Rheological properties of blended metakaolin self-compacting concrete containing recycled CRT funnel glass aggregate

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Abstract

Rheology is a field of fluid mechanics that studies the flow of materials and the interaction between stress states and deformation according to their viscosity, elasticity and plasticity and with the appearance of new materials and the complex behaviour of concrete pumpability, since the field of civil engineering is interested in the study of concrete flow. This work will examine how the use of catodique ray tube (CRT) glass as sand replacement in proportions of 0, 10, 20, 30, 40 and 50%, and metakaolin (MK) powder in proportions of 5, 10 and 15% will affect the rheological properties of self-compacting concrete (SCC). In this investigation, the flow ability of SCC was evaluated by slump flow, L-Box, and V-funnel tests. Its resistance to segregation was measured by the sieve stability test and the yield stress and plastic viscosity was determined by a modified slump test. This investigation concluded that CRT glass improved the rheological properties and minimised the dosage of superplasticiser (SP); the best results came from concrete with 50% of CRT sand glass. This improvement helps to overcome the negative effect of MK in SCC pumpability and reduces the time of casting. An acceptable relationship between rheological properties shows that a modified slump test can be used to evaluate yield stress and viscosity.
Keywords: CRT, metakaolin, rheological properties, self-compacting concrete
Kulcsszavak: CRT, metakaolin, reológiai tulajdonságok, öntömörödő beton

1. Introduction

The advent of SCC marks a new stage in the history of concrete materials [1], and as such has several technical interests in the field of civil construction and building (pumpability, easiness and speed of implementation) [2]. The specificity of SCC lies in its fresh state behaviour, and therefore this type of concrete must be characterised by high workability and deformability while remaining stable [3-5]. These properties contribute to ensuring durable and quality structures [6, 7]. However, since the variations of chemical admixtures and supplementary materials will complicate its rheological properties, particularly its shear thickening and shear thinning behaviour [8]. Many researchers are turning to the science of rheology to design better tools to understand the workability of concrete. The most used method for placing concrete is pumping, but to determine whether concrete is pumpable or not, its rheological properties such as yield stress and plastic viscosity must be known [9]. There are two ways to evaluate its rheological properties; the first way is to use a rheometer, but its high cost means it will not be available to everyone [10]; the second way is based on the modified slump test developed by Larrard and Ferraris [11], which is simple, inexpensive, easy to implement and can be used on site.

The accumulation of waste materials is becoming more uncontrollable and is occupying more public space. This has highlighted the use of these materials for construction purposes to preserve the natural resources of aggregates, while improving the performance and durability of cementitious composites and protecting the environment against the CO_2 emissions and polluted industrial sites [12-14]. It is important to recycle television and computer monitors equipment waste because it can pose serious environmental health problems [15], particularly the chemical structure of glass that contains lead oxide (PbO) [16]. Ling and Poon [17] can treat this glass by immersing it in a bath of 5% nitric acid (HNO_3) solution for 3 hours, which will satisfy the limits of the toxicity characteristic leaching procedure (TCLP) test [18]. Hui and Sun [19] studied the use of CRT glass on the workability of mortar and found that its slump diameter increases as the glass levels of CRT increased.

MK is a pozzolanic material that can be added to a cementitious material and may improve the performance of concrete [20], however it can have a negative effect on its rheology at fresh state [21]. Many investigators showed that metakaolin affects the rheological property of SCC; the irregular shape of MK enabled it to show a shear thickening behaviour and increase the viscosity of the mixture [22-25].

This study will assess the use of CRT glass and MK powder as a substitute in sand and cement respectively on the rheological properties of SCC with a low environmental impact.

2. Materials and experimental program

2.1 Materials

Ordinary Portland cement (CEMI 42.5) was used in all SCC mixes. Metakaolin, which is used as cement replacement, was obtained from kaolin calcination at 850°C for 3 hours [26]. The chemical and physical properties of cement and MK are given in *Table 1*. X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM) images of MK are also provided in *Fig. 1* and *Fig. 2* respectively. The superplasticizer (SP) used is a powerful water reducing agent based polycarboxlic-ether type with a density of 1.07 and a solid matter content of 30%.

