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Thermo-mechanical characterization of building component with crushed millet stalk fiber

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ABSTRACT: This paper is a contribution to the valuation of the millet stalk fiber as insulation material in building. To do this, the millet stem is crushed in two sizes and each size obtained is mixed with different Arabic gum content, which acts as a binder. Arabic gum is an effusion of sap from a trunk of acacias from Senegal. This material is still unusable largely because a big quantity is thrown in the nature. The influence of millet stem size and Arabic gum content on mechanical and thermal properties was evaluated. As for the resistance in flexion, we found a null value for all the samples. The compression resistance of samples varies from 0.8 to 1.5 MPa with a percentage of the binder evolving from 3 to 11.27 %. These values of the mechanical resistance are in strong proportionality with the binder dosages. The thermal conductivity varies from 0.113 to 0.914 W. m-1. K-1 with an effusivity going from 228 to 183 J.m-2. °C-1.s-1/2. The results showed that the conductivity and the effusivity increase with the content by linking of the material.

KEYWORDS: thermal conductivity, thermal effusivity, millet stalk fiber, gum Arabic, fiber.

1 INTRODUCTION

The environmental impact of the conventional building materials (cement, brick, and aluminum, wood and steel) is important. The production of these materials consumes a lot of thermal and electric energy and partially pollutes the air, the water and the earth [1]. With the increase of the demand for housing, this production is exponential [2]. In Senegal the construction industry consumes 54.7 % of energy, according to the energy information system of the country. They also favor a strong energy consumption in the exploitation phase of the building. According to the database of the project of thermal insulation materials production with Typha in Senegal, in western Africa, 25 to 30 % of produced electricity is consumed by buildings. The environmental low-cost alternative development of building materials stands out as a priority problem. Consequently, several solutions were implemented. Among these, we can note the development and the use of natural and local materials, including the use of plant fibers in construction. These vegetable fibers are widely available, low-cost and their use under construction creates new outlets for the agricultural materials. Younouss Diéye and al [3] showed that Typha australis fiber is a good candidate for the development of insulation materials. Therefore, a good natural material of insulation becomes the key of the game in the design and the construction of energy-efficient buildings using materials with environmental low impact. In this context, several researchers used various types of vegetable fibers (hemp, straw, linen, bamboo, hairs of animals, cork, typha etc.) mixed with other compounds (cement, clay, sand, gypsum, mortar, concrete, etc.) to make composite materials [4-5].

N. Benmansour [6] determined the mechanical and thermal properties of a new material composed of cement, sand and of palm tree fibers. The results reveal that the incorporation of palm tree fibers reduces the thermal conductivity and the compression resistance of the composite while reducing the weight. H. Ball and al [7] studied the thermal properties of the laterite bricks with additives of millet waste. They found a dependence of the thermal properties of the water amount of the material. P Meukam [8] and al studied the effect of the sawdust addition on the thermal properties of laterite brick stabilized with cement. They showed that sawdust addition increases the thermal performances of the laterite brick stabilized with cement. F. Collet [9] made a comparative study of hygric behavior of three hemp concrete. The results underline a high humidity transfer and storage capacity of these three materials. The mechanical properties and the hygroscopic behavior of compressed earth brick stabilized with cement with additives of palm-tree fibers was made by B. Taallah and al [10]. The best compression resistance was obtained with the brick stabilized at 8 % of cement with 0, 05 % of palm tree fiber additives. The increase of the content in cement and a decrease of the content in fiber creates a decrease of water absorption. Millogo [11] made the experimental analysis of the mechanical properties of compressed adobe block strengthened with fibers of hibiscus cannabinus. The authors show a mechanical improvement of the adobe block properties by fibers. The use of lime and rice husk to stabilize the mud or compressed brick was studied by In. SETYO and al [12]. The results show that the compression and flexion resistance of clay brick are improved by the addition of lime and rice husk ash. The best quantity of lime and of rice husk ash in this study is obtained for an equivalent percentage of lime and rice husk ash. Rafael and al [13] studied the effect of the addition of sugar cane bagasse and some lime on mechanical properties of the compacted blocks of earth. They found that additives of fibers increase slightly the resistance to the compressed block. M.T DIATTA and al determined the thermo-physical and mechanical properties of Typha concrete [14]. They show that the thermal insulation of concrete is improved by typhas fiber additives. Luiz C. Roma Jr and al [15] evaluated the thermal performance of cement tile reinforced with eucalyptus fibers. The thermal performances found for the authors are acceptable. J. Lima and P. Faria [16] estimated the influence of the addition of two natural fibers: the straw and the typha on the physical and mechanical properties of the earth. The mechanical and thermal characteristics found show that the addition of these fibers contributes to the linear decrease of the withdrawal of drying and the thermal conductivity. Luamkanchanaphan and al [17] studied the physical, mechanical and thermal properties of the insulating panels prepared from narrow-leave cataille fibers by using Diisocyanate of diphenyl methyl alcohol (MDI) as binder. According to their results, they conclude that the insulating panels prepared from narrow-leave cataille fibers are an excellent insulation material of, energy-efficient and environment-friendly.

