Use of recycled aggregates from different sources in the production of SCC Part II: Hardened state properties

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Abstract

The mechanical resistance, water absorption, porosity and problems of dimensional variation due to shrinkage prove to be primordial and of great importance for evaluating of the durability of self-compacting concrete (SCC) based on recycled coarse aggregates. In part II of this study, ordinary gravel is partially replaced (50 and 100%) by recycled gravel for the preparation of eight compositions, with a constant water/binder ratio (W/B) = 0.4 and a binder dosage equal to 475 kg/m³. Physical and mechanical properties of SCC are evaluated through a number of laboratory tests. According to the findings of this study, the water absorption and porosity of SCC with recycled coarse aggregates are generally high, and can reach up to double that of the control SCC. Shrinkage of SCC is significant, however mechanical resistance is low compared to SCC with oridinary gravel. The results also suggest that, using binary mixtures can significantly improve the durability of SCC.

Keywords: Recycled aggregates; brick; marble; bituminous aggregates; SCC, strength, water absorption, shrinkage
Kulcsszavak: újrahasznosított adalékanyagok; tégla; márvány; bitumenes adalékanyagok; SCC, szilárdság, vízfelvétel, zsugorodás

1. Introduction

SCC are very fluid concretes that flow and are placed under their own weight without the use of any internal or external energy. This fluidity is achieved by using a large amount of paste and a superplasticizer. The selection of aggregates (fine and coarse) thus plays a significant role in obtaining the best properties. To achieve a good performance-cost ratio, it is vital to have a clear grasp of the influence of physical parameters on the performance of SCC [1, 2]. Public buildings, bridges, and industrial structures are demolished but never recycled after natural disasters such as earthquakes and floods, or as a result of aging and degradation. Furthermore, natural resources in particular areas are depleted, sea sand is restricted. Therefore, aggregates are brought from long distances, and public landfills are overburdened. Unfortunately, research on waste recovery in building and public works is uncommon. Aside from the considerable shortage in aggregates encountered in recent years, demolition and building waste is significant and rarely recovered. Recycled aggregates are essentially aggregates obtained by recycling concrete from demolition. Indeed, these aggregates have different applications in the field of civil engineering, particularly in road construction and in the preparation of concrete for different buildings. In addition, the current environmental policy promotes their use with a view to reducing the consumption of raw materials and complying with environmental rules. The use of recycled aggregates in concrete [3-6], such as SCC, is hindered by many technical codification texts. Some researches have been carried out to use waste as recycled aggregates in ordinary concrete and in SCC, among these researches the study of the influence of crushed sand by Benabed [3] and the recovery of construction and demolition waste (brick and concrete in particular) by Azzouz et al. [4], Douara [5] and Nezergui [6]. In addition, the lack of knowledge about the durability of these concretes generates mistrust among the users. As a result, a better understanding of the behavior of concretes including such aggregates could aid in the development of this type of application. Hence, this project was conducted to contribute to the development of the recycling industry and the recovery of building and demolition wastes in order to use recycled gravel in the manufacture of SCC On one hand. On the other hand, to understand the primary element influencing the selection of the granular skeleton in an optimal SCC formulation. The purpose of this research is to investigate the effect of recycled gravel characteristics, types, classes, and nature on the physical and mechanical properties of SCC at hardened state. This study will contribute to the advancement of knowledge about the production of SCC by judicious choices of available gravels.

2. Materials and experiments

2.1 Materials

In this study, Ordinary Portland cement (CEM I 42.5) was used in the preparation of the various SCC mixtures, with density and specific surface areas of 3.15 and 3700 cm²/g, respectively. A marble powder (MP) was used as mineral addition with a rate of substitution of 10%. This powder has

