HIGHLY WORKABLE ECO-FRIENDLY CONCRETES – INFLUENCE OF THE CONSTITUENTS ON THE RHEOLOGICAL PROPERTIES

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ABSTRACT

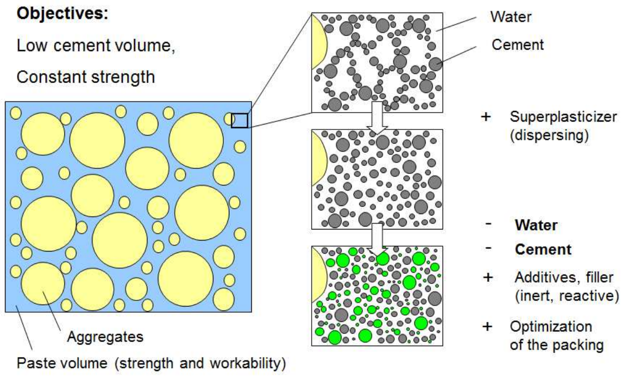
The objectives of the present study are the rheological properties of highly workable eco-friendly concretes with reduced water and cement content. The replacement of water and cement with reactive substitutions and inert fillers with certain finesses leads to a higher packing density of the concrete. The yield stress of the fresh concrete can be limited by the use of high performance superplasticizers and an optimized particle size distribution. However, due to the low water content, Eco-concretes have a significantly higher plastic viscosity compared to conventional concretes. For the application in practice, the viscosity should be limited to an acceptable value. In several test series the influence of the mix proportion on the rheological properties was analyzed. It was observed that for a given water content, replacement of cement with fly ash, normal and ultra-fine limestone powder, and silica fume reduces the plastic viscosity and increases the flow yield stress. Furthermore, it was found that highly flowable eco-friendly concretes with very low cement content (up to 135 kg/m^3) can be achieved by an optimized paste volume of about 320 and 360 l/m^3 for water-powder ratios of 0.35 and 0.30, respectively.

Keywords: Eco-friendly concrete, rheological properties

INTRODUCTION

ECO-FRIENDLY CONCRETE. The major environmental impact of concrete comes from the CO_2-emissions during cement production as a result of the calcination and grinding process. The CO_2-emissions are mainly related to the decalcination of the limestone, the fuel consumption and the electricity consumption [1]. Approximately five percent of the global anthropogenic CO_2-emission is connected with the production of 3.3 billion tons of cement per year (2010) [2]. Therefore, the reduction of the cement-clinker content has positive effects on the environmental life cycle assessment of the concrete and can be achieved by the optimization of the mixture design [3]. The use of superplasticizer and high reactive cements as well as the optimization of the particle size distribution and the reduction of the water volume allows a significant reduction of the Portland cement clinker in the mixture (Figure 1). Essential is the addition of mineral fillers like limestone powder to provide an optimal paste volume in the low water mix. In addition the already practicable substitution of the cement clinker by secondary raw materials like fly ash or furnace slag is an appropriate opportunity but limited by the availability of these resources. It has to be considered, that a certain paste volume is necessary to maintain the required workability. This implies that a minimization of the paste content and hence an additional reduction of the water and cement content is based on an optimization of the aggregates packing.

Figure 1. Evolution from the traditional mixture proportion to cement reduced eco-friendly concrete [3]



