



## MECHANICAL PERFORMANCE OF ASPHALT MIXES INCORPORATING WASTE GLASS

Fernando Moreno-Navarro<sup>1</sup>, Miguel Pérez-Martínez<sup>2</sup>, Jesús Martín-Marín<sup>3</sup>,  
Miguel Sol-Sánchez<sup>4</sup>, María del Carmen Rubio-Gámez<sup>5</sup>✉

Laboratory of Construction Engineering of the University of Granada (LabIC.UGR),  
School of Civil Engineering Avda, Severo Ochoa, s/n C.P., 18071 Granada, Spain  
E-mails: <sup>1</sup>fmoreno@ugr.es; <sup>2</sup>mperez@ugr.es; <sup>3</sup>jesusmm@ugr.es; <sup>4</sup>msol@ugr.es; <sup>5</sup>mcrubio@ugr.es

**Abstract.** This paper shows the results obtained in a research project that analyzes the mechanical performance of asphalt concrete containing waste glass as a substitute of part of the aggregate. The mechanical performance of an AC16S asphalt mix with different percentages of glass (0%, 8% and 15%) and different types of filler was assessed with the moisture sensitivity test, the stiffness modulus test, and the cyclic triaxial compression test in order to analyze their response to moisture action and plastic deformation as well as to calculate their stiffness modulus. Results show that the reuse of waste glass as a substitute for the sand fraction in low dosages (8%) produced asphalt mixes with mechanical properties that were suitable for road surfaces course, being the calcium carbonate the more appropriate filler.

**Keywords:** asphalt mixes, mechanical performance, waste glass.

### 1. Introduction

Road engineering consumes large quantities of natural resources, which has a major impact on the environment. With a view to minimizing adverse environmental impacts, new construction techniques that permit the recycling of waste materials as a substitute for the raw materials used in road building (Huang *et al.* 2007; Sanchez-Alonso *et al.* 2011; Tam, V. W. Y., Tam. C. M. 2006) have been developed. Among the different experiences, the use of waste glass is highlighted as an alternative to natural aggregates in the manufacture of asphalt mixes (Airey *et al.* 2004; Arabani 2011). The recycling of this waste material as aggregate in asphalt mixes has been a practice for the last decades (Malisch *et al.* 1975).

It is generally the case that after being cleaned and disinfected, waste glass is recycled to make new containers. However, this solution is not always viable because of the deterioration often suffered by the waste glass during collection and storage. Given that glass is an inorganic material of great compressive strength, it is a very competitive alternative in order to be reused as a component in asphalt mixes or cement concrete, as a decorative element, as a filter medium, or as binder in bricks and ceramics (Dyer, Dhir 2004; Karamberi *et al.* 2006; Sobolev *et al.* 2007).

The particle size of the glass in the road surface course is generally smaller than 4.75 mm (Michael *et al.* 2002)

though in some cases, it is 9.5–15.3 mm in mixes used for the base layers. Nevertheless, certain authors recommend the use of fine particles since in this case, particle surfaces are more fragmented and slightly rougher, which causes them to adhere better to the binder (Wu *et al.* 2005). Furthermore, the use of larger particles causes tire abrasion and increase risk of puncture (Huang *et al.* 2007); reduce resistance to skidding (Wu *et al.* 2005) and produce problems during the road construction project due to the fracture of glass particles during mix compaction (Malisch *et al.* 1975).

Most researchers recommend the use of glass as a substitute for natural aggregate in percentages lower than 15% for upper asphalt pavements (Wu *et al.* 2005) despite the fact that certain projects have used dosages of up to 30% of the aggregate weight in base layer mixes (Nicholls, Lay 2002). The main reason for limiting the quantity of this waste material in the mix is that a large quantity of glass produces a corresponding reduction in certain mix properties such as stability (Su, Chen 2002), stiffness (Arabani 2011), resistance to plastic deformations (Wu *et al.* 2005), and indirect tensile strength (Airey *et al.* 2004).

In addition to the significant environmental benefits stemming from the use of this waste material in asphalt mixes, it has other advantages as well. For example, the reuse of waste glass in mixes improves night-time visibility since it increases the amount and intensity of the light

reflection on the road surface (Michael *et al.* 2002; Su, Chen 2002). Moreover, it has also been found that certain glass particle sizes improve skid resistance (Day, Schaffer 1994; Malisch *et al.* 1975).