Properties	OCG		WMG		RBG		DCG		BMG	
Size (mm)	(3/8)	(8/16)	(3/8)	(8/16)	(3/8)	(8/16)	(3/8)	(8/16)	(3/8)	(8/16)
Absolute density	2.691	2.673	2.71	2.695	2.216	2.227	2.568	2.592	2.286	2.292
Apparent density	1.365	1.395	1.368	1.392	0.946	0.949	1.127	1.18	1.128	1.048
Compactness (%)	50.72	52.19	50.48	51.65	42.69	42.61	43.89	45.52	49.34	45.72
Porosity (%)	49.28	47.81	49.52	48.35	57.31	57.39	56.11	54.48	50.66	54.28
Water absorption (%)	2.31	1.46	0.44	0.28	10.91	9.67	8.23	5.90	1.11	1.60
Surface cleanliness (%)	0.29	0.19	0.81	0.18	0.78	0.26	1.79	1.27	0.28	0.39
Elongation coefficient	0.33	0.57	0.30	0.48	0.34	0.37	0.39	0.64	0.42	0.62
Kurtosis coefficient	0.33	0.45	0.38	0.39	0.33	0.48	0.33	0.43	0.33	0.47
Los-Angeles (%)	25.1	21.1	32.7	28.3	42.8	46.3	34.5	26.4	23.8	25.6
Micro-Deval (%)	8.2	5.2	8.1	15.6	16.1	36.8	12.9	11.2	8.4	11.9

Table 1 Properties of the aggregates used [7]
1. táblázat A felhasznált adalékanyagok tulajdonságai [7]

a density of 2.70 and a fineness of 3600 cm^2/g. A high water-reducing superplasticizer was employed. A river sand SA (0/5) of siliceous nature was used with a density of 2.65. As coarse aggregates, an ordinary crushed gravel (OCG) of limestone nature, and four types of recycled gravel: recycled gravel (GWM) produced by crushing white marble waste, recycled gravel (GRB) produced by crushing red brick waste, recycled gravel (GDC) produced by crushing demolition concrete and gravel (GBM) recycled produced by recycling bituminous mixtures. The different properties of the aggregates used are summarized in *Table 1* [7].

2.2 Testing

Nine (09) mixtures of SCC were prepared in the laboratory, in these mixtures recycled gravel was used as a substitute for ordinary gravel, with substitution rates by volume of 0, 50 and 100%. All mixtures are characterized by a powder content equal to 475 kg/m^3, water/binder (W/B) = 0.4 and sand/mortar (S/M) ratio = 0.5 [7]. Mix-proportions of the different SCC are given in *Table 2*.

From each concrete mixture, prismatic specimens 7×7×28 cm in size were cast. After casting, the specimens were unmolded and transferred to conservation at temperature of 20 ± 2 °C and 100% of relative humidity until the time of test. For each mix, three specimens were used to determine tensile strength and six specimens to measure compressive strength at 3, 7, 28, 56 and 90 days. The strength was measured according to NF P18-455 standard [8]. The density hardened SCC is determined in accordance with NF P18-435 standard [9]. While, the water absorption test was carried out in accordance with NF P 10 502 standard [10]. Drying shrinkage was carried out in accordance with NF P 18 432 standard [11].

3. Results and discussion

In the Part I of this investigation [7], the influence of the type of coarse aggregates on fresh properties of SCC was studied. The obtained results are summarized in *Table 3*.

3.1 Hardened density

The density of hardened SCC mixture is shown in *Fig. 1*. Form this figure, it is obseved that recycled gravel SCC has a low density when compared to control concrete (SCC1), with the exception of mixes containing recycled gravel from marble waste GWM (SCC2 and SCC6), which having a density similar to that of ordinary gravel (OCG). As a result, the density of