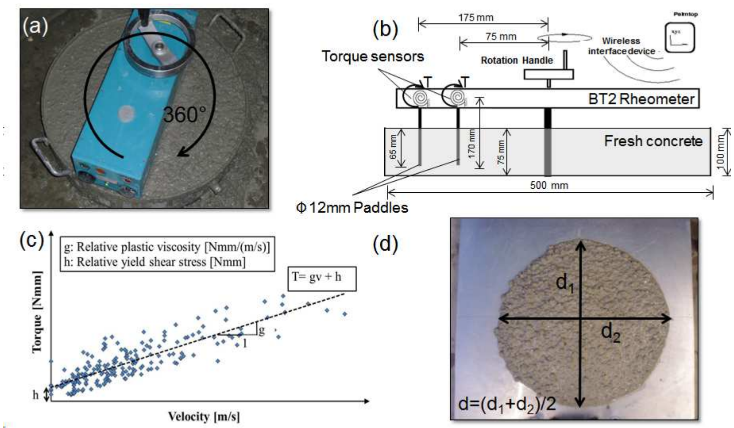
RHEOLOGY OF CONCRETE

Several models are developed to understand the rheological properties and concrete flow as a non-Newtonian fluid [4, 5]. Among them, Bingham model is frequently cited as a reliable model to judge and predict the flow behavior of concrete based on its two fundamental parameters (the plastic viscosity η and the yield stress τ). It is well agreed that the rheology of concrete is influenced by water content, mixture temperature, type and packing density of binder and the degree of hydration. For a given water content, an increase in normalized solid concentration results in a considerable growth of plastic viscosity of mixture [6]. Vikan and Park concluded that the addition of limestone powder and silica fume increases the flow resistance of cementitious pastes in combination with sulphate-formaldehyde condensate superplasticizers [7-9]. Similarly, Esping reported that an increased BET(H_2O)-area of limestone powder results in a remarkable increase in both plastic viscosity and yield stress values [10]. Influence of super-fine fillers on rheology of cement pastes depends mainly on the water-cement ratio. For a water-cement ratio ≤0.22 an increase in superfine fillers led to a reduction in plastic viscosity and yield stress, while an inverse behavior was reported for a water-cement ratio ≥ 0.24 [10]. Instinctly, due to the low water content, eco-friendly concretes may exhibit a higher plastic viscosity than conventional concretes. Therefore, it is important to optimize the plastic viscosity in order to ease the placing and handling process.

TEST METHODS

In order to investigate the rheological properties of eco-friendly concrete mixtures, the portable BT2-Schleibinger™ concrete rheometer was employed. The rheological measurement was conducted 15 minutes after water addition. For this purpose, concrete was poured into the container and the device placed in the center (Figure 2-a). During the manual revolution, velocity and corresponding torque values – imposed on two 12 mm paddles- were measured and recorded digitally by means of the rheometer. The relative fundamental rheological parameters; i.e. relative plastic viscosity and relative yield stress, based on the Bingham model were calculated (Figure 2-d). The tests were conducted under laboratory condition in an air temperature of 20°C. The table flow and slump flow of fresh mixtures were measured according to DIN EN 12350-5 and [11] for first and second test series, respectively (Figure 2.d). Six 150 mm cubic samples of each mixture were cast for compressive strength test at 1 and 28d ages. The one-day compressive strength was measured after demolding and the other specimens were stored in water for 7 days. After that, the specimens were moved into a climate chamber at the temperature of 20°C and relative humidity of 65 % for 20 days.

Figure 2. a) table flow test; b) schematic view of BT2 rheometer; c) actual view of BT2 rheometer; d) calculation of rheological parameters



3. MIX PROPORTION

This study is basically divided into two parts. In the first part, the target was to optimize the plastic viscosity of eco-friendly concretes with low amount of cement and water. In the second part, the rheological behavior of highly workable and self-compacting water reduced eco-friendly concretes was investigated.

In the first test series, starting with the reference concretes with a cement content of 280 kg/m³, the cement content was reduced from 385 kg/m³ to 123 kg/m³ (see Table 1 and 2). In order to have a constant paste content of about 259-275 l/m³, the cement was substituted by additives. Also the water volume was reduced gradually. The lowest water content was 110 kg/m³. To maintain sufficient workability the powder content (<0.125 mm) was increased up to 440 kg/m³ by the addition of fly ash, limestone powder and silica fume. The table flow of approx. 550 mm was adjusted by changing the dosage of superplasticizer. The CEM I 52.5 R Portland cement clinker (C) with high early strength and a high strength class as well as Portland limestone cement (CEM II/A-LL 32.5 R) with a clinker content up to 85 % were used. Two types of limestone powder; "normal" (N) with Blaine value of 3,100 and ultra-fine (U) with the Blaine value of 16,000 cm²/g as well as fly ash (F) with Blaine value of 2990 cm²/g and silica fume (SF) were considered as the additives. The cement content was limited to 100, 70, 50 and 30%. The normal limestone powder substituted stepwise with 10, 20, 30 % of ultra-fine limestone powder, 25, 50, 75 and 100 % fly ash as well as 7 and 14 % silica fume. In the second test series, the influence of the paste volume (with a constant paste/mortar ratio) as well as the water-powder ratio on the rheology of cement reduced eco-friendly concretes were investigated, in order to achieve highly flowable and self-compacting concretes with the slump flow of about 700 mm. The paste content was increased gradually up to 390 l/m³ with two different water-powder ratios of 0.35 and 0.30. The cement content was limited up to 50 and 30 % of the total powder content. Two conventional SCC mixes with 60 % Portland cement and w/p= 0.43 were the reference SCC mixtures. Detailed mix proportions of the concretes investigated in test series 2 are presented in Table 3.