Chemical properties Oxide content (%)	Cement	Metakaolin
SiO_2	20.83	50.30
Al_2O_3	4.13	41.81
Fe_2O_3	5.58	1.5
CaO	62.19	0.08
MgO	1.42	0.4
K_2O	2.30	0.81
Na_2O	0.38	0.09
TiO_2	0.028	0.024
Loss on ignition	2.04	5.77
Physical properties		
Specific gravity (g/cm³)	3.12	2.45
Blain fineness (cm²/g)	3300	7000

Table 1 Chemical and physical properties of cement and metakaolin
1. táblázat Cement és metakaolin kémiai és fizikai tulajdonságai

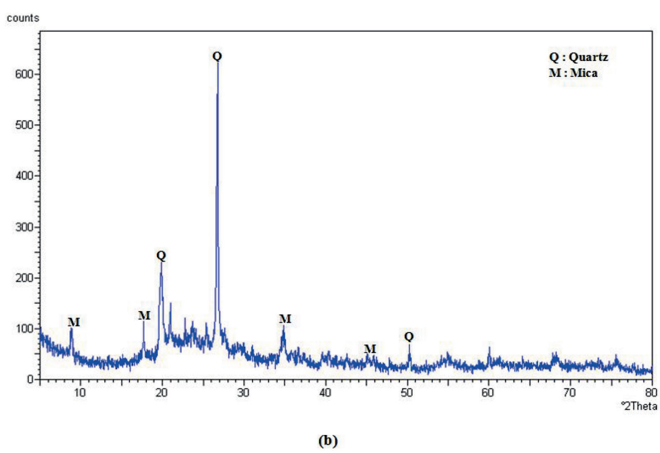

Fig. 1 X-ray diffraction of MK
1. ábra Metakaolin röntgendiffraktogramja

River sand is used as a natural fine aggregate. Waste CRT funnel glass was treated with 5% nitric acid (HNO_3) for 3 hours to remove the lead oxide, and then is used as sand replacement at levels of 0, 10, 20, 30, 40 and 50%. Two types of gravels from limestone crushing (G 3/8 and G 8/15) are used in this study. The physical properties and the particle size distribution of the used aggregates are presented in *Table 2* and *Fig. 3* respectively.

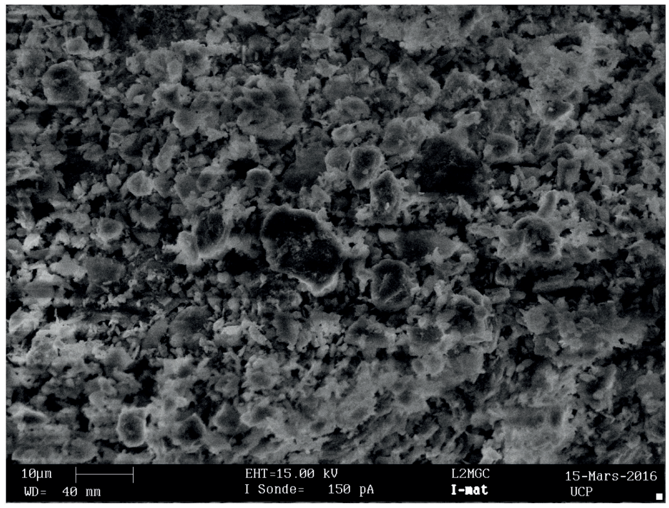

Fig. 2 Scanning electron microscope (SEM) of MK
2. ábra Metakaolin pásztázó elektronmikroszkópos felvételen

Properties	Type of aggregates			
	Fine aggregates		Coarse aggregates	
	Sand	CRT glass	Gravel 3/8	Gravel 8/15
Specific density (g/cm³)	2.7	2.75	2.69	2.68
Fineness modulus	2.44	2.16	-	-
Sand equivalent (%)	81	-	-	-
Water absorption (%)	0.83	0	3.2	3.5
Los Angeles coefficient (%)	-	-	13	15

Table 2 Physical properties of the used aggregates
2. táblázat Az alkalmazott adalékanyagok fizikai tulajdonságai