S/M = 0.5 W/B = 0.4 Constituents		Family A					Family B			
		SCC 1 100% OCG	SCC 2 100% WMG	SCC 3 100% BMG	SCC 4 100% DCG	SCC 5 100% RBG	SCC6 (50%OCG +50%WMG)	SCC7 (50%OCG +50%BMG)	SCC8 (50%OCG +50%DCG)	SCC9 (50%OCG +50%RBG)
Cement (kg/m^3)		433.7	433.7	433.7	433.7	433.7	433.7	433.7	433.7	433.7
Marble powder (kg/m^3)		41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3
Sand (kg/m^3)		901.5	872.3	916.6	937.7	960.5	883.1	901.9	914.7	920.7
Ordinary gravel (kg/m^3)	(8/16)	546.0	—	—	—	—	281.7	246.9	254.6	231.8
	(3/8)	270.8	—	—	—	—	139.6	122.4	126.2	114.9
Recycled gravel (kg/m^3)	(8/16)	—	588.3	444	451.9	350.2	285.0	247.8	243.2	212.5
	(3/8)	—	293.7	220.9	221	172.7	142.3	123.3	118.9	104.8
Water (kg/m^3)		197.0	182.9	205.6	252.8	273	193.0	202.7	228.4	240.3
Superplasticizer	Sp (%)	1.00	1	1	0.9	0.9	1	1	1	1
	Sp (kg/m^3)	4.8	4.8	4.8	4.3	4.3	4.8	4.8	4.8	4.8

Table 2 Mix-proportions of the different SCC [7]
2. táblázat Az öntömörödő betonok (SCC-k) keverékarányai [7]

SCC mix.		Slump flow test		J-Ring test			V-Funnel test	Sieve stability segregation test	L-Box test
		D (mm)	T500 (s)	Dj (mm)	T500J (s)	Bj (cm)	Tv (s)	π (%)	H_2/H_1 (%)
Family (A)	SCC 1	734	1.6	711	1.95	1.58	6.15	6.30	82.51
	SCC 2	722	1.85	706	2.25	1.88	6.90	6.90	80.60
	SCC 3	765	0.95	728	1.25	1.43	5.30	18.65	90.36
	SCC 4	697	1.9	688	2.20	1.08	7.35	9.68	93.70
	SCC 5	682	1.95	663	2.40	2.03	7.10	10.15	78.23
Family (B)	SCC 6	732	1.85	698	2.05	1.67	6.65	7.38	86.10
	SCC 7	728	1.35	704	1.90	1.64	5.85	15.28	83.67
	SCC 8	739	1.75	712	1.95	1.18	6.90	8.96	90.20
	SCC 9	717	1.70	681	2.10	1.86	6.85	10.28	80.33

Table 3 Fresh properties of SCC made with different types of coarse aggregates [7]
3. táblázat Különböző típusú durva aggregátumokkal készült öntömörödő betonok (SCC) friss tulajdonságai [7]

SCC with recycled coarse aggregates is often lower than that of the reference SCC (SCC1 with 100% OCG). The figure also shows a general increase in the density of concrete of family B compared to recycled SCC in family A, which is due to a reduction in the amount of recycled gravel (100%, 50%), because these SCC contain 50% OCG gravel, which has a higher density than recycled gravel.

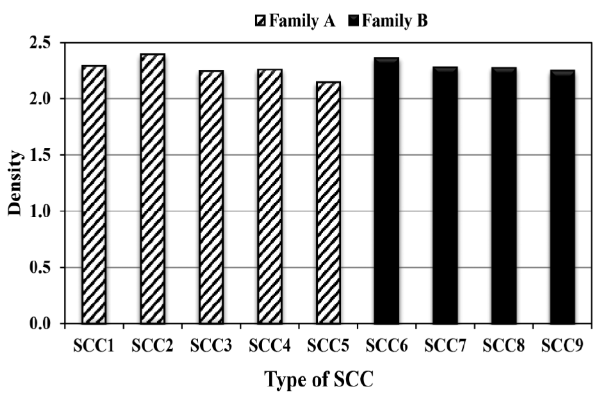

Fig. 1 Haredened density of the different SCC mixtures
1. ábra Az öntömörödő betonkeverékek (SCC) szilárdulás utáni sűrűsége

3.2 Compressive strength

The *Fig. 2* and *3* depict the evolution of compressive strenght of different SCC made with the different types of recycled aggregates. The strength of all mixes increases with age. It should be emphasized that the compressive strength of SCC made with recycled gravel changes over time in the same way that SCC1 does; however, it decreases depending on the proportion of substitution in recycled gravel.