RESULTS AND DISCUSSIONS

Compressive strength. Results for one and 28-days compressive strength are presented in Table 1 to Table 3. Results indicate that most of cement reduced concrete mixtures had equal or higher compressive strengths than conventional mixtures. This can be attributed to the lower water content. Increase in fly ash, silica fume and ultra-fine limestone powder could significantly promote the compressive strength. It seems that the presence of ultra-fine limestone powder is more efficient when lower amount of cement is used. This can be resulted by comparison the compressive strength of mixes with 50 and 30 % of cement for w/p= 0.35. Meanwhile, comparison of one day and 28 days compressive strengths of mixtures reveals a higher rate of strength development for mixtures containing fly ash due to slow pozzolanic reactions.

Table 1. Mix design and results of the mixes with w/p= 0.60 and 0.35

Mix design (Series 1)	**Unit**	**Conventional (w/p= 0.60)**		**Cement reduced (w/p= 0.35)**									
		C280-CEM I 52.5 R-w170	**C280-CEM II/A-LL 32.5 R-w170**	**C385-CEM I 52.5 R-w135**	**C270-CEM I 52.5 R-LSP115-w135**	**C190-CEM I 52.5 R-LSP190-w135**	**C115-CEM I 52.5 R-LSP270-w135**	**C190-CEM I 52.5 R-LSP175-SF 15-w135**	**C190-CEM I 52.5 R-LSP165-SF 25-w135**	**C190-CEM I 52.5 R-LSP140-FA 45-w135**	**C190-CEM I 52.5 R-LSP95-FA 95-w135**	**C190-CEM I 52.5 R-LSP45-FA 140-w135**	**C190-CEM I 52.5 R-FA 180-w135**
CEM I 52.5 R	[kg/m³]	280	-	385	270	190	115	190	190	190	190	190	190
CEM II/A-LL 32.5 R	[kg/m³]	-	280	-	-	-	-	-	-	-	-	-	-
Fly Ash (EN 450)	[kg/m³]	-	-	-	-	-	-	-	-	45	95	140	180
Limestone powder (N)	[kg/m³]	-	-	-	115	190	270	175	165	140	95	45	-
Silica Fume	[kg/m³]	-	-	-	-	-	-	13	25	-	-	-	-
Water	[kg/m³]	170	170	135	135	135	135	135	135	135	135	135	135
Superplasticizer	[kg/m³]	0.0	0.0	6.4	3.7	2.6	2.0	2.5	2.8	3.4	2.8	2.7	2.4
River sand 0-2 mm	[kg/m³]	522	522	504	504	504	493	504	504	504	504	504	504
River gravel 2-8 mm	[kg/m³]	477	477	477	477	477	477	477	477	477	477	477	477
River gravel 8-16 mm	[kg/m³]	826	826	826	826	826	826	826	826	826	826	826	826
Clinker/powder	[%]	100	85	100	70	50	30	50	50	51	50	50	50
Paste volume	[l/m³]	259	262	262	267	266	271	265	266	268	273	274	275
Water/clinker	[-]	0.61	0.61	0.35	0.50	0.71	1.17	0.71	0.71	0.71	0.71	0.71	0.71
Table Flow[1)]	[mm]	445	485	600	510	620	610	530	490	605	570	560	520
Relative plastic viscosity	[$\times 10^{-3}$ Nmm/(m/s)]	9.8	6.7	59.0	19.6	42.5	90.9	24.5	28.8	55.4	39.5	31.5	31.3
Relative flow yield stress	[Nmm]	6505	5264	1191	2006	946	1578	1579	1758	303	790	1553	1458
1d Compressive strength	[MPa]	21.2	7.0	63.8	33.3	18.6	8.4	23.8	25.8	21.9	17.5	17.5	14.8
28d Compressive strength	[MPa]	51.5	38.5	106.7	88.5	63.0	30.6	68.3	79.0	68.1	71.5	72.3	70.1

