WASTE MATERIALS IN CONCRETE – ACCEPTABLE DETERIORATION OR IMPROVEMENT?

Ing. Ján Jerga, PhD.
Institute of Construction and Architecture of the Slovak Academy of Sciences, Dúbravská cesta 9, 845 03 Bratislava, Slovakia, jan.jerga@savba.sk

Ing. Martin Križma, PhD.
Institute of Construction and Architecture of the Slovak Academy of Sciences, Dúbravská cesta 9, 845 03 Bratislava, Slovakia, martin.krizma@savba.sk

Ing. Terezia Nürnbergerová, PhD.
Institute of Construction and Architecture of the Slovak Academy of Sciences, Dúbravská cesta 9, 845 03 Bratislava, Slovakia, terezia.nurnbergerova@savba.sk

Summary

Systematic search is performed in the last years on the topic of mineral aggregate replacement in concrete by waste products. Polystyrene beads from waste packing, so as particles from tire rubber belong to the most used, recently also the electrical and electronic equipment waste. By the analysis of requirement for structural application it is shown, that a deliberate addition of waste could proper modify the mechanical and physical properties of concrete. So the replacement of mineral aggregate by the waste products could lead to the reaching of required properties and need not be regarded from the standpoint of acceptable deterioration. Finally the use of vegetable fibres (waste at production of paper, cloth, or rope) is discussed.

Keywords: waste, polystyrene beads, tire rubber, electrical and electronic equipment waste, concrete

1 Introduction

The utilization of waste materials in concrete has a longer tradition than we realize. Originally it was a question of feeling of builder, how much of used bricks or stones will the mixture tolerate, with respect to the purpose of the structural element (e.g. massive foundations). The present industry with its huge production of waste requires systematic, sophisticated attitude. It is the question of analysis of resulting properties of cement composite material, which should satisfy usually to a variety of demands. The strength alone is often not the principal one. Many concrete elements and structures should dispose of the ability e.g. to absorb noise, absorb energy at the cars crash or restrict the thermal conduction. Required properties could be achieved by the replacement of mineral aggregate with waste products. It could be the rubber particles from waste tires, polystyrene beads from used packing, most recently also the electrical and electronic equipment waste.

How is the situation in development countries? Surely the problems with waste as in industrial countries reached already these regions. But there is a specific use of waste having an important relevance. It is the use of vegetable fibres. An overview of working characteristics is presented in the contribution and the application of the material for structural elements is outlined.

To answer the question in the title of this paper, the analysis of concrete properties modification by replacement of mineral aggregate with waste product, or the use of vegetable fibres, is necessary. Predominantly it is the relation between strength and elasticity modulus, closely connected with rheological properties, especially with shrinkage.

2 Mineral aggregate replacement

2.1 Polystyrene beads

The substitution of the mineral aggregate with polystyrene beads leads to the production of lightweight concrete with a wide range of densities. A great part of expanded polystyrene is a waste material from packaging industry. It is reported in [2, 8, 10, 17, 20, 21] the use of polystyrene concrete in curtain walls, cladding and tilt-up panels, carrying walls of low thermal conduction, composite flooring systems (e.g. repairing wood floors of old buildings), as the sub-base material for a pavement, bridge decks, for floating marine structures (quay), so as for overlaying layer for protection against impact loading. While at some applications the emphasis is led on the specific density, in some structural elements also the higher values of strength are required, which necessitate to optimize the mix composition.

The distribution of the stress in the composite material depends on the sizes of the inclusions and on the ratio of the elasticity moduli of the matrix and the inclusions. Higher modulus of elasticity of the aggregate comparing with the matrix will cause the stress concentration in the aggregate. However at lightweight concrete it is quite opposite. E.g. the modulus of elasticity of polystyrene beads is negligible. It is well known that the compressive strength increases when the pore size or the size of inclusions decreases.