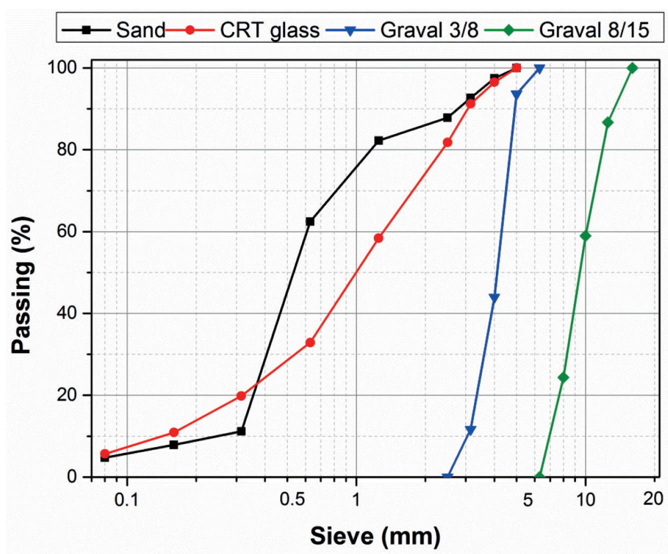

Fig. 3 Particle size distribution of fine and coarse aggregates
3. ábra A finom és durva adalékanyag szemeloszlás görbéi

2.2 Mixture proportions

To investigate how a combination of MK and CRT glass would affect the rheological properties of all the SCC mixtures, nineteen mixtures were prepared. The control mixture was made with Portland cement as a binder and natural sand as

Mix ID	Binder (OPC+MK)		W/B	Coarse aggregates (kg/m³)	Sand (kg/m³)	CRT glass (kg/m³)	SP (%)
	OPC (kg/m³)	MK (kg/m³)					
Control	469.59	0	0.4	823.24	909.78	0	0.8
MK5+CRT0	446.11	18.68	0.4	823.24	909.78	0	0.85
MK5+CRT10	446.11	18.68	0.4	823.24	818.80	90.98	0.85
MK5+CRT20	446.11	18.68	0.4	823.24	727.82	181.96	0.85
MK5+CRT30	446.11	18.68	0.4	823.24	636.85	272.93	0.83
MK5+CRT40	446.11	1868	0.4	823.24	545.87	363.91	0.83
MK5+CRT50	446.11	18.68	0.4	823.24	454.89	454.89	0.8
MK10+CRT0	422.63	37.35	0.4	823.24	909.78	0	1.1
MK10+CRT10	422.63	37.35	0.4	823.24	818.80	90.98	1.1
MK10+CRT20	422.63	37.35	0.4	823.24	727.82	181.96	1.1
MK10+CRT30	422.63	37.35	0.4	823.24	636.85	272.93	1.05
MK10+CRT40	422.63	37.35	0.4	823.24	545.87	363.91	1
MK10+CRT50	422.63	37.35	0.4	823.24	454.89	454.89	0.95
MK15+CRT0	399.15	56.03	0.4	823.24	909.78	0	1.2
MK15+CRT10	399.15	56.03	0.4	823.24	818.80	90.98	1.2
MK15+CRT20	399.15	56.03	0.4	823.24	727.82	181.96	1.2
MK15+CRT30	399.15	56.03	0.4	823.24	636.85	272.93	1.15
MK15+CRT40	399.15	56.03	0.4	823.24	545.87	363.91	1.15
MK15+CRT50	399.15	56.03	0.4	823.24	454.89	454.89	1.1

Table 3 Mix proportions of different SCC mixtures
3. táblázat A különböző SCC keverékek összetételei

fine aggregate, while in the remaining mixtures the cement was partially replaced by MK at 5, 10 and 15% and sand was replaced by CRT glass at levels of 0, 10, 20, 30, 40 and 50%. This step would determine the quantity required for each material in the batch to obtain a concrete with the desired properties, the Okamura's method [27] was used to determine mixture proportions of SCC. The proportions of all the SCC mixtures are given in *Table 3*.

2.3 Mixing procedure

The mixing procedure was as follows: the powder and aggregates were mixed together for half a minute (30 s), then 70% of the mixing water was added and mixed for 1 min. The remaining 30% of water containing the superplasticiser and the concrete was added and mixed for 1 min. This procedure continued for another 5 minutes and then stopped for 2 minutes. The concrete was mixed again for 30 seconds to ensure the properties of self-compacting concrete [28].

2.4 Test methods

According to EFNARC guidelines for SCC committee [29], the slump flow diameter and time required to reach a slump diameter of 500 mm (EN 12350-8), the V-funnel flow time (EN 12350-9), the L-box height ratio (EN 12350-10) and sieve stability (EN 12350-11) were carried out to characterise the filling, passage, and segregation of the fresh concrete.