[1)] Table flow test according to DIN EN 12350-5

Table 2. Mix design and results of the cement reduced concretes with w/powder= 0.30

Mix design (Series 1)	**Unit**	**w/p= 0.30**							
		C210-CEM I 52.5 R-LSP210-w125	**C210-CEM I 52.5 R-LSP (N/F) 185/20-w125**	**C210-CEM I 52.5 R-LSP (N/F) 165/40-w125**	**C210-CEM I 52.5 R-LSP (N/F) 145/60-w125**	**C125-CEM I 52.5 R-LSP (N/F) 285-w125**	**C125-CEM I 52.5 R-LSP (N/F) 255/30-w125**	**C125-CEM I 52.5 R-LSP (N/F) 230/55-w125**	**C125-CEM I 52.5 R-LSP (N/F) 200/85-w125**
CEM I 52.5 R	[kg/m³]	208	208	208	208	123	123	123	123
Limestone powder (N)	[kg/m³]	208	187	166	146	286	257	229	200
Limestone powder (F)	[kg/m³]	-	21	42	62	-	29	57	86
Water	[kg/m³]	125	125	125	125	125	125	125	125
Superplasticizer	[kg/m³]	3.4	3.3	3.3	3.5	3.2	2.5	2.9	2.6
River sand 0-2 mm	[kg/m³]	493	493	493	493	493	493	493	493
River gravel 2-8 mm	[kg/m³]	477	477	477	477	477	477	477	477
River gravel 8-16 mm	[kg/m³]	826	826	826	826	826	826	826	826
Clinker/powder	[kg/m³]	50	50	50	50	30	30	30	30
Paste volume	[l/m³]	271	271	271	271	272	272	272	272
Water/clinker	[-]	0.60	0.60	0.60	0.60	1.02	1.02	1.02	1.02
Slump flow[1)]	[mm]	580	595	495	570	620	550	595	530
Relative plastic viscosity	[$\times 10^{-3}$Nmm/(m/s)]	67.6	50.1	44.8	38.9	120.2	56.9	43.0	45.9
Relative flow yield stress	[Nmm]	797	1045	1314	782	333	1045	1366	1579
1d Compressive strength	[MPa]	27.7	28.2	28.2	32.7	12.6	14.4	13.8	17.9
28d Compressive strength	[MPa]	73.5	73.1	72.7	77.6	41.9	43.8	45.1	48.3

[1)] Table flow test according to DIN EN 12350-5

Table 3. Summarized mix design and results of the cement reduced concretes with different grading curve and paste volume