Our work is centered in this perspective with the use of millet stalk fibers as building materials. Millet is the most cultivated cereal in Senegal. It is grown everywhere in the country and accordingly occupies a dominating place of rain-fed agriculture within the country [18]. It represents more than 60 % of the sown-cereal surfaces, with a national production of at least 1 000 000 tons / year. Its exploitation creates important sources of gain for farmers, but part of the plant in particular its stalk is thrown in nature. The latter constitutes an agricultural waste in abundance in all over the country, in particular in the agro-pastoral rural areas. Its wide availability makes of it a product used in the past in rural areas for house construction by junction of stalks in the form of fences. Important-unused quantities of millet stalk are scattered in fields and burned before of the rainy season to be eliminated. Then its use as construction material is a softening of the penalties undergone by farmers to get rid of it and a solution to avoid their incineration which has an impact on the environment.

The aims of this paper is to determine the mechanical and thermal properties of a millet stem fibre-based material for use as insulation material in the building. The mechanical and thermal properties determined are the resistance in compression and in flexion, the thermal conductivity and the thermal effusivity. The originality of this work compared to the work cited above is the use of millet stalk fiber as an insulating material with as gum arabic binder. To do this, the millet stem is cut in two sizes. Each size is dosed with different levels of gum arabic. This allows to know the effect of the size of the millet stalk fibers and the gum arabic content on the mechanical and thermal properties of this composite material.

2 EXPERIMENTATION

2.1 MATERIALS

2.1.1 BINDER

The binder is constituted by mixture of gum Arabic with some water. The used Arabic gum is an effusion of sap running from a trunk of acacia trees of Senegal. A quantity of Arabic gum in powder is dissolved totally in some water. The quantities of Arabic gum powder used are 250g, 200g, 100g and 60g. Every quantity of powder is dissolved in 1,5l of water. The various obtained concentrations are respectively noted A, B, C and D. A mixer allowed to stabilize the dosage. On every obtained concentration, a volume is taken to serve as a binder in the sample manufacturing.

2.1.2 FIBER

Fibers are used as a matrix. They are obtained after extraction of millet. These stalks are dried in natural conditions. Two different fiber-sizes are used and are represented on figure 1. The sieve analysis (Fig.2) is made for two samples (G1 and G2) to determine the various diameters and the length of fibers. The grading analysis established according to the standard X11-

501 AFNOR is represented in figure1. The curve shows a distribution of the size of fine fibers, with an average diameter of 0, 3 mm, noted (G1), a distribution of the size of fibers, with an average diameter of 0, 7 mm, noted (G2).