A compressive strength model accounting the porosity of the inclusions, so as the inclusion size is derived in [17]. A hyperbolic function was proposed in the form

$$f_{cc} = \left(\frac{\alpha \left(1 - \frac{p}{p_{\max}} \right)}{\alpha + \frac{p}{p_{\max}}} \right) f_{cm} \tag{1}$$

where f_{cc} is the compressive strength of the lightweight concrete, f_{cm} is the compressive strength of the matrix, p is the porosity due to the inclusions, p_{max} is the maximum porosity and α is the coefficient depending on the size of the sphere. The packing density of the dry mixtures is defined as the maximum volume concentration, which could be attained. According to [11], citing C. F. Gauss and J. Kepler, the average packing density in three-dimensional Euclidean space with identical spheres could be expressed as

$$\frac{\pi}{\sqrt{18}} \cong 0.74048. \tag{2}$$

It is obvious that the contemporary use of spheres with different sizes or shapes will influence the packing density.

Experimental results on the two-phase material consisting from high strength mortar and expanded polystyrene spheres (EPS) are reported in [17]. The matrix was composed from CEM I 52.5 cement, class A silica fume, a rounded quartz sand with a maximum diameter 400 μm and a polycarboxylate-based superplasticizer. EPS without coating of three different diameters: 1, 3 and 6 mm with the specific gravity equal to 0.033, 0.019 and 0.017 respectively were used, each of them separately. (Specific gravity is defined as the ratio of a given substance density to the density of water.) Concretes with the specific gravity 0.6, 0.8, 1.0, 1.1, 1.4 and 2.3 (pure matrix) were designed with the polystyrene content from 23.31 to 0 kg.m^{-3}. To avoid the segregation the specimens were cast without vibration.

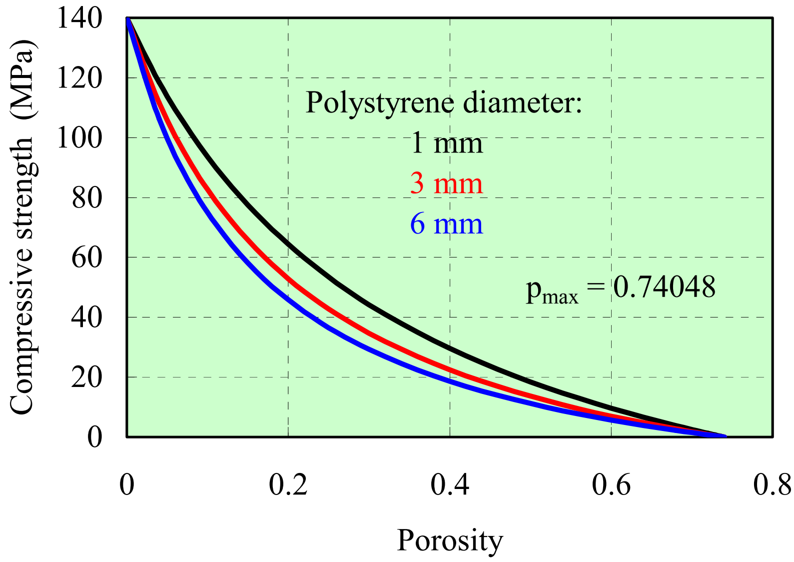

Fig. 1 Compressive strength versus porosity according to [17]

The α values from Eq. (1) were calculated from the approximation of experimental data. There magnitudes for the polystyrene diameter 1, 3 and 6 mm are 0.46, 0.29 and 0.22 respectively. The dependence of the compressive strength (probably cylinders 110x220 mm in the age of 7 days after storing in 60°C – three samples for each specific gravity and each sphere diameter) on the porosity is plotted in Fig. 1.