Mix design (Series 2)	Unit	w/p=0.43		w/p=0.35						w/p=0.30				
		C280-CEM I 52.5 R-LSP 185-w205	C305-CEM I 52.5 R-LSP 205-w220	C215-CEM I 52.5 R-LSP 215-w155	C240-CEM I 52.5 R-LSP 240-w170	C260-CEM I 52.5 R-LSP 260-w185	C135-CEM I 52.5 R-LSP 320-w160	C155-CEM I 52.5 R-LSP 355-w180	C165-CEM I 52.5 R-LSP 385-w195	C135-CEM I 52.5 R-LSP 320-w140	C145-CEM I 52.5 R-LSP 340-w145	C165-CEM I 52.5 R-LSP 385-w165	C180-CEM I 52.5 R-LSP 415-w180	C165-CEM I 52.5 R-LSP(N/F) 270/115-w170
CEM I 52.5 R	$[kg/m^3]$	280	305	215	240	260	135	155	165	135	145	165	180	165
Limestone powder (N)	$[kg/m^3]$	185	205	215	240	260	320	355	385	320	340	385	415	270
Limestone powder (F)	$[kg/m^3]$	-	-	-	-	-	-	-	-	-	-	-	-	115
Water	$[kg/m^3]$	205	220	155	170	185	160	180	195	140	145	165	180	170
Superplasticizer	$[kg/m^3]$	1.8	4.5	2.4	2.5	2.9	1.9	4.5	2.5	5.5	4.1	4.1	3.6	3.8
River sand 0-2 mm	$[kg/m^3]$	663	717	575	632	690	572	663	717	553	590	663	717	690
River gravel 2-8 mm	$[kg/m^3]$	319	268	413	361	308	394	319	268	422	387	319	268	308
River gravel 8-16 mm	$[kg/m^3]$	552	465	715	625	534	682	552	465	730	671	552	465	534
Clinker/powder	[%]	60	60	50	50	50	30	30	30	30	30	30	30	30
Paste volume	$[l/m^3]$	360	390	300	330	360	320	360	390	300	320	360	390	360
Water/clinker	[-]	0.73	0.72	0.72	0.71	0.71	1.19	1.16	1.18	1.04	1.00	1.00	1.00	1.03
Slump flow[1)]	[mm]	660	698	560[2)]	615[2)]	670	680	710	690	740	745	760	710	700
Relative plastic viscosity	$[\times 10^3$ Nmm/(m/s)]	1.5	1.5	23.8	13.6	2.0	5.2	4.2	3.2	61.8	17.7	9.4	6.2	2.7
Relative flow yield stress	[Nmm]	51	43	684	312	46	96	14	34	320[3)]	257	50	1[3)]	37
1d Compressive strength	[MPa]	20.4	19.4	NA	NA	26.0	9.0	11.8	12.3	17.2	13.0	14.3	18.6	20.5
28d Compressive strength	[MPa]	48.7	46.3	60.3	56.2	58.5	33.8	40.9	40.4	57.8	42.9	42.6	53.3	52.2

[1)] Slump flow for Self-compacting concrete according to [11] [2)] Table flow test according to DIN EN 12350-5 [3)] The minimum torque obtained from flow curve

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The values for the relative plastic viscosity of the concretes just 15 minutes after water addition are plotted in Figure 3. The results indicate the significant effect of water content on the plastic viscosity of the concrete. The lower the water content, the higher the plastic viscosity. Hence, the conventional concretes with a relative higher amount of water show low values of plastic viscosity. Preliminary studies showed that a relative viscosity below 43×10^3 Nmm/(m/s) is acceptable for ready-mix concrete and precast element contractors to produce structural concrete. Replacement of 30 % of Portland cement with normal limestone powder in mix C385-CEM I 52.5 R-w135 decreases the relative plastic viscosity but an excessive substitution of Portland cement by limestone powder leads to an increase in relative plastic viscosity. However, introduction of ultra-fine limestone powder to the mixtures could diminish the viscosity of mixtures up to 34 % due to improvement in particles packing. In comparison with the mix C385-CEM I 52.5-w135 substitution of cement with silica fume or fly ash results in a pronounced reduction of plastic viscosity, while the largest reduction was observed with replacing 115 kg replacement by normal limestone. Moreover, adding a certain amount of ultra-fine limestone powder of about 55 kg/m^3 could lessen the viscosity. This was more remarkable for lower Portland cement ratios, i. e. 30 % of total powder content. As Figure 4 reveals that the plastic viscosity is highly dependent on the paste content and is decreased significantly with an increase of paste volume. The intensity of this reduction has an inverse relation with the contents of water and Portland cement. Regardless to the clinker/LSP ratios, the paste volume of about 320 l/m^3 for w/p= 0.35 and 360 l/m^3 for w/p= 0.30 can be assumed as the viscosity-threshold contents. It means that no significant change in viscosity could be observed beyond these contents. According to the visual observations and impressions during casting and placing, an acceptable viscosity without any segregation was observed for these paste contents, whereas a profound thixotropic behavior for plastic viscosity was observed for mixes with w/p= 0.30 due to a very low water content. The reducing effect of ultra-fine limestone powder on the plastic viscosity was also remarkable in mixture with 30 % of ultra-fine limestone powder. It has to be mentioned that supplementary tests are needed to investigate the passingability resistance of self-compacting mixes.