A modification to the slump flow test allowed the rheological characteristics of fresh concrete, the yield stress (τ_0), and the viscosity (μ) to be evaluated (*Fig. 4*) [11].

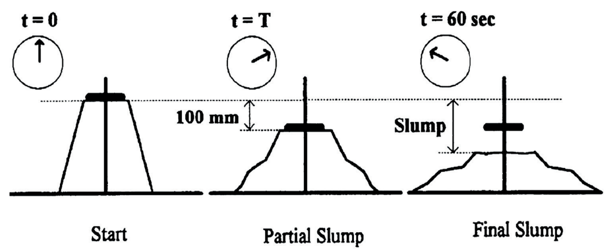

Fig. 4 Description of modified slump test
4. ábra A módosított roskadási terülés vizsgálat leírása

The yield stress was associated to the final slump (S) and the plastic viscosity was related to the time (T) to slump down to a height of 100 mm. The rheological parameters were calculated using the following empirical equations:

$$\tau_0 = \frac{\rho}{347}(300 - S) + 21 \quad (1)$$

$$\mu = \rho.T.1{,}08.10^{-5}(S - 175) \quad (2)$$

τ_0: yield stress (Pa);
μ: plastic viscosity (Pa.s);
S: final slump (mm);
ρ: specific gravity of fresh SCC (kg/m³);
T: time of partial slump (s).

3. Results and discussion

3.1 Slump flow and T_{500} time test

Fig. 5 shows the fresh properties of all the SCC, where the flow time T_{500} was less than 2.25 s and the slump flow diameters of all SCC mixes groups are 700 and 800 mm; this indicates good deformability and comply with the EFNARC recommendations [29]. These results indicate that MK reduces the slump flow diameter, unlike the control concrete. This decrease with 15% of MK is quite remarkable. There was an increase in slump flow and flow time (T_{500}) in SCC when the mixture contained CRT glass. This increase was significant compared to natural sand, particularly when the percentage of CRT glass reached 50%. This improvement may be due to differences in texture between sand and glass, which better fill the space between the coarse aggregates, and furthermore, glass sand has low water absorption and a smooth surface [30-32]. It can be concluded that combining CRT glass with MK had a beneficial effect on the spread of slump.