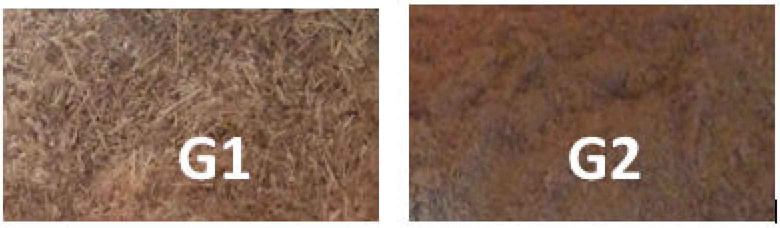

Fig. 1. Millet Stalk crushed for various sizes

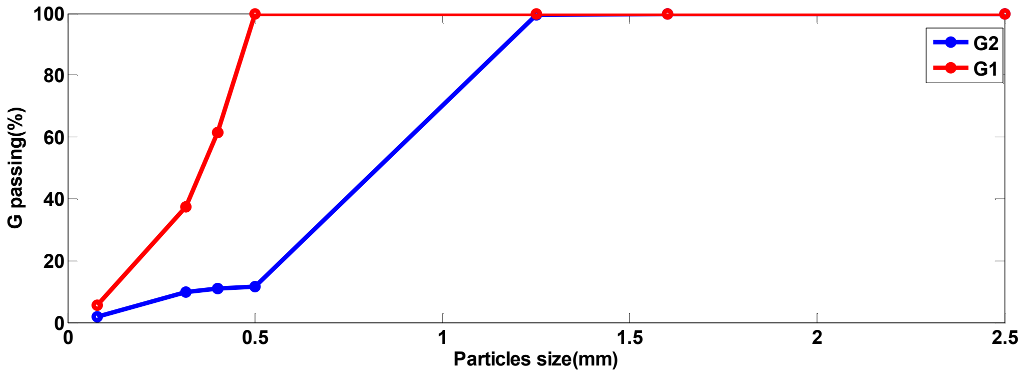

Fig. 2. Grading curve of millet fiber

2.1.3 PREPARATION OF SAMPLES

Samples were built by a mixture of the fiber of crushed stalk of millet and the Arabic gum solution. The weight composition of the various samples is given in table1. For the mechanical tests, a mold of 4×4×16 cm^3 was used for the preparation of samples and for the thermal tests a mold of 10×10×2.5 cm^3. After compacting the material stemming from the mixture in molds, the various samples were dried in an oven with a constant temperature of 90 degrees during 72 hours. Figures 3 and 4 respectively show samples for the thermal tests and those intended for the mechanical tests. The density and the porosity of the material are represented in table 2. The porosity was obtained by using the following equation:

$$P = \frac{M_{sat} - M_{\sec}}{\rho_{eau} V_0} \qquad (1)$$

Msec is the mass of the dried sample, it was measured after drying at 105°C in a ventilated study.

Msat is the mass of the water-saturated sample, it was measured after saturation.

V0 is the apparent volume of the sample, it is calculated by measuring the dimensions of the sample.

ρeau is the density of water.

Fig. 3. Sample Picture for thermal test

Fig. 4. Sample Picture for mechanical test

Table 1. Masses of the various components

Mixtures	Pourcentage gum Arabic	Percentage of Fiber	Percentage of Water
G1A	10.47%	40.68%	50.85%
G1B	8.26%	29.76%	61.98%
G1C	4.95%	20.77%	74.28%
G1D	2.97%	22.67%	74.36%
G2A	11.27%	21.14%	67.60%
G2B	9.25%	21.35%	69.40%
G2C	4.83%	22.66%	72.51
G2D	3.18%	21.18%	75.64%

Table 2. Density and porosity of samples

Mixtures	Density (kg/m^3)	Porosity(%)
G1A	414.8	66.3
G1B	350	74.3
G1C	342.3	76
G1D	335.7	81.6
G2A	375.9	82
G2B	322.4	86.8
G2C	310.6	89
G2D	288.7	93.4

2.2 MECHANICAL CHARACTERIZATION

The compression resistance and in flexion is determined by using type E0160 mechanical press having a maximal strength of 250 kN. The speed of the applied strength is of 2 kN / dry. The test is made with three samples for every mixture. The resistance test in the compression consists in placing a sample of prismatic shape in the press as represented on figure 5. For the measure of the resistance in flexion, the sample is arranged as shown on figure 6. The principle consists in applying a pressure to the standard sample and in measuring its tension in the breaking point. The maximal constraint which the sample can support before the break is the traction resistance or the compression resistance. It is defined by:

$$\sigma = \frac{F}{S} \qquad (2)$$

S is the section of the sample in mm^2, F is the applied strength (N) and is the constraint in MPa