Nevertheless, despite these advantages, there are still problems that limit a more widespread use of waste glass in asphalt mixes. These are related to stripping, especially when in the presence of water (Hughes 1990; Su, Chen 2002). The smooth surface of the glass particles and their low adhesion to the asphalt binder facilitates detachment, thus contributing to the rapid degradation of the bituminous material. This is avoided by using chemical anti-stripping additives or hydrated limestone (Arabani 2011), which reduces stripping by improving mix cohesion. This improves mix resistance to plastic deformations and enhances its stiffness (Wu *et al.* 2005).

## 2. Objectives

This research was conducted to advance and foment the reuse of waste glass as a substitute for natural aggregate in asphalt mixes. The objective of the study was to evaluate the mechanical performance of mixes with different percentages of glass (0%, 8%, and 15%) and also to analyze the filler type used since this directly affects mix cohesion. For this purpose, calcium carbonate filler and cement filler were compared with a view to analyzing the anti-stripping properties of the cement, whose pozzolanic nature would presumably enhance mix cohesion even in the presence of water.

## 3. Methodology

The methodology followed to achieve the considered objectives started with the Marshall test according to NLT-159 Standard for Road Tests of the Spanish Road Study Center. It was used to determine the optimum bitumen content in weight of mixture of each of the job mix formulas. The mechanical performance of the mixes was assessed with the moisture sensitivity test by EN 12697-12:2003 *Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 12: Determination of the Water Sensitivity of Bituminous Specimens*, the stiffness modulus test by EN 12697-26:2004 *Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 26: Stiffness*, and the cyclic triaxial compression test by EN 12697-2:2002+A1:2007 *Bituminous Mixtures – Test Method for Hot Mix Asphalt – Part 2: Determination of Particle Size Distribution*. These tests were used to compare asphalt mixes that varied in waste glass dosage and filler type in order to analyze their response to moisture action and plastic deformation as well as to calculate their stiffness modulus.

### 3.1. Materials

The asphalt mix used in this study was asphalt concrete AC16S for the surface course according to Spanish regulations *Dirección General de Carreteras 2008: Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes PG-3*, which is found in roads and highways all over the world. The aggregates in all of the mixes were

ophite for the coarse fraction (12/18 and 6/12), and limestone for the fine fraction (0/6). Table 1 lists the aggregate properties. The binder used was conventional 50/70 bitumen with a penetration value (EN 1426:2007 *Bitumen and Bituminous Binders – Determination of Needle Penetration*) of 68 mm and a softening point (EN 1427:2007 *Bitumen and Bituminous Binders – Determination of the Softening Point – Ring and Ball Method*) of 48.1 °C. Table 1 shows the characteristics of the calcium carbonate and cement filler.

The waste glass in this study came from the decoration industry and had a maximum particle size of 5 mm, a porosity of 0.3%, and a density of 2.5 g/cm<sup>3</sup>. This waste was used in the mix as a substitute for the fine fraction. The grain-size characteristics of the glass are listed in Table 1.

### 3.2. Test program

This research study analyzed the impact of filler type and waste glass dosage on the mechanical performance of asphalt mixes. Accordingly, 6 AC16S job mix formulas were designed with 2 different fillers (cement and calcium carbonate) and different percentages of waste glass (0%, 8%, and 15% of the total weight of the mix).

In the 1<sup>st</sup> phase of the study, the mixes were designed and the optimum bitumen content was determined. Since the Marshall test, developed according to NLT-159, was used for this purpose, 3 sets of 3 test cylinders were manufactured. Each cylinder had a diameter of 101.6 mm and a height of 63.5 mm, and each set of cylinders had a different percentage of bitumen (4%, 4.5%, and 5%). For each bitumen dosage, the mean value of the following parameters was calculated:

- voids in the mineral aggregate in %;
- voids in the asphalt mix in %;
- bulk density in g/cm<sup>3</sup>;
- deformation in mm;
- stability in kN.

These values determined the optimum bitumen content in the following tests to evaluate the mechanical performance of each job mix formula.

The first of these tests was the moisture sensitivity test by EN 12697-12:2003 *Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 12: Determination of the Water Sensitivity of Bituminous Specimens*, which was used to ascertain the effect of the filler type and waste glass percentage on the cohesion of the mixes in the presence of water. The moisture sensitivity test involved the manufacture of 6 test cylinders with a diameter of 101.6 mm and a thickness of 60 mm, compacted with 50 blows on each side by a Marshall hammer. The cylinders were subsequently divided into 2 sets of 3 cylinders: a dry set and a wet set. The set of dry cylinders was stored at room temperature in the laboratory (20±5 °C), whereas a vacuum was applied to the wet set for 30±5 min until a pressure of 6.7±0.3 kPa was obtained. The cylinders were then immersed in water at a temperature of 40 °C over a period of 72 h.