Higher compressive strengths are reached at mixtures with smaller polystyrene diameters. This influence however ceases at high porosity. The term porosity expresses the neglecting of the elasticity modulus of polystyrene. The use of more rigid inclusions will cause the non-zero value at p_{max}. Another source of improvement is the proper choice of fraction to enhance maximum packing density, which will cause the upward shift of the curves. Further results would be needed for the compositions of the original mixture with larger aggregates.

Strength and deformation properties of polystyrene aggregate concrete with six different mix compositions are presented in [21]. Spherical-shaped polystyrene beads with hydrophilic type chemical coating (particle and bulk densities 67 and 35 kg.m^{-3}) were used. The beads completely passed through a 4.75 mm sieve and 90% was retained on a 2.36 mm sieve. Further components were the coarse and fine sand, cement, water, at mixtures

5 and 6 also silica fume and 10 mm crushed basalt as a coarse aggregate. The wet densities ranged from 1165 to 1350 kg.m^{-3}, the content of the polystyrene aggregate in fresh concrete was from 33.0 to 36.4% by volume. Based on measured values for cylinder strength and modulus of elasticity for polystyrene aggregate concrete the relationship

$$E = 1.146\rho^{1.1} f^{0.5} \tag{3}$$

was derived, where E is the modulus of elasticity (MPa), ρ is the air-dried density (kg.m^{-3}) and f is the compressive cylinder (Ø150.300 mm) strength (MPa).

The secant modulus of elasticity of lightweight aggregate concrete (GPa) is defined in [23] by the equation

$$E_{lcm} = E_{cm}.\eta_E = 22\left(\frac{f_{cm}}{10}\right)^{0.3}\left(\frac{\rho}{2200}\right)^2, \tag{4}$$

where f_{cm} is the average cylinder compressive strength of concrete (MPa) and ρ is the air-dried density (kg.m^{-3}).

The initial tangent modulus of aerated concrete is defined in [22] in the form

$$E_{bi} = 500.R_{me}, \tag{5}$$

where R_{me} is the average compressive strength (both quantities in MPa).

Shrinkage of polystyrene aggregate concrete was measured on prisms 100x100x380 mm in [21]. After demoulding after 24 hours they were cured in water for 7 days and consequently placed in the laboratory conditions of 22±3°C and 65±5% RH.

The limit value and the rate of deformation increase are of interest when comparing with other concretes. The hyperbolic three-parametric (a, b, c) equation

$$y(t) = a + b\frac{t}{c+t} \tag{6}$$

according to [7] was found to be suitable for the approximation of the time (t) course of measurements $y(t)$. In the time equal to the parameter c the half of the long-term increment b will be reached. Hence the name *halftime* was introduced for the parameter c, which is used for the characterization of the time development of the long-term process.

The shrinkage deformations of concrete made from mixes 5 and 6 with 10 mm basalt coarse aggregate and the silica fume were approximated with Eq. (6). The halftime c equal to 10.7 and 13.0, so as the limit value 0.789 and 0.720 ‰ were obtained for the mixes 5 and 6 respectively. It is expected that the shrinkage of polystyrene concrete will be higher than that of normal weight concrete [3] due to the lower rigidity of polystyrene beads, which do not restrain the shrinkage of the matrix.

2.2 Tire rubber particles

Extensive investigations were performed about the incorporating of rubber particles into asphalt concrete with the aim to improve the fatigue characteristics and the resistance against cracking. Fewer articles could be found about the replacing of mineral aggregate in concrete by waste rubber chips [5, 19, 24, 27].

The application of rubber aggregate obtained by mechanical grinding of material from the automotive industry waste in concrete is described in [1]. After the volume reduction the particles were sieved into three groups of 1-4, 4-8 and 8-12 mm size grading respectively and separated into compact rubber aggregates (CRA) with smooth surfaces and the strain before fracture (ratio of the length increase to the initial length) equal to 85% and expanded rubber aggregate (ERA) with alveolar surfaces and the strain before fracture of 200 %.

Tab. 1 Influence of the volume of rubber aggregate on the physico-mechanical properties of concrete (approximations (Eq. 7) calculated on the basis of experimental results presented in [1]).

