, berley reeds and rubber cuttings additives, including bar chat representation

4. Conclusion

In this work, the effect of different percentage by mass of saw dust, rubber cuttings and berley reeds additives on the cooling rate of clay were investigated using the lump system analysis modelling. The cooling rate serves as the performance metrics for ballistic performance of clay used in the construction of clay box. The smallest minimum cooling rate ($1.89 \times 10^{-03} \text{°C/s}$) obtained in this work are from clay doped with 10% by mass of rubber cuttings, making clay doped with 10% rubber cuttings the best additive for enhancing the ballistic p of clay used in clay box construction. Generally, while 10% by mass of additives always give the smallest values of cooling rate, pure clay also give comparatively low values of cooling rate ($2.04 \times 10^{-03} \text{°C/s}$). This enables the ballistic testing experimentalist to choose between a pure clay or 10% rubber cuttings doped clay in constructing the clay box used for the ballistic testing of body armour.

5. The Program

```
//THE COMPUTATIONAL PROGRAM WRITTEN AND COMPILED USING THE Dec-C++4.9.9.2
#include<iostream>
#include<cmath>
#include<fstream>
using namespace std;
class proc{
private:
float K,L,h,t,p,c,Te,To;
float T_arr[21];
const int cnst;
public:
proc():cnst(29340){
cout<<"Please enter some variables before program execution.\n"
<<"\n\t Enter K:_____\b\b\b\b";
cin>>K;//we got value for K
cout<<"\n\t Enter L:_____\b\b\b\b";
cin>>L;//we got value for L
cout<<"\n\t Enter p:_____\b\b\b\b";
cin>>p;//we got value for p
cout<<"\n\t Enter c:_____\b\b\b\b";
cin>>c;//we got value for c
cout<<"\n\t Enter Te:_____\b\b\b\b";
cin>>Te;//we got value for Te
cout<<"\n\t Enter t:_____\b\b\b\b";
cin>>t;//we got value for t
cout<<"\n\t Enter h:_____\b\b\b\b";
cin>>h;
cout<<"\n\t Enter the value of To_____\b\b\b\b";
cin>>To;
```

```

        cin.get();}
int start_proc(){
    //starting the iteration
    for(int i=0;i<=20;i++){
        t+=10;
        T_arr[21]=((To-Te)*exp((-h*K*t)/(p*c*L*L))+Te; }}
int output(char filename[]){ ofstream pfile(filename);
    if(!pfile){cout<<"\nError! Failed to open file: "<<filename<<endl; return 0;}
    pfile << "\tResultant_temperature(T)\t|\telapsed_time (t)\t\n"
        << "-----\n";
    pfile.setf(ios_base::fixed, ios_base::floatfield);//used to avoid most output of
exponentials
    for(int i=0;i<=20;i++){
        pfile <<"\t|\t"<<T_arr[i]<<"\t|\t\n";}
    pfile.close();
    for(int i=0;i<=20;i++){
        cout <<"\t|\t"<<T_arr[i]<<"\t|\t\n";}
    cout<<"Program finished!!!";}
};

int main(){
    proc pro; pro.start_proc(); pro.output("output.txt");
    cin.get();
    return 0; }

```

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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