The next step was to perform an indirect tensile strength test on each set. This was done at a temperature of 15 °C, and after a previous adjustment period of 120 min

to this temperature. The results of the experiment are expressed in terms of the retained strength of the test cylinders after dividing the mean strength of the wet cylinders into the mean strength of the dry cylinders (ITSR, %).

The study of the mechanical performance of the mixes was completed by analyzing their stiffness, in reference to the EN 12697-26:2004, at different temperatures (5 °C, 20 °C and 40 °C). The cyclic triaxial compression test according to EN 12697-2:2002+A1:2007 was also applied to assess their resistance to plastic deformations. In this way, it was possible to analyze the impact of the waste glass dosage and filler type on the bearing capacity of the mixes as well as their resistance to plastic deformations.

The stiffness modulus test involved the manufacture of test cylinders for each of the job mix formulas. These specimens had a diameter of 101.6 mm and a thickness of 60 mm, and were compacted with 75 blows on each side by an impact compactor. The stiffness modulus was determined by applying a series of 15 indirect-tensile

haversine-shaped load pulses lasting 3 s each. The first 10 pulses helped the specimens adjust to the load intensity and duration. The following five pulses determined the stiffness modulus of mix, which was calculated as the mean value of the 5 pulses. After this value was determined, the cylinder was turned so that the modulus of the perpendicular diameter was also calculated. If this value was not 80–110% of the first value, the test was not considered valid. The final stiffness modulus value was the mean of the two diameters.

The cyclic triaxial compression test involved the combined application at a constant temperature of 40 °C of a confining load of 120 kPa and another cyclic sinusoidal out-of-phase axial loading of 300 kPa at a frequency of 3 Hz during 12 000 load cycles. For this test, 2 test cylinders were manufactured for each job mix formula with a diameter of 101.6 mm and a sawed-off height of 50 mm. The creep and permanent deformation parameters for each mix were calculated as the mean of the values obtained for

**Table 1.** Reference values of the aggregates, mineral dust, and waste

Test	Sieve, mm	Coarse aggregate ophite		Fine aggregate limestone	Cement filler	Carbonate filler	Waste glass
		12/18	6/12	0/6			0/5
	22.4	100	100	100	100	100	100
	16	50	100	100	100	100	100
	8	0	33	100	100	100	100
Aggregate size, percentage passing, % (EN 933-1:2012)*	4	0	2	86	100	100	84
	2	0	1	62	100	100	9
	0.500	0	1	26	100	100	2
	0.250	0	1	18	–	–	1
	0.063	0.1	0.8	12.1	98	75	0.2
Percentage of fractured face, % (EN 933-5:1998)*		–	99	–	–	–	–
Flakiness index, % (EN 933-3:1997)*		2.62	20	–	–	–	–
Resistance to fragmentation (L.A.), % (EN 1097-2:1998)*		–	11	–	–	–	–
Cleaning (organic impurity content), % (UNE-EN 13043:2003)*		0.01	0.04	–	–	–	–
Relative density and absorption (EN 1097-6:2000)*	Bulk density, g/cm <sup>3</sup>	2.89	2.87	2.74	–	–	–
	DSSS, g/cm <sup>3</sup>	2.84	2.78	2.70	–	–	–
	Density after drying, g/cm <sup>3</sup>	2.82	2.73	2.68	–	–	–
	Water absorption after immersion, %	0.86	1.87	0.84	–	–	–
Sand equivalent, % (EN 933-8:1999)*		–	–	78	–	–	–
Bulk density, g/cm <sup>3</sup> (NLT-176/92)*		–	–	–	0.7	0.6	2.5