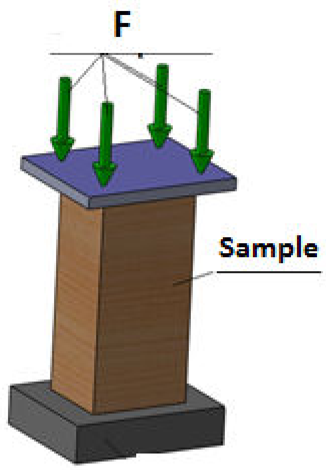

Fig. 5. Compression test

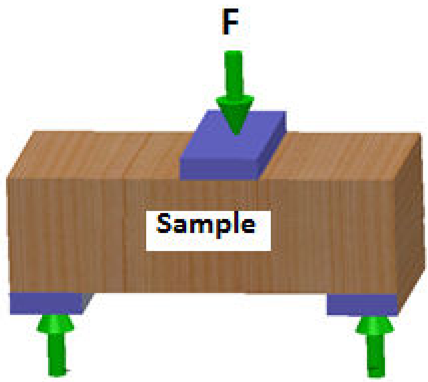

Fig. 6. Test of resistance in flexion

2.3 THERMAL CHARACTERIZATION

The method of the asymmetric hot plan is used to measure the conductivity and the thermal effusivity. The plan of the experimental device of this method is on figure 7. The asymmetric experimental device is described in detail by Younouss and al [3]. A constant flow of heat is sent through the heating element and of recorded the variation of the temperature in the center of this same heating element. The modelling of this system by using the method of the quadripoles and the Laplace transform allows to obtain the variation of the theoretical temperature in the center of the heating element. This theoretical temperature depends on looked thermal properties. In the modelling, we consider that the heat transfer in the center of the heating element is unidirectional and the temperature at the level of the block of aluminum is constant. The principle of the method consists in identifying the value of E and λ allowing the overlap of the experimental and theoretical curve. The equations of the model are the following ones:

$$\begin{bmatrix}\theta_s\\ \Phi_{01}\end{bmatrix}=\begin{bmatrix}1 & 0\\ C_sS_p & 1\end{bmatrix}\begin{bmatrix}1 & R_c\\ 0 & 1\end{bmatrix}\begin{bmatrix}M & N\\ O & P\end{bmatrix}\begin{bmatrix}0\\ \Phi_1\end{bmatrix}=\begin{bmatrix}M_1 & N_1\\ O_1 & P_1\end{bmatrix}=\begin{bmatrix}0\\ \Phi_1\end{bmatrix} \tag{3}$$

$$\begin{bmatrix}\theta_s\\ \Phi_{02}\end{bmatrix}=\begin{bmatrix}M_i & N_i\\ O_i & P_i\end{bmatrix}\begin{bmatrix}0\\ \Phi_2\end{bmatrix} \tag{4}$$

Avec:

$$M=P=\cosh\left(\frac{E}{\lambda}\sqrt{pe}\right);\ N=\frac{\sinh\left(\frac{E}{\lambda}\sqrt{pe}\right)}{ES\sqrt{p}};O=ES\sqrt{p}\sinh\left(\frac{E}{\lambda}\sqrt{pe}\right) \tag{5}$$

$$M_i=P_i=\cosh\left(\frac{E_i}{\lambda_i}\sqrt{p}e_i\right);\ N_i=\frac{\sinh\left(\frac{E_i}{\lambda_i}\sqrt{p}e_i\right)}{E_iS\sqrt{p}}; \tag{6}$$

$$O_i=E_iS\sqrt{p}\sinh\left(\frac{E_i}{\lambda_i}\sqrt{p}e_i\right) \tag{7}$$

λ Is the thermal conductivity of the sample; E the thermal effusivity of the sample is; e the thickness of the sample is; λi I the thermal conductivity of the polystyrene; Ei the effusivité of the polystyrene; ei the thickness of the polystyrene; θs Laplace Transform of temperature Ts (t); Cs is thermal capacity of the element warming by area unit; Rc the thermal resistance of contact between the heating element and the sample; Φ1 Laplace Transform of the heat flow crossing the block of upper aluminum; Φ2 Laplace transform of the heat flow crossing the block of lower aluminum; Φ01 Laplace transform of heat flow density of in the heating element (Upstream); Φ02 Laplace transform of the heat flow density in the warming element (downstream).