	Sieve size (mm)	Type of rubber aggr.	Approximation coefficients			
			A	B	C	D
ρ (kg.m^{-3})	1÷4	CRA	$-9.731 \cdot 10^{-4}$	0.1037	-10.52	1834.9
		ERA	$-2.152 \cdot 10^{-3}$	0.3203	-23.35	1833.0
	4÷8	CRA	$3.046 \cdot 10^{-5}$	$3.306 \cdot 10^{-2}$	-7.785	1832.1
		ERA	$-2.695 \cdot 10^{-3}$	0.3371	-20.94	1832.8
	8÷12	CRA	$-5.416 \cdot 10^{-4}$	$6.059 \cdot 10^{-2}$	-6.416	1831.7
		ERA	$-2.894 \cdot 10^{-3}$	0.3239	-18.06	1832.5
f_c (MPa)	1÷4	CRA	$-4.662 \cdot 10^{-5}$	$3.338 \cdot 10^{-2}$	-3.070	82.507
		ERA	$-8.967 \cdot 10^{-4}$	0.1117	-4.920	81.746
	4÷8	CRA	$-5.594 \cdot 10^{-4}$	$7.974 \cdot 10^{-2}$	-4.139	82.164
		ERA	$-1.266 \cdot 10^{-3}$	0.1435	-5.594	80.771
	8÷12	CRA	$-7.599 \cdot 10^{-4}$	0.1023	-4.796	82.185
		ERA	$-1.473 \cdot 10^{-3}$	0.1613	-5.969	79.986
f_{fl} (MPa)	1÷4	CRA	$3.061 \cdot 10^{-6}$	$-1.406 \cdot 10^{-3}$	$4.179 \cdot 10^{-2}$	3.3004
		ERA	$-2.176 \cdot 10^{-6}$	$-8.392 \cdot 10^{-4}$	$3.809 \cdot 10^{-2}$	3.3912
	4÷8	CRA	$6.993 \cdot 10^{-7}$	$-1.340 \cdot 10^{-3}$	$3.272 \cdot 10^{-2}$	3.2392
		ERA	$1.103 \cdot 10^{-5}$	$-1.653 \cdot 10^{-3}$	$3.904 \cdot 10^{-2}$	3.2891
	8÷12	CRA	$1.666 \cdot 10^{-5}$	$-2.346 \cdot 10^{-3}$	$3.934 \cdot 10^{-2}$	3.1614
		ERA	$1.445 \cdot 10^{-5}$	$-1.699 \cdot 10^{-3}$	$2.561 \cdot 10^{-2}$	3.1751
E_d (GPa)	1÷4	CRA	$9.359 \cdot 10^{-5}$	$-4.623 \cdot 10^{-3}$	-0.3111	24.908
		ERA	$-6.888 \cdot 10^{-5}$	$1.342 \cdot 10^{-2}$	-0.9097	24.538
	4÷8	CRA	$1.235 \cdot 10^{-4}$	$-7.847 \cdot 10^{-3}$	-0.2101	25.180
		ERA	$-3.272 \cdot 10^{-5}$	$1.019 \cdot 10^{-2}$	-0.8115	24.775
	8÷12	CRA	$1.522 \cdot 10^{-4}$	$-1.036 \cdot 10^{-2}$	-0.1273	25.494
		ERA	$-9.403 \cdot 10^{-5}$	$1.347 \cdot 10^{-2}$	-0.8000	24.846
E (GPa)	1÷4	CRA	$-2.500 \cdot 10^{-4}$	$1.857 \cdot 10^{-2}$	-0.6679	20.014
		ERA	$-3.750 \cdot 10^{-4}$	$3.286 \cdot 10^{-2}$	-1.052	20.021
	4÷8	CRA	$-3.333 \cdot 10^{-4}$	$2.643 \cdot 10^{-2}$	-0.8738	20.086
		ERA	$-5.000 \cdot 10^{-4}$	$4.036 \cdot 10^{-2}$	-1.189	20.071
	8÷12	CRA	$-5.833 \cdot 10^{-4}$	$4.357 \cdot 10^{-2}$	-1.185	20.014
		ERA	$-3.750 \cdot 10^{-4}$	$3.321 \cdot 10^{-2}$	-1.141	20.093