\* EN 933-1:2012 Tests for Geometrical Properties of Aggregates – Part 1: Determination of Particle Size Distribution – Sieving Method; EN 933-5:1998 Tests for Geometrical Properties of Aggregates – Part 5: Determination of Percentage of Crushed and Broken Surfaces in Coarse Aggregate Particles; EN 933-3:1997 Tests for Geometrical Properties of Aggregates – Part 3: Determination of Particle Shape – Flakiness Index; EN 1097-2:1998 Tests for Mechanical and Physical Properties of Aggregates – Part 2: Methods for the Determination of Resistance to Fragmentation; UNE-EN 13043:2003 Áridos para mezclas bituminosas y tratamientos superficiales de carreteras, aeropuertos y otras zonas pavimentadas [Aggregates for Bituminous Mixtures and Surface Treatments for Roads, Airfields and Other Trafficked Areas] (Spanish standard); EN 1097-6:2000, EN 1097-6:2000/AC:2002 Tests for Mechanical and Physical Properties of Aggregates – Part 6: Determination of Particle Density and Water Absorption; EN 933-8:1999 Test for Geometrical Properties of Aggregates – Part 8: Assessment of Fines – Sand Equivalent Test; NLT-176/9. Densidad aparente del polvo mineral en toluene [Bulk Density of the Mineral Powder in Toluene (Spanish standard)]

each pair of test specimens. Table 2 lists the tests performed during this research and the types of mixes studied.

#### 4. Discussion of results

To compare the effect of the filler, the mixes studied had the same mineral skeleton and only varied in the percentage of filler added (depending on the grain-size characteristics of each one) in order to comply with the grain envelopes required by Spanish regulations *PG-3 General Technical Specifications for Construction of Roads and*

*Bridges* for AC16S mixes. Table 3 shows the grain sizes of each of the mixes in this research study.

#### 4.1. Marshall test

The Marshall test' results in regards to the optimum bitumen content of the mixes are shown in Table 4. As the table shows, the optimum amount of binder had to be increased with higher waste glass percentages. The lack of adhesion between the glass particles made it necessary to increase the percentage of binder in order to improve the properties

**Table 2.** Mix types

Asphalt mix	Glass, %	Filler	Tests for each mix
AC 16 S Car	0	Calcium carbonate	Marshall Test
AC 16 S Car8%G	8	Calcium carbonate	Water Sensitivity Test
AC 16 S Car15%G	15	Calcium carbonate	
AC 16 S Cem	0	Cement	Stiffness Test
AC 16 S Cem8%G	8	Cement	Cyclic Triaxial Compression Test
AC 16 S Cem15%G	15	Cement	

Note: the name of each mix indicates the asphalt mix type (AC 16 S), the type of filler used, and the content of glass

**Table 3.** Aggregate size and percentage shared of the job mix formulas

Mix/Sieves	Combined geometry					
	AC 16 S Car	AC 16 S Car8%G	AC 16 S Car15%G	AC 16 S Cem	AC 16 S Cem8%G	AC 16 S Cem15%G
22.4	100	100	100	100	100	100
16	91	95	95	91	95	95
8	60	63	63	60	63	63
4	42	43	43	42	43	43
2	29	28	26	28	28	26
0.500	12	12	11	11	12	11
0.250	8	9	8	7	9	8
0.063	3.8	4.5	4.5	3.9	5.9	5.4
Percentage shared of each component						
Ophite 12/18	18	10	10	18	10	10.0
Ophite 6/12	33	40	49	33	40	40.0
Limestone 0/6	44	36	29	45	36	29.5
Filler	5	6	6	4	6	5.5

**Table 4.** Marshall test results

Mix/Test	Optimum bitumen content, %	Bulk density, g/cm <sup>3</sup>	Voids in the mix, %	Voids in the mineral aggregate, %	Marshall stability, kN	Marshall deformation, mm
AC 16 S Car	4.0	2.477	3.6	13.1	12.731	1.5
AC 16 S Car8%G	4.5	2.473	4.7	14.3	9.391	2.1
AC 16 S Car15%G	4.8	2.456	4.4	15.8	6.610	2.9
AC 16 S Cem	4.0	2.426	5.3	14.8	10.359	2.0
AC 16 S Cem8%G	4.5	2.446	5.7	16.4	8.418	2.1
AC 16 S Cem15%G	5.0	2.416	5.7	17.4	5.904	2.3

of the mix. When the bitumen content was higher than the optimum amount, there were indications of creep because of the saturation of the mix. This occurred because the waste glass lacked porosity, and its smooth surface meant that the binder film was not as thick as that of the aggregates, which caused its migration.

Despite the fact that the bitumen content and mineral skeletons were similar in the different waste glass percentages, there were fewer voids in the calcium carbonate mixes than in the cement mixes. The densities obtained with both types of filler were very similar while the mixes with more waste glass had a higher percentage of voids and were of lower density. This is possibly due to compaction problems associated with mixes manufactured with glass (Hughes 1990).

