Available online at www.sciencedirect.com
ScienceDirect
Procedia - Social and Behavioral Sciences 160 (2014) 323 – 331
Procedia Social and Behavioral Sciences

XI Congreso de Ingeniería del Transporte (CIT 2014)

Density, adhesion and stiffness of warm mix asphalts

Ángel Vega-Zamanillo[a*], Miguel A. Calzada-Pérez[a], Elsa Sánchez-Alonso[a], Hernán Gonzalo-Orden[b]

[a]*University of Cantabria, Department of Transports, Avda. Los Castros s/n, 39005 Santander, Spain*
[b]*University of Burgos, Department of Civil Engineering, C/ Villadiego s/n, 09001 Burgos, Spain*

Abstract

This study presents the results of different laboratory tests related to the density, adhesion (sensitivity to water test) and rigidity (resilient module) of bituminous mixtures, manufactured at three different temperatures (160 °C, 140 °C and 120 °C), with three additives: a surfactant made up of different amino substances, a paraffin obtained by the Fisher-Tropsch synthesis process which is totally soluble in bitumen, and a synthetic zeolite in powder form which causes the bitumen to micro-foam,. Test samples have been compacted by impact, according to the Marshall method, and kneading, according to gyratory machine. To evaluate these properties an asphalt concrete mixture has been chosen, with a binder, B-50/70, and a maximum size of aggregates of 16 mm, which is usually placed in the surface layer of the pavement. The densities obtained by the two compaction methods are easy to reach. Densities will decrease if the temperature of manufacturing is lower. All mixtures compacted by gyratory machine at different temperatures displayed very good behavior of water sensitivity; but not all mixtures compacted by impact achieved this. The additives improve the adhesion between aggregate and binder. The stiffness moduli decreased in all mixtures for both types of compaction when the temperature was higher, and this reduction is less pronounced in the mixes manufactured with the gyratory compactor. Mixtures with additives tend to reduce the module, except paraffin.

Peer-review under responsibility of CIT 2014.

Keywords: Warm mix asphalts; additives; gyratory compactor; stiffness modulus; temperature.

1. Introduction

Various methods of compaction can be used at a laboratory scale to simulate the conditions obtained at real-scale. These include direct compression, impact hammering, gyratory shear, vibration, simulated rolling, etc. (Khan & Kamal, 2008). The choice of one method over another will depend on the mix design method chosen, varying with it the properties of bituminous mixes as the percentage of air voids (Khan, Al-Abdul Wahab, Asi, & Ramadhan, 1998). In many countries, the Marshall method is utilized for mix design (Anjan & Veeraragavan, 2010). With this method, the specimens are manufactured by impact, and the optimum asphalt binder content is determined by the

Corresponding author. Tel.: +34942201753; fax: +34942201703.
E-mail address: vegaa@unican.es

1877-0428
Peer-review under responsibility of CIT 2014.
doi:10.1016/j.sbspro.2014.12.144

study of the percentage of air voids (Garnica, Delgado, & Sandoval, 2005). This process of mix design is empirical and shows some limitations determining the effects of traffic loads and environmental conditions on the pavement (Asi, 2007). The Superpave mix design is based on the use of the gyratory compaction, and requires a series of previous steps of material characterization (binder and aggregates analysis) for subsequent design of the mix using the volumetric method (Asi, 2007). The gyratory compaction more accurately simulates the loads and the pressure generated by the traffic during the pavement lifetime (Khan, Al-Abdul Wahab, Asi, & Ramadhan, 1998), and simulates the effect of field kneading compaction (Anjan & Veeraragavan, 2010). The specific compaction conditions of this method are: 30rpm, 600kPa and a slight angle of 1.25º. In contrast, in Europe the norm stipulates an angle of 0.82º (EN 12697-31 2008). This difference of angles produces a variation in the percentage of air voids for the same number of cycles. Garnica, Gómez, & Delgado, (2003) studied the effect of the slight angle on the compaction. They showed that the percentage of air voids obtained was very influenced by the change of angle, being difficult to reach percentages of air voids lower than 6% for angles lower than 1.25º. Other studies showed that a change in angle of 0.02º caused the variation of the air voids content by 0.22% at 100 cycles and the variation of the optimal binder content by 0.15% (Brown & Buchanan, 2001).