At 28 days, the resistance of the combinations SCC2, SCC3, SCC4, SCC5, SCC6, SCC7, SCC8, and SCC9 decreased by 5, 46, 16, 39, 9, 24, 10, and 18%, respectively, as compared to the reference mixture (SCC1). As a result, the maximum compressive strength after 28 days is attained in the reference concrete SCC1 and is equivalent to 39.54 MPa, but the loss in strength at 28 days of recycled SCC mixes is of the order of 5 to 46% when compared to SCC1. It is observed that, the compressive strength values in the medium and long term of mixtures made from OCG and GWM gravel (SCC1 and SCC2), as well as the mixture of two types of these SCC6 gravel, are higher than the other values of mixtures based on recycled gravel. This can be explained by the fact that the strength of the concrete is influenced by the texture and shape of coarse aggregates. As a result, the adhesion strength between OCG and GWM and the cement paste is stronger than that of recycled gravel.

With regard to the binary mixtures of the family B (contain 50% OCG), a reduction in resistance was noted compared to SCC1. For SCC7, the reduction in resistance is primarily due to an increase in the W/B ratio and the effect of the mortar of the old inert concrete which is attached to the gravel coming from the crushed concrete, which hinders the good progress of the cement hydration [12]. For SCC8, the reduction in resistance is primarily due to the crushed brick gravel which has a high water absorption. For SCC9, this reduction in resistance is related to the bitumen that covers the grains of coarse aggregates. The lowest compressive strength at 28 days is attained in SCC3 (100% GBM) and is 21.18 MPa. This decrease can be due to bituminous gravel (GBM), which is less stiff than other gravel and, when compressed, will crush and slide against one other rather than resisting the compression. Benabed [13] demonstrated that the resistance of SCC after hardening is affected by the W/B ratio, the quality and type of the aggregates, the technique of conservation, and the test expiration date. Pandaa and Balb [14] have shown that the compressive strength of SCC diminishes as the rate of recycled coarse aggregates increases. According to Persson [15], the compressive strength difference between SCCs and regular concrete is 20 MPa and 5 MPa for water/binder ratios W/B = 0.4 and 0.5, respectively.

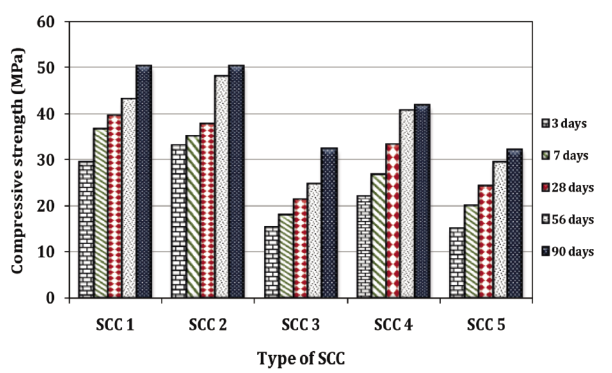

Fig. 2 Compressive strength of SCC mixtures (family A)
2. ábra Az öntömörödő betonkeverékek (SCC) nyomószilárdsága (A minták)

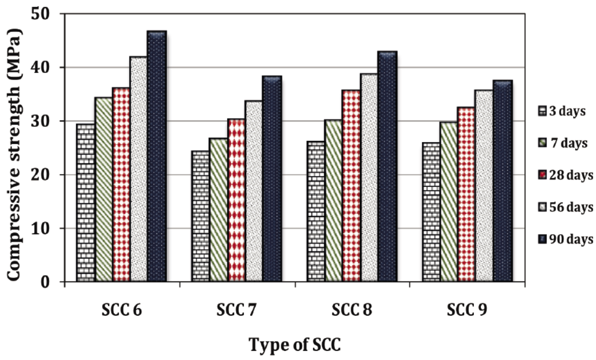

Fig. 3 Compressive strength of SCC mixtures (family B)
3. ábra Az öntömörödő betonkeverékek (SCC) nyomószilárdsága (B minták)