The Marshall strength' values show that there was slightly more deformation with greater quantities of waste glass (which is normal since the bitumen content was also somewhat higher). In contrast, as also observed by other authors (Su, Chen 2002; Wu *et al.* 2005), higher percentages of waste glass caused mix stability to decrease since the glass reduced mix cohesion. The deformation values were the same though the Marshall stability of the calcium carbonate mixes was higher than that of the cement mixes.

#### 4.2. Moisture sensitivity test

The specimens manufactured with the optimum bitumen percentages determined by the Marshall test were then evaluated for moisture sensitivity. Table 5 shows the density and strength values obtained in this test.

In the same way as in the Marshall test, the results showed that the density of the cylinders decreased as more waste glass was added to the mix. This was due to the compaction problems described in the previous section. Furthermore, the densities of the cement mixes and the calcium carbonate mixes were again very similar. This seemed to indicate that the nature of the filler did not affect the compactability of the mix.

In consonance with Wu *et al.* (2005), the indirect tensile strength of the mixes decreased as more glass was added. This tendency regarding mix strength coincided with that observed in the Marshall test. Accordingly, the calcium carbonate mixes were found to be slightly stronger than the cement mixes. However, in the presence of water, the cement filler reduced the moisture sensitivity of the

mixes, thus increasing their retained strength. A possible reason for this is that cement has greater binding power when it comes in contact with water, and this increases the cohesion of the asphalt mastic.

#### 4.3. Stiffness modulus test

Another important aspect of the mechanical performance of the mixes is their stiffness modulus, which provides information about their bearing capacity and flexibility. In this respect, results showed that the stiffness modulus tended to increase as more waste glass was added to the mix, as was also the case in Arabani (2011) (Figs 1 and 2). This occurred because of the compressive strength of the waste glass, which provided the mix with greater bearing capacity.

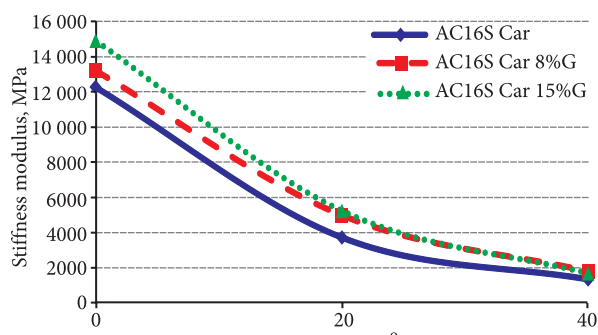


Fig. 1. Variation of the stiffness modulus of the carbonate samples with temperature

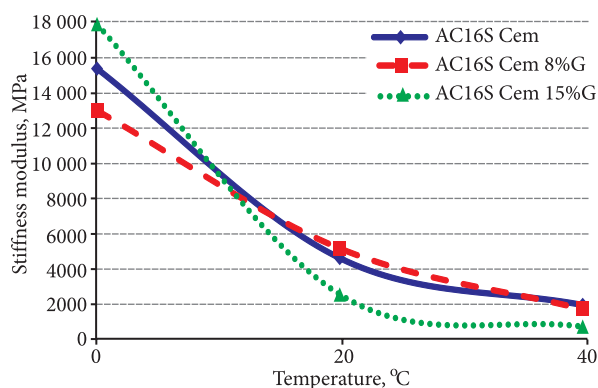


Fig. 2. Variation of the stiffness modulus of the cement samples with temperature.

Table 5. Moisture sensitivity test results

Mix/Test	Density		Voids in the mix, %	Voids filled by binder, %	ITSR*		ITSR,* %
	Dry group, g/cm <sup>3</sup>	Wet group, g/cm <sup>3</sup>			Dry group %	Wet Group %	
AC 16 S Car	2.467	2.460	4.0	70.5	2199.8	1660.7	75
AC 16 S Car8%G	2.411	2.410	6.8	60.6	1507.5	1287.7	85
AC 16 S Car15%G	2.397	2.392	3.4	76.9	1690.7	1272.0	75
AC 16 S Cem	2.452	2.452	4.3	68.7	1821.0	1428.3	79
AC 16 S Cem8%G	2.431	2.428	6.0	63.8	1508.0	1508.0	100
AC 16 S Cem15%G	2.422	2.409	5.7	67.4	1429.3	1243.2	87

\*ITSR – Indirect Tensile Strength Ratio

Results also showed that the choice of filler had little effect on the stiffness modulus. In this sense, the mix components with the highest impact were the aggregates. The filler fraction was thus not very important though the mixes with cement filler had a stiffness modulus that was slightly higher than the mixes with calcium carbonate filler.