After the development of matrix products (2 and 3), the following expressions were obtained:

$$\Phi_{01} = \theta_s \frac{P_1}{N_1} \tag{8}$$

$$\Phi_{02} = \theta_s \frac{P_i}{N_i} \tag{9}$$

The heat flow is :

$$\Phi_0 = \Phi_{01} + \Phi_{02} \tag{10}$$

$$\Phi_0 = \theta_s \left(\frac{P_1}{N_1} + \frac{P_i}{N_i} \right) \tag{11}$$

And we deduce the value of θ_s by the relation:

$$\theta_s = \Phi_0 \frac{1}{\left[\frac{P_1}{N_1} + \frac{P_i}{N_i} \right]} \tag{12}$$

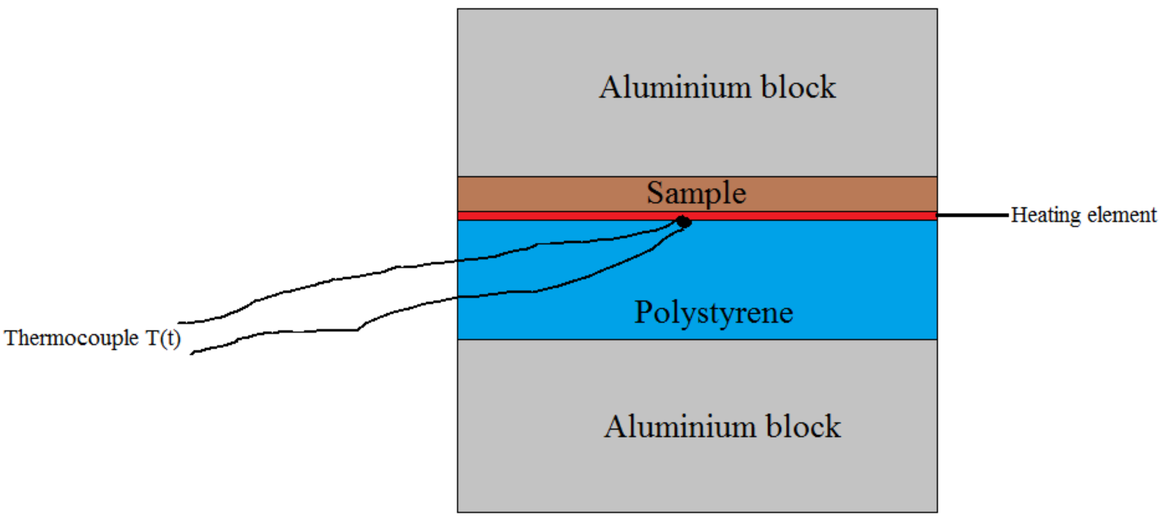

Fig. 7. Scheme of the hot plate asymmetric device [3]

3 Results and Discussion

3.1 Mechanical results

The mechanical test consists in determining the resistance in flexion and the resistance in compression. As for the resistance in flexion, we found a null value for all the samples. Which shows the flexibility of millet stalk fibers. The variation of the resistance in compression according to the percentage of the binder is represented on figure 8 and 9. We observe an increase of the resistance in compression according to the percentage of gum Arabic. The increase of the percentage of gum Arabic, generates a decrease of the porosity of the sample as shown in tableau2. The porosity is the main factor of decrease of the resistance in compression. This resistance varies from 0.61 to 1.496 MPa for the samples of G1 grain size and from 0.451 to 1.37 MPa for the samples of G2 grain size. The increase size of fibers causes a decrease of compressive strength of the samples. Indeed, the increase size of fibers increases the porosity of samples.

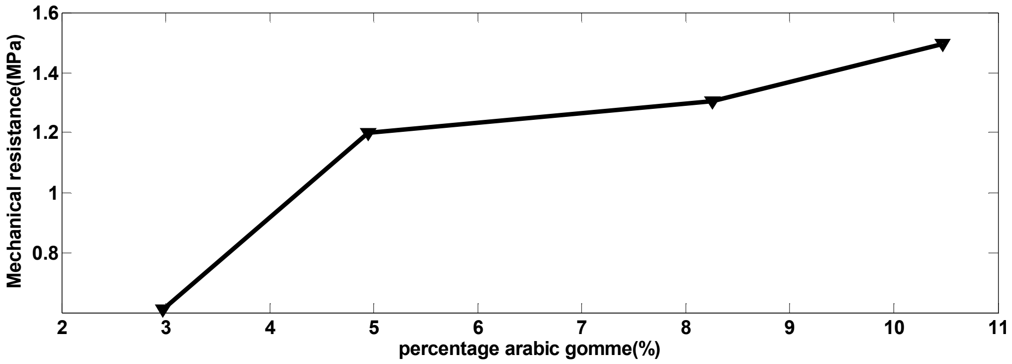

Fig. 8. Variation of the mechanical resistance according to the percentage of gum arabic for G1