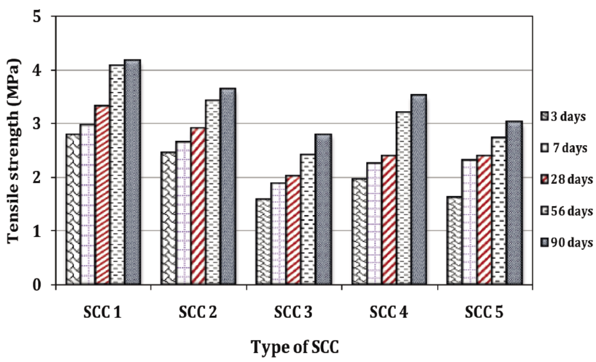

Fig. 4 Tensile strength of SCC mixtures (family A)
4. ábra Az öntömörödő betonkeverékek (SCC) szakítószilárdsága (A minták)

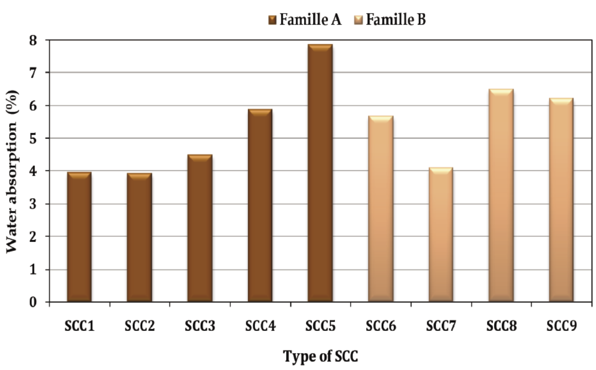

Fig. 5 Tensile strength of SCC mixtures (family B)
5. ábra Az öntömörödő betonkeverékek (SCC) szakítószilárdsága (B minták)

3.3 Tensile strength

Fig. 4 and *5* show the tensile strength results of all mixtures, which showed the same tendency as the compressive strength. Tensile strength diminishes as the fraction of recycled coarse aggregates increases from 50% to 100%. At 28 days, the SCC1, SCC2, and SCC6 combinations have the highest tensile strength values, which are 3.32, 2.90, and 2.92 MPa, respectively. This rise is explained by the substantial roughness of the surface of the OCG and GWM gravel particles. The flexural strength of the combinations including crushed aggregates improved. This is explained by the angularity of the gravel grains, which ensures good adhesion between the grains and the cement matrix in one hand. In the other hand by the presence of micro-fines filling the micropores, which allows densification of the cement paste microstructure [16]. The addition of coarse bituminous aggregates to the various SCC combinations (SCC3 and SCC7) reduces the bearing capacity of the materials, as seen in *Fig. 4* and *5*. This drop can be attributed to poor adhesion between the cement paste and the gravel grains of asphalt mixes as a result of the bitumen that covers the grains of (GBM) and the cement paste, resulting in a low tensile strength.

3.4 Water absorption by immersion

Fig. 6 shows that water absorption of different mixtures of SCC. It can be seen that the water absorption of greater SCC mixtures with recycled gravel (excluding SCC2) are higher than for the control concrete SCC1 of ordinary gravel (OCG). When the degree of substitution in recycled gravel increases, the percentage of water absorption increases up to 2 times (SCC5). The proportion of substitution in recycled gravel (50% or 100%) increases the water absorption of recycled SCC. Because of its gravel (GRB), which has a higher water absorption coefficient than other gravel, recycled SCC prepared with crushed brick gravels (SCC5 and SCC9) are somewhat more permeable than other recycled concretes and have water penetration that can exceed double that of the reference concrete. It may be concluded that the nature and percentage of recycled gravel have a substantial influence on water absorption by immersion of recycled SCC. According to Topcu et al. [17], a decrease in concrete density is accompanied by an increase in air volume, which diminishes the compactness and, as a result, increases the porosity of the mixture.