Despite the acknowledged importance of the aggregate in regards to stiffness, in most cases, neither the addition of waste glass nor the filler type had a significant effect on the stiffness modulus. In this sense, as the service temperature of the mixes increased, the influence of the waste glass and filler type decreased, as reflected in the similarity of their stiffness modulus.

#### 4.4. Cyclic triaxial compression test

The cyclic triaxial compression test evaluates the plastic deformations of mixes by reproducing the traffic loads transmitted by the repeated passing of vehicles. At the same time it takes the service stresses and strains into account by means of a confining load. The plastic deformation results obtained in the cyclic triaxial compression test (Fig. 3) showed that there was slightly less plastic deformation when small amounts of glass were added to the mix. This was due to the strength of this material when subjected to compressive forces and repeated loads (which increased its creep modulus). Nevertheless, the addition of more waste glass increased deformations (to levels similar to those of the reference mix) because the previously mentioned compressive strength was counteracted by a reduction in internal cohesiveness caused by the addition of higher percentages of waste glass (in the same way as in the moisture sensitivity test).

The effect of filler type on mix response to plastic deformations was insignificant. Both fillers had very similar values though those of the calcium carbonate mixes were slightly better because the mastic was more cohesive.

#### 5. Conclusions

This paper has described the results obtained in a research study that evaluated the mechanical performance of asphalt mixes manufactured with waste glass as a substitute for the fine fraction of natural aggregate. It also analyzed the influence of the filler type used. The results obtained led to the following conclusions:

1. A larger dosage of waste glass required a correspondingly larger dosage of bitumen in order to optimize the mechanical properties of the mix. Moreover, the greater the amount of glass in the mix, the lower was its density. This means that the mix had more air voids because of compactability problems.

2. The higher waste glass dosage studied considerably reduced the indirect tensile strength of the mixes as well as their stability; there is less adhesion between the waste glass and the binder, which reduced the internal cohesion of the mixes and made them lose strength as the percentage of waste glass increased.

3. The use of calcium carbonate filler produced more cohesive asphalt mastic that improved the strength of the mixes manufactured with glass in comparison to those with cement filler. Nevertheless, in the presence of moisture, the retained strength of the cement mixes was greater because of the greater binding power of cement when it came into contact with water (thus improving adhesiveness).

4. A higher waste glass dosage in the mixes produced an increase in stiffness. This was due to the compressive strength of the glass, which gave the mix a greater bearing capacity. The type of filler used did not significantly affect this mechanical property.

5. The use of waste glass to replace the fine fraction of the natural aggregate did not significantly affect the performance of the mixes in terms of their resistance to plastic deformation. However, the mixes with lower waste glass percentages were more resistant to deformation (because of the strength of glass when subjected to compressive forces and repeated loads). When the waste glass dosage was higher, this positive effect was cancelled out by the loss of mix cohesion.

6. Finally, regardless of the type of filler used, the reuse of waste glass as a substitute for the sand fraction in low dosages (8%) produced asphalt mixes with mechanical properties that were suitable for road surfaces courses.

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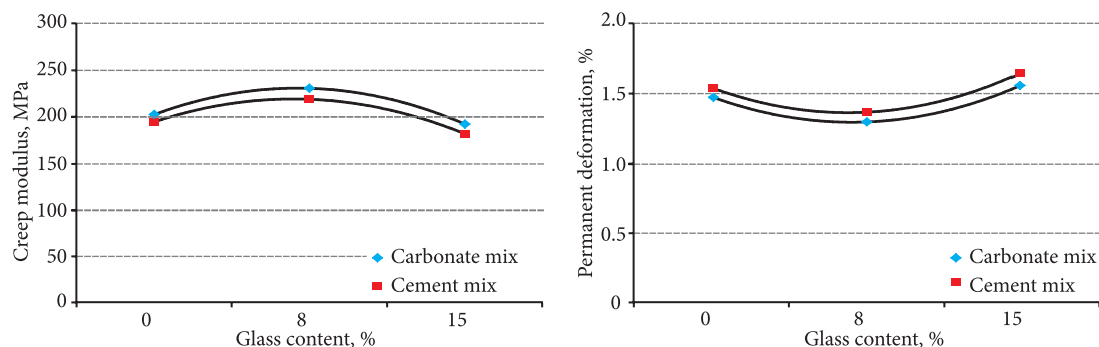


Fig. 3. Results of the cyclic triaxial compression test

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