Some studies compared the Marshall and Superpave mix designs for HMA (Khan & Kamal, 2008). They used different design aggregate gradations with a maximum aggregate size of 19mm. The optimum binder content to achieve 4% air voids for both procedures was different, being 0.5% w/m higher in the case of the Marshall Method. The mechanical tests showed that the Superpave samples had higher Marshall stability, greater water resistance and higher resilient moduli tested at 40ºC, due to the improvement of the mineral skeleton and the lower binder content of Superpave mixes. DelRio-Prat, Vega-Zamanillo, Castro-Fresno, & Calzada-Pérez (2010) compared the two types of compaction, measuring the energy necessary to compact the bituminous mixes in the laboratory. In the case of the Marshall method, the energy required is constant because it is a compaction by impact; while in the case of the gyratory machine, the energy was calculated using new parameters called Mix Energy Indexes (MEI1 and MEI2, in kJ/kg), which were obtained through the curve of shear effort. The results showed that mixes compacted with gyratory machine needed less energy for compaction than the Marshall for the same percentage of air voids.

The disappearance of natural resources and raw materials represents a change of mentality in the construction of civil engineering. Within the field of roads, the design of hot bituminous mixtures is being improved, using warm mix asphalts in the construction of new pavements, manufactured at temperature below the conventional, and adding small amounts of chemical products. This means significant energy savings in manufacturing and compaction of pavement layers made of bituminous materials.

There are different types of commercial additives. Many of them are used in bituminous mixes to reduce energy consumption (the manufacturing temperatures is reduced), while maintaining or even improving some of the mechanical properties required in Hot-Mix Asphalt (HMA). The advantages of the use of these mixes, called Warm Mix Asphalt (WMA) or Half-Warm Mix Asphalt (HWMA) depending on the manufacture temperature and type of binder used, are: 20-75% of energy savings, decrease of emissions (50% for VOC's, 30-40% for CO_2 and SO_2, 10-30% for CO, 60-70% for NO_x, 20-25% for dust), 30- 50% less fumes and odors, hauling the mixture from greater distances and ease of compaction (Kristjansdottir, Muench, Michael, & Burkeet, 2007), (You & Goh, 2008), (Sue, Maekawa, & Hachiya, 2009).

Laboratory tests were done to determine the mechanical properties of these new materials. In The United States, several studies have been done with different additives, demonstrating that the stiffness modulus of mixes manufactured with this additives did not change compared with a HMA. As for the resistance to rutting, the use of someone decreased the rutting resistance compared to HMA at the same temperature; in contrast, others did not affect rutting (Hurley & Prowell, 2005a, 2005b).

Mohammed, Saadeh, & Cooper, (2008), carried out various tests with an additive, demonstrating less tensile strength under indirect tension than in HMA. Also, the mixture with the additive had a lower stiffness modulus than the conventional mix's, about 1,500MPa at 25ºC. Akisetty, Lee, & Amirkhanian, (2009) studied the influence of temperature on the manufacture of crumb rubber-modified asphalt mixes with additives. They concluded that using either additive the laying temperature could be reduced with respect to a HMA, while maintaining a suitable percentage of air voids.

In Europe, a study was carried out on the use of an additive, using different amounts of additive and types of penetration binders. It was found that mixes with the additive increased the stiffness modulus and the resistance to rutting, but did not change the resistance to water in comparison to HMA made with the same bitumen (Silva, Oliveira, Peralta, & Zoorob, 2010). The Vilnius Gedimias Technical University (GVTU) Road Research Laboratory did laboratory tests manufacturing mixtures at different temperatures, with various additives in different proportions. They determined that WMA has less Marshall stability than its HMA counterparts, and the content of voids was higher (Vaitkus, Čygas, Laurinavičius, & Perveneckas, 2009).

2. Experimental research

In this research, a comparative study of impact and gyratory compaction, as defined by the European standard, has been done by The Road Technology Laboratory of the University of Cantabria. The influence of the type of compaction on the mechanical properties of HMA and WMA has been analyzed. Two mechanical properties, water sensitivity and stiffness modulus were measured, for mixes compacted by both procedures at different manufacturing and compaction temperatures, using additives that enable the reduction of the working temperatures. Three manufacture temperatures were used: the manufacturing temperature in HMA (160ºC), and the temperatures used in WMA (140ºC and 120ºC). The compaction temperatures selected were the same than the manufacture (160ºC, 140ºC and 120ºC) which are coming into the compaction temperature range of HMA (160ºC-138ºC) and WMA (135ºC-120ºC) (You & Goh, 2008). The pre-compacted specimens were placed in an oven at the specified compaction temperatures for a 30-minute equilibrium period. Three warm additives with different nature were tested.