3.5 Water absorption by capillary

Fig. 7 depicts the variation of water absorption by capillary of the various SCC. It is noticed that the type of gravel has a major influence on the capillary absorption of SCC. SCC5 has the highest capillary absorption value of any mixture; it absorbs more than other mixtures due to its crushed brick gravel (GRB), which has a greater water absorption coefficient than other gravel (Abs 10%). Because of the presence of mortar on the grains, the grains of (GRB), which are totally crushed materials, have very angular forms, have a rougher surface, lower density, and greater capillary absorption than gravel grains (OCG). The density falls and the absorption increases correspondingly as the grain size of (GRB) lowers (Fraction 8/16 minimal fraction 3/8), due to the increasing proportion of mortar adhering or which constitutes the grains of minimal fraction.

Capillary absorption is reduced when bituminous mixtures are used as 100% coarse particles (SCC3). This is owing to bitumen's hydrophobic nature, which interferes with water absorption [18], so the cement matrix is more absorbent whereas bitumen-coated (GBM) grains are hydrophobic. The high water absorption values of SCC based on recycled coarse aggregates are a proper indication of this form of SCC high porosity and permeability, and therefore of the negative influence of using these recycled gravels on the durability of the concretes. SCC mixes made with recycled gravel, in general, have a higher water absorption capacity than control concrete (SCC1). This is certainly related to the huge number of capillary holes by volume. Water is one of the most sensitive elements affecting the characteristics of concrete, according to extensive study. Water has various significant roles in this, including hydration of cement grains, flexibility of fresh concrete, and internal cohesiveness of fresh concrete [19].

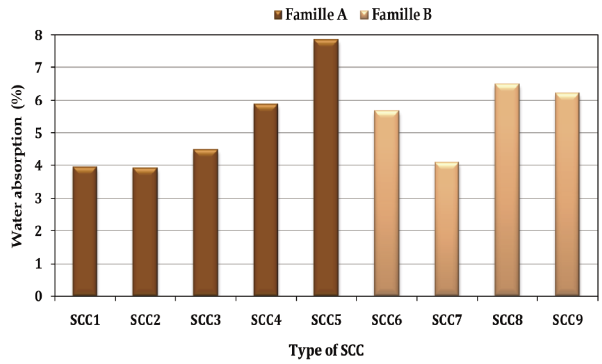

Fig. 6 Water absorption by immersion of SCC mixtures
6. ábra Az öntömörödő betonkeverékek (SCC) vízfelvétele vízbe merítéssel

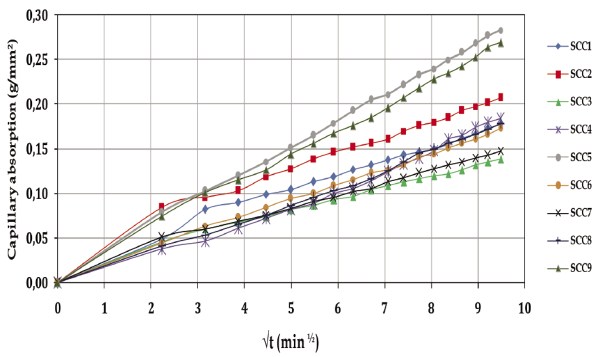

Fig. 7 Water absorption by capillarity of SCC mixtures
7. ábra Az öntömörödő betonkeverékek (SCC) kapilláris vízfelvétele

3.6 Shrinkage

Fig. 8 shows shrinkage of the different SCC. It can be noted that SCC made entirely of recycled gravel is much greater than that of the reference concrete SCC1 made entirely of conventional gravel. This figure also reveals that the maximum shrinkage of SCC3 based on bituminous mixes (GBM) is 36% more than that of SCC1 at 28 days, increasing to 43% at 120 days. This is mostly due to the bitumen that covers the grains of this gravel acting as a water store, compensating for the drying of the cement paste for a period. The shrinkage process does not begin until all of the water trapped inside this gravel has evaporated. The shrinkage of SCC made with crushed brick gravel (GRB) is more than that of SCC1 and grows by 26% at 28 days of age; after that, it eventually increases to 23% at 120 days. The shrinkage of SCC4 contains crushed concrete gravels (GDC) is higher than that of SCC1 and reaches an increase of 8% at 120 days. This substantial shrinkage is most likely owing to the high porosity of recycled gravel as well as the high degree of water absorption of the mortar that covers the gravel. Kenai and Debieb [8] discovered that open-air concrete mixes based on crushed concrete gravel and crushed brick gravel shrink more than control concrete based on natural aggregates. Concerning the last two groups of concretes produced (SCC8 and SCC9), which are based on a binary mixture of gravel of 50%OCG + 50%GDC and 50%OCG + 50%GRB, they generally present with a delayed withdrawal compared to SCC1 from an early age, with an average decrease of 33% - 41% that can reach 13% -15% at 120 days. Shrinkage issues are significantly more likely in SCC made with recycled gravel, due to the additional water consumption during manufacturing. Only after the whole evaporation of the amount of water trapped within these gravels does shrinking occur. As a result, intelligent selection of superplasticizer type and percentage can lead to a reduction in concrete shrinkage [12], and so the addition of a superplasticizer minimizes the shrinkage of recycled SCC.