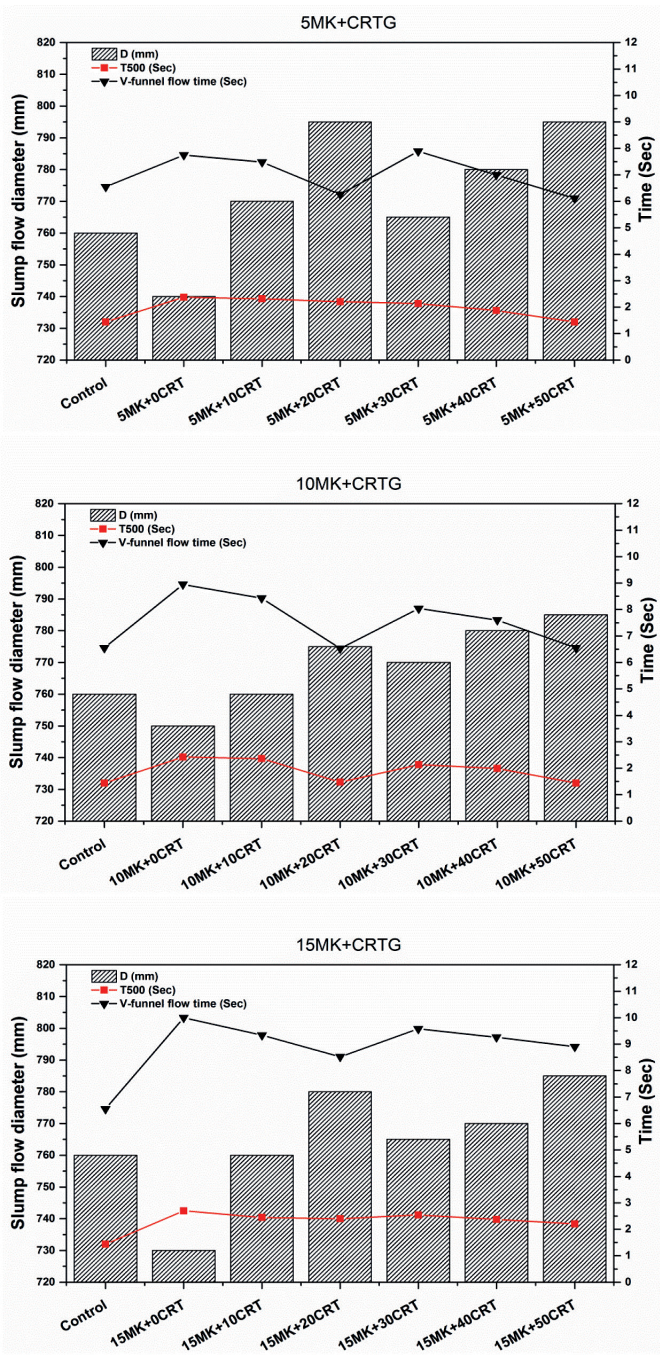

Fig. 5 *Slump flow diameter and V-funnel time of different SCC mixes*
5. ábra *A különböző öntömörödő keverékek roskadási terülési átmérője és V-tölcsér kifolyási ideje*

3.2 V-funnel flow time

Based on the results of the V-funnel test, all SCC mixtures were very stable because their flow times were less than the recommended value (12 s). *Fig. 5* shows that the addition of MK increases the flow time and viscosity by up to 15%, but it needed water and a superplasticiser to have desired self-compacting properties due to the high specific surface area of MK [33]. Rahmat and Yasin, [34] studied the fresh properties of SCC with MK and noted that the flow time increased as the amount of MK increased with a higher dose of SP. Moreover, substituting sand with CRT glass reduced the flow time so that it converged more rapidly towards the lower threshold. The best flow times occurred by adding 50% glass into all the group mixes, this and a low dose of SP reduced the viscosity also facilitated the pumpability of concretes in confined areas. *Fig. 6* plots the relationships between the V-funnel flow times and T_{500} slump flow for all groups and shows that the coefficient of correlation (R^2 superior of 0.8) has an acceptable linear correlation between the two variables.

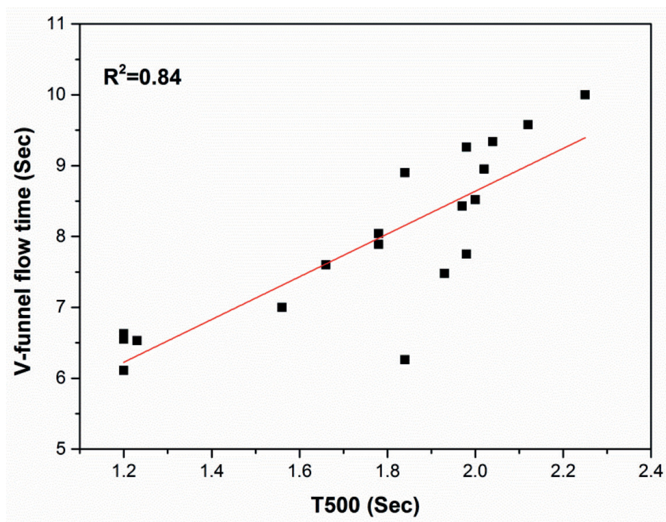

Fig. 6 *Relationship between V-funnel time and slump flow time T500*
6. ábra *V-tölcsér kifolyási idő és roskadási terülési idő (T500) kapcsolata*

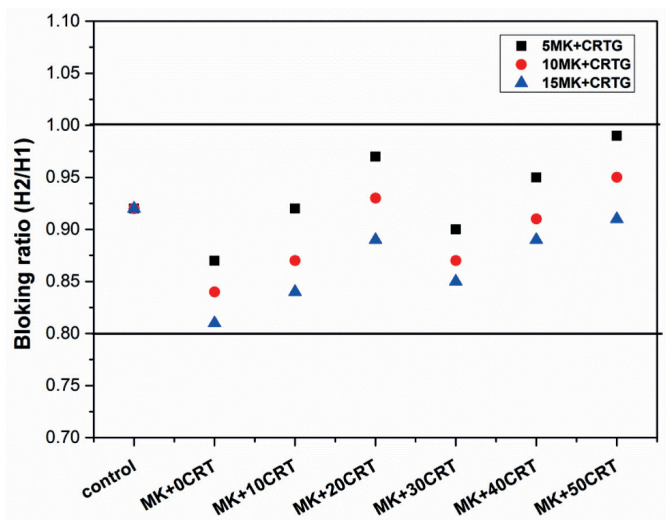

Fig. 7 *Blocking ratio of different SCC mixes*
7. ábra *Különböző SCC-keverékek blokkolódási aránya*