CPJ CEM II 32.5 type cement was used; prisms (40x40x160) mm with CRA and ERA were produced and moist cured for 28 days at 20°C and 98% relative humidity. The influence of the volume of rubber aggregate on the dry unit weight ρ, compressive strength f_C, flexural strength f_{fl}, so as the dynamic E_d and static E modulus of elasticity (at 28 days) was investigated. To enhance the transparency and to help at the estimate of the designed concrete properties the results presented in [1] were approximated by the cubic polynomial

$$f = AV^3 + BV^2 + CV + D, \qquad (7)$$

where f is the physico-mechanical property and V the volume of the rubber in (%). The approximation coefficients A÷D are presented in Tab. 1. All dependencies, except of the flexural strength, exhibit a decreasing tendency. Maximum values of flexural strength are reached at the volume ratios of about 20%. From the value of 35% the strength start to decrease significantly. Helpful could be also the dependence between the compressive strength f_C and the dry unit weight ρ. Similarly as in Eq. (7) cubic polynomial in the form

$$f_C = A\rho^3 + B\rho^2 + C\rho + D \tag{8}$$

was used for the approximation of measurements presented in [1].

Tab. 2 Influence of the dry unit weight on the compressive strength of concrete (approximations (Eq. 8) calculated on the base of experimental results presented in [1]).

Sieve size (mm)	Type of rubber aggregate	Approximation coefficients			
		A	B	C	D
1÷4	CRA	$-3.442 \cdot 10^{-7}$	$2.085 \cdot 10^{-3}$	-3.852	2256.5
	ERA	$1.115 \cdot 10^{-8}$	$1.192 \cdot 10^{-4}$	$-3.145 \cdot 10^{-1}$	189.82
4÷8	CRA	$8.368 \cdot 10^{-7}$	$-3.389 \cdot 10^{-3}$	4.535	-1998.0
	ERA	$1.673 \cdot 10^{-7}$	$-4.977 \cdot 10^{-4}$	$4.648 \cdot 10^{-1}$	-128.11
8÷12	CRA	$1.611 \cdot 10^{-6}$	$-6.514 \cdot 10^{-3}$	8.446	-3430.2
	ERA	$4.578 \cdot 10^{-7}$	$-1.749 \cdot 10^{-3}$	2.229	-947.1

The effect of rubber chips on the brittleness of rubberized concrete (important in structures exposed to crashing) was investigated in [25]. For the brittle material most of the energy at the fracture is elastic, while for a tough material it is plastic. To reduce the brittleness of concrete it is the endeavour to increase the plastic energy – by adding different materials. An important circumstance which could affect the properties of rubberized concrete is the rubber source (truck or car tyres), so as the grinding process. Both could influence the amount of steel and textile fibres, as well as the shape and texture of the fibre [6]. Two inorganic materials are sometimes added into concrete. It is the glass, which creates a non-negligible part of the solid waste [26] and the metallic aggregate in the various forms [28]. The question of durability is of primary importance [4] at the evaluation of the material. The action of aggressive agents [12÷14], of seismicity [15, 16] and of the deformations expected [9, 18] should be taken into account.

3 Vegetable fibres

Vegetable fibres, together with animal and mineral fibres create a subset - natural fibres, as a supplement to man-made fibres. Due to high prices of industrially manufactured fibres the use of vegetable fibres is widespread for low-cost housing in development countries. It should be emphasized, that the primary and traditional aim of vegetable fibres is their use for making paper, cloth, or rope. For addition in the cement composites usually only the remained part (waste), not satisfying the requirements for the intended purpose, is used.