2.1. Materials

For this study, a type of aggregate gradation called Asphalt Concrete (AC) (EN 13108-1, 2008), with a maximum aggregate size of 16mm was selected (AC16Surf). The particle sizes were classified and fitted to the centre of the grading envelope (Table 1). Coarse ophite aggregates and limestone sand were used, which are the most commonly used in Spain to manufacture bituminous mixes.

Table 1. AC16Surf aggregate gradation.

Particle size, D (mm)	22	16	8	4	2	0.500	0.250	0.063
Max. Percent passing (%)	100	100	75	50	38	21	15	7
Min. Percent passing (%)	100	90	60	35	24	11	7	3
Selected gradation	100	95	67.5	42.5	31	16	11	5

The mixes were manufactured with a penetration binder of 60-70dmm, B-60/70, the most widely used in Spain, obtaining the optimum asphalt binder content by the Marshall method (EN 12697-30, 2007) by analyzing air voids (EN 12697-8, 2003) in a Reference mix (R mix) manufactured at 160ºC, leading to 4.85% w/m. This optimal binder content was used in the manufacture of all the mixes studied.

Different types of mixes were analyzed, Reference mix (R mix) with unchanged conventional bitumen and three mixtures with additives (A1-A2-A3). The characteristics of the additives used are:

- A1: a surfactant, made up of different amino substances, which improves the adhesion between aggregate and bitumen. This additive is added to the bitumen in a ratio of 0.3-1% in weight of binder (w/b) according to the type of bitumen.
- A2: Paraffin obtained by the Fischer-Tropsch synthesis process, which is totally soluble in bitumen. This product reduces the binder viscosity at low temperatures, improving the compactability of the mix and increasing the resistance to surface deformation. The amount of product added to the bitumen is 3% w/b.
- A3: a synthetic zeolite in powder form with a proportion of 21% by mass in water, which causes the bitumen to micro-foam, thus improving the manageability of the mix and the laying process.0.3% by mass of the total mix (w/m) is added.

These different commercial additives were added in the amounts recommended by the manufacturers: for A1 0.4%w/b, for A2 3% w/b and for A6 0.3% w/m.

2.2. Compaction design

Two different methods of compaction were utilized, impact compaction (the Marshall method) and gyratory compaction. To analyze the effect of the type of compaction, work temperatures and the use of additives, other variables such as the type of aggregates and gradation, and type and percentage of bitumen were maintained constant. First, Marshall-type specimens (diameter 101.6mm, height 63.5mm) at different numbers of blows depending on the test (50blows/face for water sensitivity and 75 blows/face for stiffness modulus) were manufactured at different temperatures and with different types of additive. They were then tested according to the European standards 12697-12 (2006) and 12697-26 (2006), respectively.

In the case of the specimens manufactured with the gyratory machine (diameter=100.0 mm), instead of determining the optimum asphalt binder content according to the Superpave method, the bulk specific gravities by physical dimensions of Marshall-type specimens were calculated (EN 12697-6 2007), using them to determine the limit of compaction (Table 2).

Table 2. Specific gravities with the gyratory compactor at different temperatures, (g/cm^3).

Mix	Test	160º	140º	120º
R	Water sensitivity	2.447	2.424	2.412
	Stiffness	2.488	2.461	2.441
A1	Water sensitivity	2.430	2.411	2.410
	Stiffness	2.462	2.460	2.455
A2	Water sensitivity	2.471	2.461	2.459
	Stiffness	2.493	2.489	2.480
A3	Water sensitivity	2.469	2.464	2.432
	Stiffness	2.486	2.471	2.469

In this way the effect of laying the bituminous mixes on the mechanical properties can be compared, without taking into account more variables, such as the binder percentage, which in the case of gyratory compaction, tends to be greater than for the Marshall method for the same aggregate gradation (Anjan & Veeraragavan, 2010). In the gyratory compaction, a vertical pressure of 600kPa, with a compaction angle of 0.82º and a speed of 30 rpm were applied as indicated by the European Standard EN 12697-31 (2008).