3.3 L-box test

With respect to the filling capacity estimated by the H_2 / H_1 ratio measured by the L-box test; all the SCC groups had a ratio H_2 / H_1> 0.8 which is in accordance with the EFNARC limitations [29]. *Fig. 7* shows that the introduction of CRT glass gave a good filling capacity, mobility, and the passage of SCC through heavily scrapped areas. Kou and Poon [35] studied the properties of SCC prepared with recycled glass aggregate and found that the ability to fill in L-box improved when the amount of recycled glass increased.

3.4 Sieve stability test

The results presented in *Fig. 8* show that all SCC had the highest stability, whereas the low milt value was due to the lack of paste that can stick to the aggregates. However, there is an optimal dosage of around 50%, beyond which stability decreases as the volume concentration of CRT glass increases because the less viscous concrete makes it easier to pass through the sieve. Umehara et al [36] reported that this decrease in the viscosity of concrete is consistent with a reduction in stability. These results will be confirmed later through the results of viscosity.

3.5 Yield stress

Fig. 9 shows the evolution of yield stress of all the SCC mixes; note that mixtures containing MK without CRT sand glass showed a shear-thickening fluid effect due to the increase in yield stress. The optimal dose was 15% MK. Parviz et al [37] reported that the rheological properties of SCC mixes with partial replacement of metakaolin reached a higher yield stress than with other mineral admixtures. Hassan and Lachemi [38] studied the effect that metakaolin had on the rheology of SCC and found that the yield stress increased as the percentage of MK increased. The incorporation of CRT sand glass helps to reduce the yield stresses, which results in a shear thinning effect, but beyond the optimal dosage of 50%, the yield stress decreased due to the effect of increasing the volume of CRT sand glass.

3.6 Plastic viscosity

The plastic viscosity of SCC containing different dose of CRT glass and MK are shown in *Fig. 10*; it shows that the viscosity increased by 36% when 15% MK was added. Güneyisi and Gesoğlu [39] investigated the effect that MK had on the viscosity of self-compacting mortar and concluded that mortars with 15% MK required a higher viscosity; nevertheless an increase in CRT sand glass reduced the plastic viscosity. The combined use of CRT sand glass has important benefits in terms of the negative effect of MK on the pumpability of concrete and the casting time.

3.7 Correlation between rheological properties

Fig. 11 highlights the relationship between yield stress and slump flow for all the SCC mixtures. Note that the yield stress decreased as the slump flow diameters increased, but the relationship between slump flow and yield stress obtained by the modified slump test showed a good correlation with the