According to [29] the vegetable fibres could be divided into four categories. The fibres in *leafs* provide the strength and rigidity, so as the support to liquid-conducting vessels. Because stiffer and coarser than fibres from stem or bast, they are termed also as *hard fibres*. Widespread are the plants from the agave family, from which one of the most common for the use of the leaf fibres is the *sisal* (binomial name – agave sisalana). The second group of fibres comes from *stems* or *bastes*. The bundles of fibres, held together by the cellular tissue and by gummy and waxy substances, have the function to strengthen the stalk of the plant. *Hemp* (Philippines), *jute* (India, China, Bangladesh), *flax* and *ramie* (China grass) are some known examples. *Wood fibres* are marked by their rigidity. In [29] they are mentioned as the strengthening agent for fibres obtained from *bamboo* and *reeds*. *Surface fibres* are comprised usually of a single cell on the surface of stems, leafs, fruits and seeds of plants. *Cotton* is the most significant representative of the seed-fibre group, however for its high price it is not suitable for the reinforcing of cementitious materials.

The properties of FRC are relevantly affected by the concentration of fibres, which could be expressed by the volume percentage. According to [32] the high volume percentage could be considered in the range 3 to 12%, moderate in the range 1 to 3% and low in the range 0.1 to 1.0%. When using conventional mixing equipment the low and moderate range of volume percentage is suitable. Four main difficulties at the use of natural vegetable materials as reinforcement for cement based materials are mentioned in [30]. It is (*a*) the low elastic modulus comparing with the cement paste or concrete, (*b*) the tendency to absorb water, (*c*) susceptibility to fungal decay and insect attack and (*d*) variation in fibre dimensions, strength and modules.

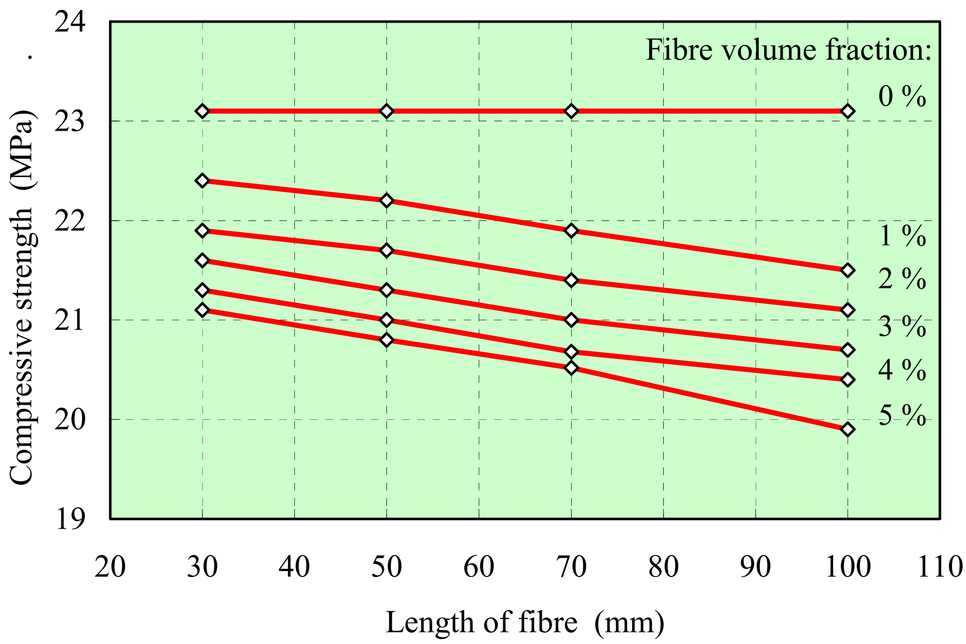

Fig. 2 Dependence of the compressive strength on the length of the fibre according to results in [30].