Figure 3. Relative plastic viscosity of concrete mixtures with different additions.

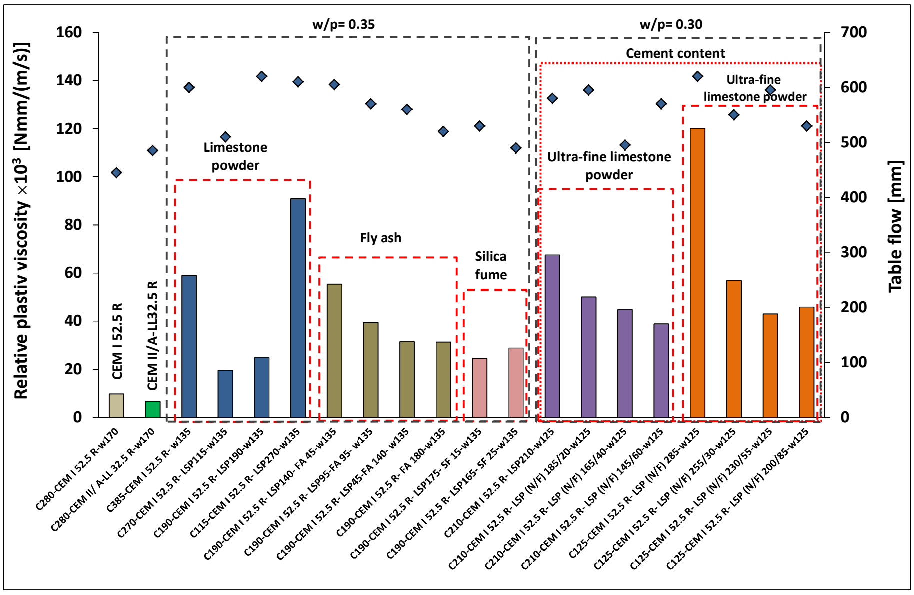
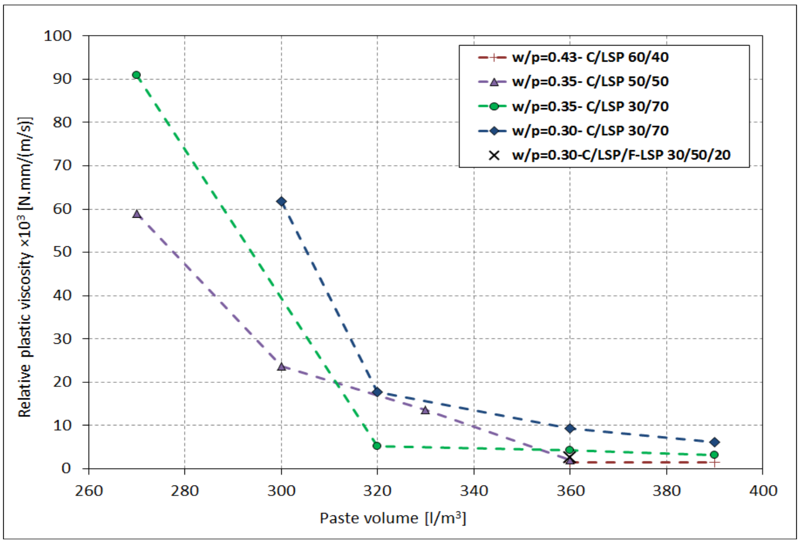


Figure 4. Relative plastic viscosity of different mixtures as a function of w/p and paste content.



5. Conclusion

According to the results, the following conclusions can be derived:

1. For cement reduced concretes the same compressive strength can be achieved in comparison with the conventional mixtures with a reduction of clinker from 280 to 165 kg/m^3.

2. Replacement of Portland cement with normal limestone powder reduces the plastic viscosity. Further reduction is possible when normal limestone powder is substituted partially with ultra-fine limestone powder, fly ash or silica fume.

3. The use of ultra-fine limestone powder to reduce the viscosity was more efficient with lower clinker content and w/p ratio.

4. In order to achieve a highly flowable mixture, the optimum paste volume was observed to be about 360 and 320 l/m^3 for mixture with w/p= 0.30 and w/p= 0.35, respectively. At this no sign of sedimentation was observed.

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