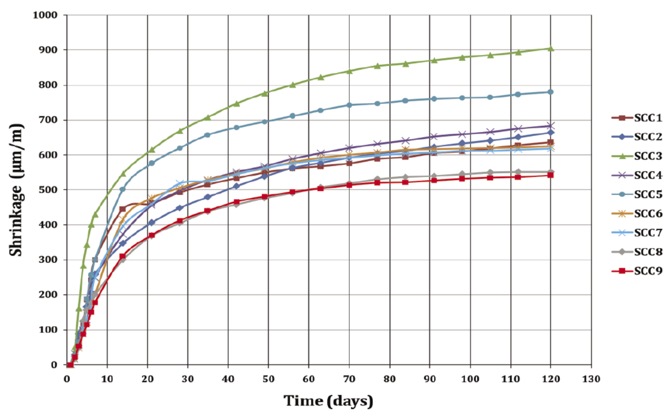

Fig. 8 Evolution of shrinkage during open-air curing of SCC
8. ábra A zsugorodás alakulása az Az öntömörödő betonok (SCC) szabadlevegőn történő szilárdulása során

4. Conclusions

The results of this work can lead to the following conclusions:

- Depending on the type of gravel, it is found that the control SCC of ordinary crushed gravel (OCG) and the SCC of crushed marble waste (GWM) have fairly similar characteristics at the hardened state. The findings show that gravel (GWM) can be technically used as a substitute in SCC.
- The compressive and tensile strength of SCC made with different types of recycled gravel increase proportionally with time, although the rate of change is not similar for the different mixtures. The obtained strengths are acceptable compared to those of the reference SCC based on ordinary gravel.
- The maximum values of mechanical strength at 28 days are obtained for SCC with 100% ordinary crushed gravel (OCG). All the tests carried out show unequivocally that the incorporation of recycled gravel (except GWM) is very detrimental to the mechanical resistance of SCC, which decreases with the increase in the dosage of recycled gravel substitution.
- The study of the influence of recycled gravel on shrinkage has shown high shrinkage at young. The higher shrinkage is achieved by the composition of SCC of 100% asphalt mix gravel (GBM). In practice, in a hot climate, this type of increase in concrete shrinkage can

be detrimental to its use in structural elements sensitive to cracking such as slabs and walls.

- The water absorption of SCC made from recycled gravel is higher than that of a control SCC made from 100% ordinary crushed gravel (OCG) and can reach double that of the control SCC. The high water absorption of recycled SCC is due to the high porosity of recycled gravel (GRB and GDC) which induces the addition of a large quantity of water to guarantee acceptable flowability. In terms of porosity accessible to water, a strong increase is observed with the increase in the proportion of recycled gravel. In addition, this is linked to the presence of the old mortar on the surface of recycled aggregates (GDC) and the material of clayey origin which makes up large aggregates (GRB).
- Replacing ordinary gravel with partially or totally recycled gravel in concrete offers a new source of supply and saves materials and quarries. Therefore the possibility of using waste gravel in SCC, as recycled gravel reduces environmental pollution and provides economic value for waste, There is also a significant growth potential of recycled aggregate as an appropriate solution for sustainable development in the construction industry.

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