FRC beams 100x100x500 mm and cubes 150^3 mm using sisal fibre were prepared and tested in [30]. The cement content was 373 kg.m^{-3}, fine and coarse aggregate in the amount of 708.8 and 1063.2 kg.m^{-3} was used together with 205 kg.m^{-3} of water. The fibre volume reached from 0 to 5% and the fibre length from 30 to 100 mm. Moderately modified mix proportion was applied for the toughness index determination. Dry chopped fibres were added to the mix before adding the water. The compressive strength was determined on cubes 150^3 mm, cured 28 days before crushing. Each result represents an average of three values. With the increasing length of fibre and the fibre volume fraction the compressive strength is decreasing (Fig. 2). Beams 100.100.500 mm containing fibre lengths of 30, 50, 70 and 100 mm with volume fractions of 0, 1, 2, 3, 4 and 5% were used in [30] for modulus of the rupture determination at the four point loading test from the equation

$\sigma = F.l/b.h^2$ (F is the force, l the span, b and h are the width and depth of the beam). It could be seen from Fig. 3 that the optimum length of the fibres and the fibre volume fraction were 70 mm and 3% respectively.

For the flexural toughness determination identical beams however with the fibre length of 30 mm, fibre volume of 5% and water-cement ratio of 0.6 were used. The increase of toughness indices both I_5 and I_{10} with the increase of the age at tests (7, 14 and 21 days) was observed. The toughness of the concrete beam was substantially increased with the addition of the sisal fibre. Behaviour of soil reinforced with natural fibres is described in [31].

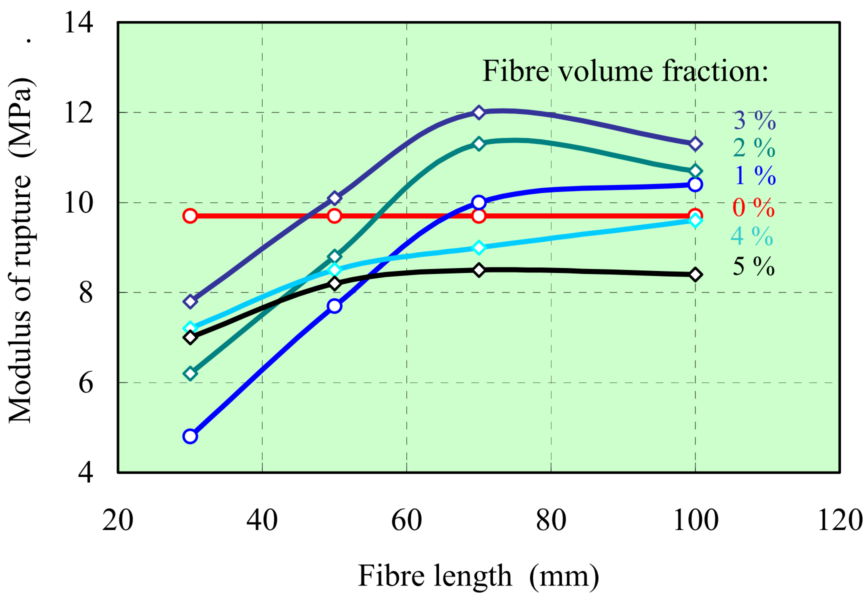

Fig. 3 Dependence of the modulus of rupture on the length of the fibre according to results in [30].

4 Conclusions

Proper modification of physical and mechanical properties could be achieved by replacing part of the mineral aggregate in concrete by polystyrene beads or chips of rubber.
The use of the waste material from packaging industry and automotive industry is significantly contributing to the protection of the environment.
The proper substitute of man-made fibres by vegetable fibres could significantly reduce the total cost of the housing in development countries.
The use of waste products in concrete could lead to the reaching of required properties and need not be regarded from the standpoint of acceptable deterioration.

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