2.3. Water sensitivity test

According to the procedure of the EN 12697-12 standard (2006), a study of binder-aggregate adhesion was done. This test analyzes the impact of the saturation and immersion of the mix in water on the resistance to indirect tensile strength in Marshall-type specimens. In Spain, the norm requires a water resistance of at least 85% for mixtures for the surface layer, and 80% in the case of base or intermediate layers, tested at 15ºC (PG-3, 2008).

Eight samples of AC16Surf B60/70 were produced for every type of mix, at the three temperatures studied and with each type of compaction, making up a total of 192 specimens. Each group of 8 samples was subsequently separated into two groups in order to obtain a similar density. One of the groups was kept for three days in a room at 20ºC and the other was submerged in water at 40ºC for three days after a vacuum treatment for 40 minutes, as the standard establishes (Figure 1). After three days, the mixes were put into a room at 15ºC for two hours prior to the test. Then, an indirect tensile strength test was performed on both groups of specimens, according to EN 12697-23 (2004), using a universal static machine.

From the stability of the indirect tensile strength test (Figure 2), the resistance to traction of the specimens kept dry (ITSd) and wet (ITSw) was calculated. The Indirect Tensile Strength Ratio (ITSR) was calculated from these values, and it is obtained by dividing (ITSw) between (ITSd).

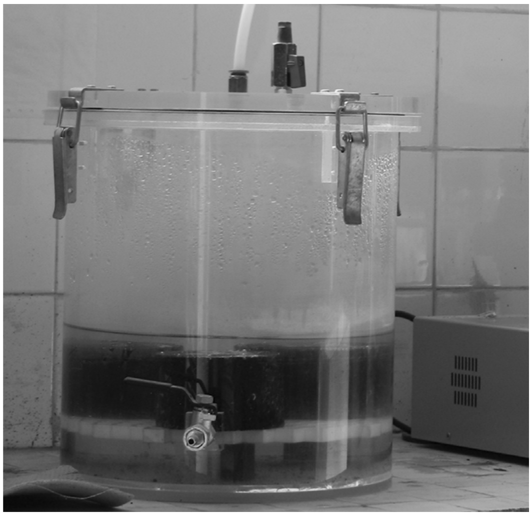

Fig. 1. Wet specimens.

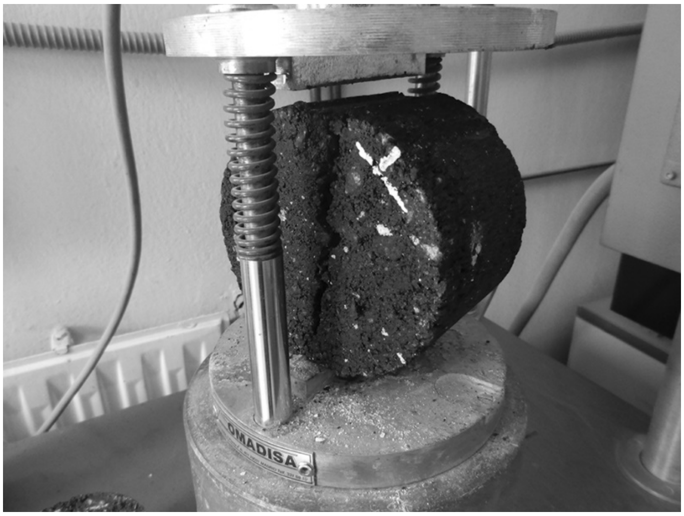

Fig. 2: Indirect tensile strength

2.4. Stiffness test

The measurement of the stiffness modulus is one of the methods used to understand the structural behaviour of bituminous mixes in roads. The stiffness modulus of the mixes has been calculated at a test temperature of 20ºC as indicated in the Spanish standard (PG-3, 2008), by the indirect tensile test (IT-CY), specified in annex C of the European norm EN 12697-26 (2006). To carry out the test, a dynamic machine with a load cell of 10kN was used.

Four cylindrical AC16Surf B60/70-type specimens were produced for every type of mixture, working temperature and type of compaction, rising to 96 samples manufactured. As specified in the norm, the samples were kept at a constant temperature of 20ºC in an air conditioned room for a period of at least 24 hours before testing.