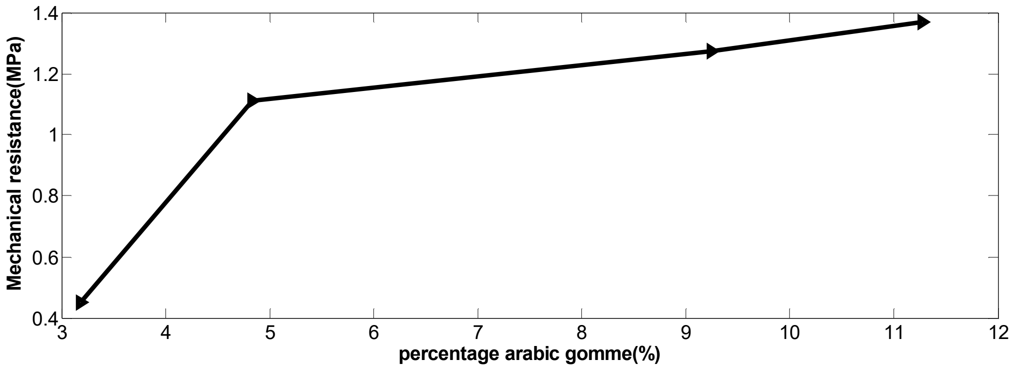

Fig. 9. Variation of the mechanical resistance according to the percentage of arabic gum for G2

3.2 Thermal Results

The thermal results are represented in the picture table 3 and 4 with the porosity. We notice that the thermal properties decrease with the decrease of the Arabic gum percentage. The dissolution of an Arabic gum mass of in the water served of binder. The decrease of the percentage of dissolved gum Arabic creates an increase of the quantity of water in the mixture Samples are dried in an oven in 90°C for 72 hours. Which generates the evaporation of a good quantity of water, leaving pores in the sample. The more the quantity of water used in the manufacturing of samples is big, the more the dry porosity of material increases. It is what explains the increase of the porosity with the decrease of the percentage of Arabic gum, which is the main factor of the decrease of thermal properties. When we rise the size of fibers, we stress the increase of the porosity of the sample. The thermal properties obtained with the samples of size grading G2 are lower than the properties thermal samples of size grading G1.

Table 3. Thermal Results of G1samples with porosity

Samples	Porosity (%)	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	Thermal Effusivity ($J.m^{-2}.°C^{-1}.s^{-1/2}$)
G1A	66.3	0.132	228
G1B	74.3	0.124	206
G1C	76	0.109	193
G1D	81.6	0.098	183

Table 4. Thermal Results of G2 samples with porosity

Samples	Porosity (%)	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	Thermal Effusivity ($J.m^{-2}.°C^{-1}.s^{-1/2}$)
G2A	82	0.119	200
G2B	86.8	0.108	178
G2C	89	0.097	180
G2D	93.4	0.091	168

4 CONCLUSION

This work concerned the mechanical and thermal characterization of a material with millet stalk with a prospect of the used as a material of construction. The dissolution of the powder of Arabic gum in some water served as a binder. The Arabic gum is an effusion of sap from a trunk of locust trees of Senegal. The main obtained results are:

- From the mechanical perspective, the values of the resistances in flexion and compression of samples are low. Which shows that this material cannot be used as a structure material. It can be combined with an element of structure.
- From the thermal point of view, a low value of conductivity was found which shows that this material is a good candidate for the manufacturing of effective insulation panels practical in diverse applications in industrial environment and in building.

These results constitute an opportunity of industrial operation of this material which is still unusable because a big quantity is thrown in the nature. Its valuation will allow to relieve the penalties of countries which even have difficulty in getting rid of it by burning them on the eve of the rainy season, which harms the environment.

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