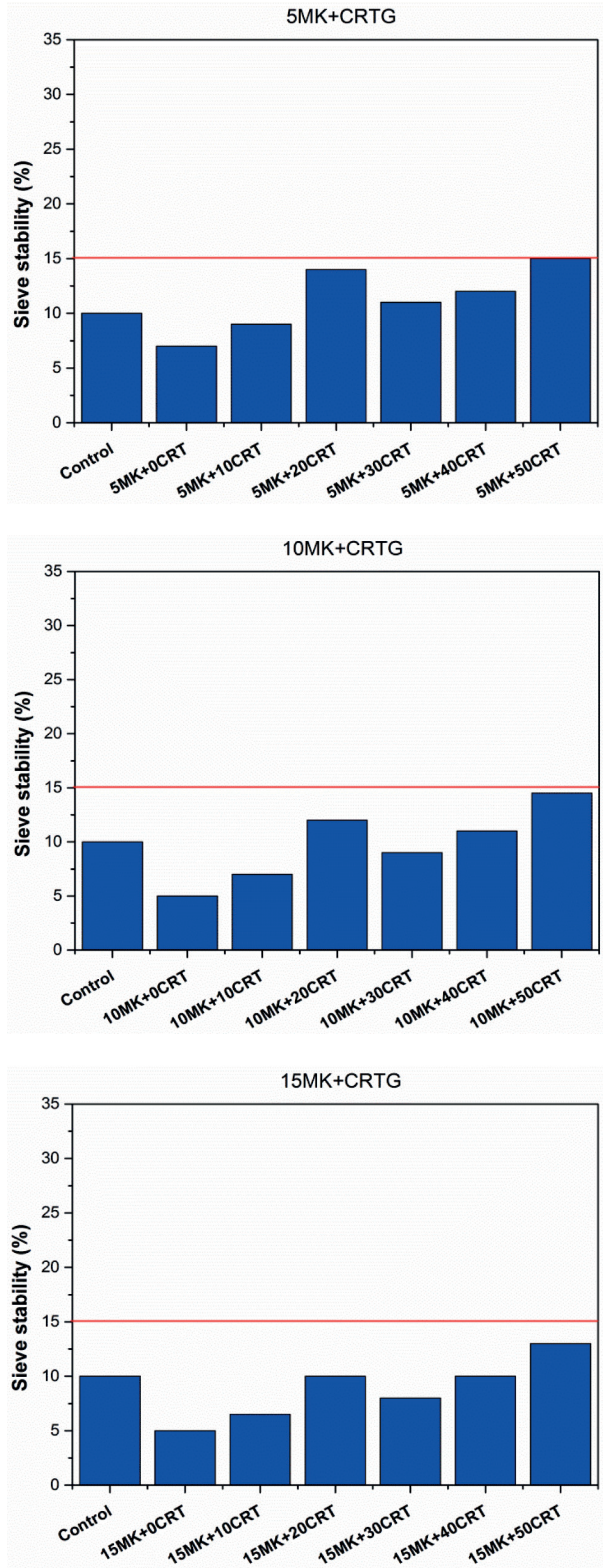

Fig. 8 Sieve stability segregation of different SCC mixes

8. ábra Különböző SCC-keverékek szitás szétosztályozódási hányada

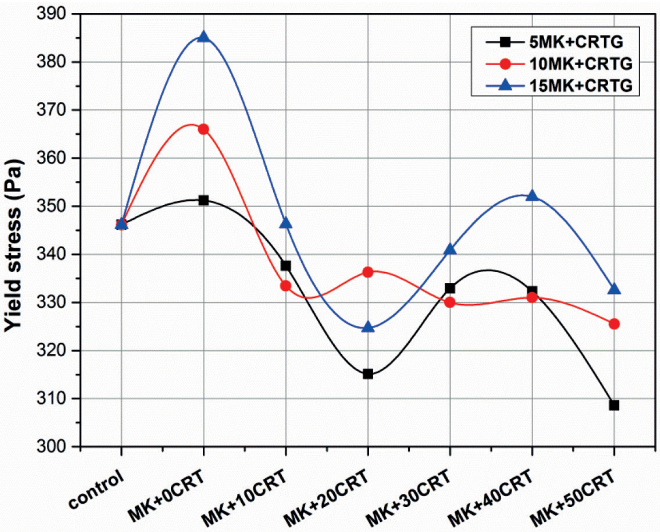

Fig. 9 Yield stress of different SCC mixes
9. ábra Különböző SCC-keverékek folyási feszültsége

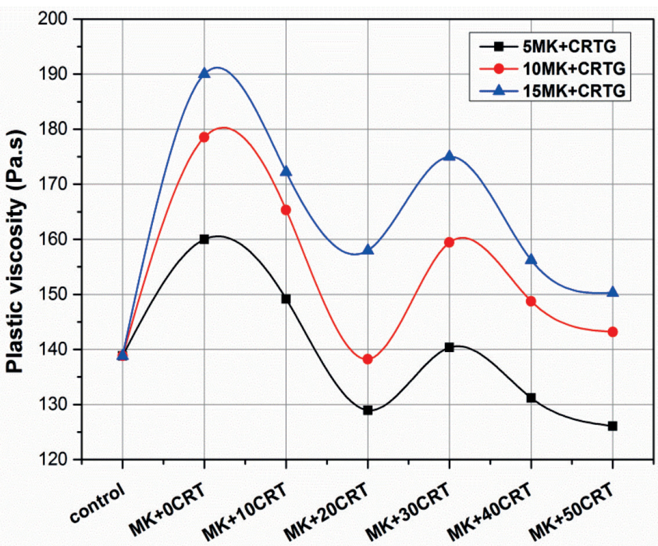

Fig. 10 Plastic viscosity of different SCC mixes
10. ábra Különböző SCC-keverékek plasztikus viszkozitása