The indirect tensile strength test was performed, applying a vertical compression load, and measuring the horizontal deformation undergone by the specimen (Figure3). Each test consisted of 16 load cycles of 3s each, using the cycles from 11 to 15 for the stiffness modulus calculation, being the previous considered as necessary for sample settling. Finally, the stiffness modulus was estimated with the maximum amplitude of the elastic deformation obtained in each one, subsequently the average of the stiffness moduli of the five cycles were calculated (EN 12697-26, 2006).

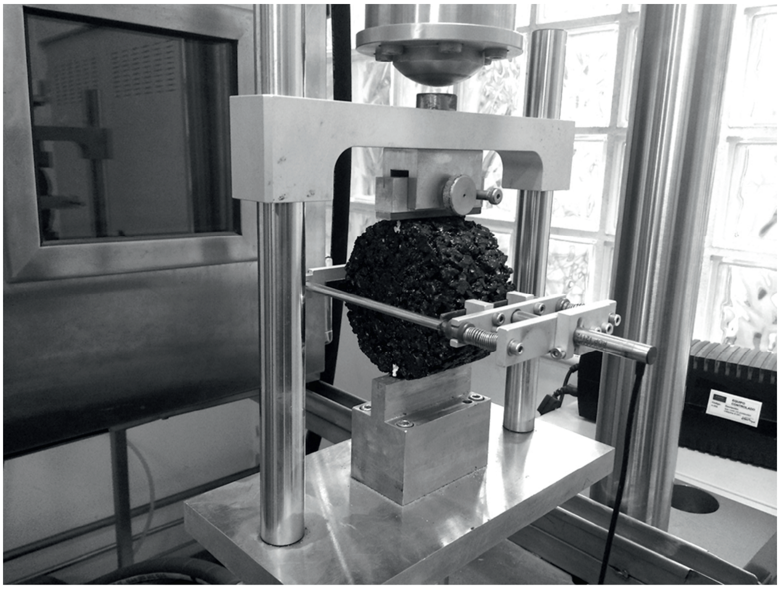

Fig. 3. Stiffness test.

3. Results

3.1. Water sensitivity

The results of %ITSR obtained for each combination of temperature, mix and type of compaction are shown in Table 3.

Table 3. Water sensivity results (%).

Mix	Marshall			Gyratory compactor		
	160ºC	140ºC	120ºC	160ºC	140ºC	120ºC
R	85	68	56	94	94	82
A1	91	80	70	98	94	81
A2	86	85	88	96	94	97
A3	85	77	63	96	95	93

In the case of the compaction by the Marshall method, all mixtures with additives improved the adhesion of the reference mixture for all test temperatures. At the temperature of manufacture and compaction of 160°C, usual conditions of manufacture in work, the chemical additive (A1) has improved the water sensitivity with regard to the reference mix (R). Mixtures with paraffin and zeolite reached the same indirect tensile strength ratio than the reference mixture at 160ºC. Decreasing manufacturing temperatures, mixtures (A2) compacted by impact method, were the only one that complied the corresponding conserved resistance in surface layer, at 140°C and 120°C. The organic additive (A2) is completely soluble in bitumen, creating a crystalline structure when the bituminous mix is cool, adding stability and improving the ITSw and ITSd values, and therefore, the ITSR ratio, compared to R mix at the same temperature. Mixtures (A1) complied the normative values for base layer and binder layer at 140º C. In the case of chemical additive (A1), his surfactant nature modified the aggregate-bitumen interfacial tension and improved the binder’s resistance to displacement by water (Castaño, Ferré, Fossas, & 2004). The mixes with zeolites

(A3) did not comply the Spanish specifications at temperatures below 160°C. The zeolite does not melt at the manufacturing temperatures of the mixes, so its effect on the %ITSR could be due to the reduction of the air void content

Comparing both compaction methods, mixes manufactured by gyratory compactor were less resistant to indirect traction, both in wet and dry specimens, to its homologous Marshall, although not its relationship. This difference could be associated with the better accommodation of the aggregates inside the mix due to the effect of kneading during the compaction process. Most of the compacted mixtures with the gyratory machine reached ITSR greater than 85%, with the exception of the reference (R) and the mixture (A1) both at 120 °C, which reached 82% and 81% ITSR, minimum value required for base layer and binder layer.

3.2. Stiffness modulus

In the case of Marshall compaction, it was observed that for R mixes, when reducing the manufacturing and compaction temperatures their stiffness moduli decreased, getting at 120ºC about half the value obtained at 160ºC. The use of different additives reduced the stiffness modulus of the mix by 20% to 40% compared to R mix at 160ºC. Comparing the stiffness moduli of the different mixes with additives at different working temperatures, it can be appreciated that the changes in their values were lower than those produced in R mix. It is interesting that additives A5 and A6 showed a greater stiffness when reducing the working temperature than R mix.

Using gyratory compaction, the stiffness moduli obtained by R mix at the three temperatures studied were closer to each other than in the case of the impact method. With the use of additives, the stiffness moduli values were closer to those of R mixes at the three temperatures. In this case, mixtures A2 produced a greater stiffness modulus than R mix when the working temperature is reduced.

With the two compaction methods, increasing the percentage of air voids by reducing the working temperature causes the stiffness modulus to decrease, which is logical because as the percentage of air voids in the mix increases, the mix becomes less rigid

The results of stiffness modulus obtained for each combination of temperature, mix and type of compaction are shown in Table 4.

Table 4. Stiffness modulus results (MPa).

Mix	Marshall			Gyratory compactor		
	160ºC	140ºC	120ºC	160ºC	140ºC	120ºC
R	9870	7996	4733	7221	5259	4850
A1	5862	5700	5255	5673	4992	4716
A2	8117	8088	7850	7834	7377	7074
A3	7263	7070	6019	7190	5900	4798

4. Conclusions

The influence of compaction on the mechanical properties of bituminous mixes has been studied in combination with the effect of manufacture and compaction temperature and the use of warm additives that help to reduce the working temperatures. The following conclusions were obtained from the data collected and the analysis of the results.

The samples made for water sensitivity test are less dense than samples made for rigidity test, because first they are compacted with 50 blows by face, and in the second case with 75 blows by face.

Comparing the two types of compaction, the gyratory samples achieved higher ITSR percentages than their Marshall counterparts, due to the different percentage of air voids obtained.

The additives improve sensitivity to the water with respect to a conventional mixture of reference at the same temperature due to the improvement of the adhesion. In the case of the gyratory compactor, all samples reached the values indicated by the Spanish normative.

The mixtures with paraffin obtained the values of adhesion for surface layers and binder layers at the three temperatures.

In the case of the study of the stiffness moduli at 20ºC, the mixtures made with the gyratory compactor are less rigid than their homologous Marshall, due to the effect of kneaded and position of the particles that take place during the compaction.

In the case of the influence of the temperature of manufacture and compaction, it has been verified that the module of the mixtures of Reference decreases in both types of compaction when the temperature is lower, being in the case of the gyratory machine a variation less accusing. In the case of the compaction by impact, the additives produce a smaller variation of the module with the temperature that the mixture of Reference, however with the gyratory machine the modules of the mixtures with additives are similar to those of Reference at the same temperatures.

In both tests, sensitivity to the water and the measurement of the stiffness modulus, influence the type of compaction, the temperatures of manufacture and compaction, and the nature of the used additive.

Acknowledgements

This paper is based on the results for the Fenix Project. The development of the Fenix Project was possible thanks to the financial contribution of the Center for Technological and Industrial Development (CDTI) within the framework of the Ingenio 2010 programme, through the CENIT Programme. The companies and research centers involved in the project wish to express their gratitude for the contribution. The authors are grateful to all organizations and companies participating in the Fenix Project: Centro de Investigación Elpidio Sánchez Marcos (CIESM), Centro Zaragoza, Construcciones y Obras Llorente (Collosa), Ditecpesa, Asfaltos y Construcciones Elsan, Intrame, Pavasal, Repsol YPF, Sacyr, Serviá Cantó, Sorigué, CARTIF, CEDEX, CIDAUT, CSIC (IIQAB), GIASA, Intromac, Labein, Universidad de Alcalá de Henares, Universidad Carlos III de Madrid, Universidad de Castilla La Mancha, Universidad de Huelva, Universidad de Cantabria, Universidad Politécnica de Cataluña, Universidad Politécnica de Madrid, and our many partners whose work capacity and effectiveness have enabled the development of this project in an environment of cooperation.

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