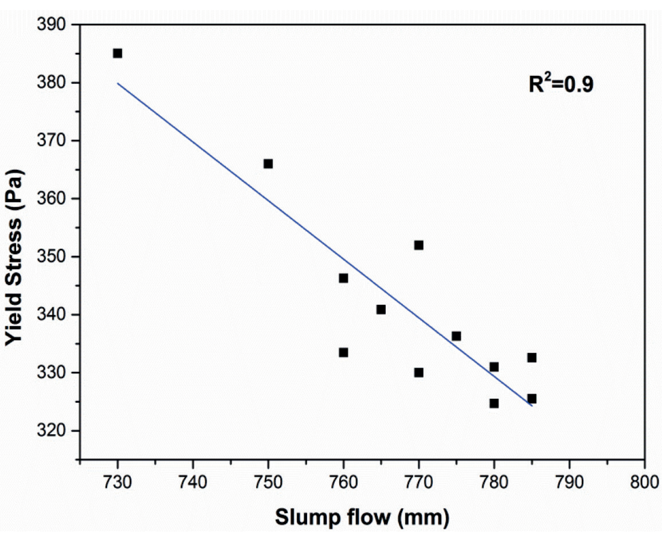

Fig. 11 Relationship between yield stress and slump flow of different SCC mixes
11. ábra SCC keverékek folyási feszültség és roskadási terülés közötti kapcsolata

coefficient R^2= 0.9. The trend of yield stress obtained by the modified slump test confirmed those found by the spreading test; this proves the relevance of this method. As *Fig. 12* shows, the plastic viscosity was proportional to the V-funnel flow times, which corroborates well with of the V-funnel time (R^2= 0.89). The obtained results are similar to those achieved by Boukendakji et al [40] and Boukhelkhal et al [41].

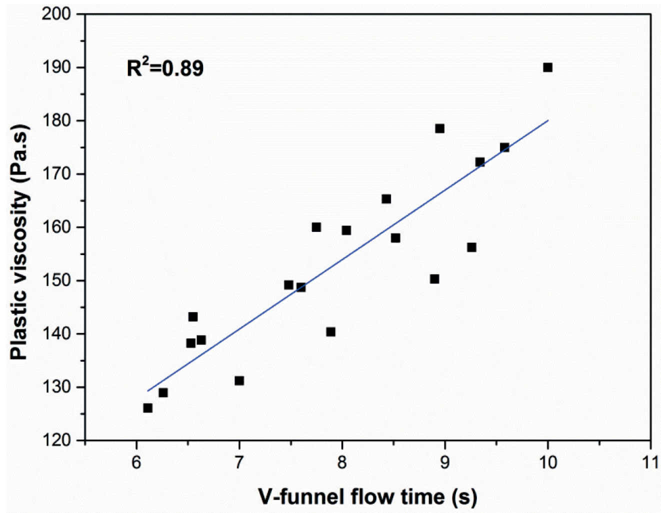

Fig. 12 Relationship between plastic viscosity and V-funnel time of different SCC mixes
12. ábra Különböző SCC-keverékek plasztikus viszkozitásának és V-tölcsér kifolyási idejének összefüggése

4. Conclusions

The use of CRT glass as fine aggregate and MK powder in SCC would not only treat the rheology of SCC (spreading, filling rate, yield stress and viscosity), it would also result in the best environmental practices by optimising and managing the waste materials, energy, and CO_2 emissions. To address these concerns, an experimental program has been set up to understand and provide answers to the questions posed in this work. The conclusions are as follows:

- The incorporation of 50% CRT glass by the mass of sand improved the workability of SCC, while low doses of superplasticiser maintained the same fresh properties; this reduction helps to lower the cost of SCC.
- An increase of 50% in CRT glass reduced sieve stability because it is related to the low viscosity of concrete that makes it easier to pass through the sieve; this leads to an increase in the segregation of SCC.
- With regard to the rheological parameters of SCC, the increase of CRT glass reduced the yield stress and plastic viscosity; the mixture with 15MK+0CRT had the highest yield stress and plastic viscosity.
- The rheological parameters and the yield stress and plastic viscosity can be evaluated using the modified slump test. An acceptable relationship between the rheological properties with the coefficient R^2 superior than 0.9, which indicates the relevance of this method.
- The combined use of CRT sand glass would have important benefits in terms of the negative effect that MK has on the pumpability and the implementation of SCC and the casting time.

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