STUDY OF THE CONSISTENCY OF FRESH CONCRETE BY SLUMP TEST AND FLOW TABLE TEST – FOCUS ON LATERAL PRESSURE ON FORMWORK

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Abstract. In this paper, the consistency of normal concrete mixtures is investigated applying standardized methods – slump test and flow table test. An analysis of the results was made to determine the relationship between the consistency measured by the two methods. It is found that, especially for mixes subjected to testing in this study, there is a correlation between the consistency of fresh concrete determined by slump test and flow table test. The relevant findings and conclusions are drawn and the possibility of using the data on consistency obtained by the slump test in determining the horizontal pressure of fresh concrete on vertical formwork according to DIN 18218 is also discussed.

Keywords: Consistency, Concrete mixtures, Slump test, Flow table test, Rheological properties, Correlation, Horizontal formwork pressure.

1. INTRODUCTION

The consistency is the main and probably the most important technological property of any concrete mixture. It is a measure for the relative mobility of fresh concrete, which provides information on another complex property – workability i.e. its ability to mix, to be compacted, to fill the formwork and to be finished with minimal efforts. In the case of high-tech concretes, the workability allows complete filling the forms (formwork, space between reinforcement bars, excavation, etc.) only under the action of its own weight or with minimal external interference (shakes, vibrations), preserving the homogeneity achieved during the mixing.

It can be said that the consistency affects indirectly the physical and mechanical characteristics of the concrete – when it is not compatible with the compaction method used, the hardened concrete does not have the necessary

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density, which may leads to decrease of important characteristics, such as freeze-thaw resistance, water tightness and, of course, strength [1, 2, 3, 4, 5, etc.].

It is well known, numerous factors have impact on the consistency, and the workability of fresh concrete, respectively, such as the amount and quality of the cement paste in the concrete, the method and duration of transportation of concrete mixture, the initial slump of concrete mixture, particle size distribution, shape and specific surface texture of aggregates, entrained air volume in concrete mixture, water content, temperature of concrete mix and the surrounding air, presence and type of chemical admixtures, etc. [5, 6, 7, 8].

The continuous particle size distribution of the aggregates (well-graded), the reduced amount of mixing water and the presence of fine particles in concrete mixture significantly helps to control segregation and improve workability. Rapid loss of workability can be prevented by continuous homogenization of the mixture, for example in the truck mixer, or by modifying the composition by means of chemical additives (concrete plasticizers and retarders). The consistency of concrete mixture and the properties of hardened concrete are additionally influenced by the size, shape and purity of fine and coarse aggregates [6, 9], which are formed during their production through the proper selection and control of the processes of crushing, sieving and washing equipment [10, 11]. Water loss caused by aggregate absorption could be avoided by using aggregates produced from crushing dense rock or by pre-wetting the available aggregates, for example by water spraying water or covering them in hot/dry weather (sometimes difficult feasible and perhaps undesirable when using lightweight aggregates). The mixing water evaporation may be considerably reduced by covering the fresh concrete with watertight polymer sheets or by treating with curing compounds. The excessive quantity of water added to achieve high slump (consistency) is the main reason for decrease of concrete properties, as it leads to bleeding, segregation and increased plastic and drying shrinkage [1, 4, 6]. The concrete mixture shall have the lowest possible water content and consistency values, respectively, that allow concreting to be carried out using the available pouring and compacting equipment.

In order to fully clarify such properties as mobility (spreading and flow ability) and stability (segregation resistance) of concrete mixtures, the methods of rheology – the science studying the plastic deformations of solid and fluid continuous media under applied stresses could be used. It is accepted that the concrete mixture is considered as a heavy fluid. Its behaviour is best fitted by the Bingham model [12] and is fully described by the shear stress and plastic viscosity [13]. In fresh concrete, yield stress (ultimate shear stress) defines the threshold between the static and dynamic state, while viscosity (shear strain rate) indicates how fast the concrete mixture flows [5, 6, 14]. From a practical point of view, these two rheological characteristics provide clear information for the specification of main technological parameters during the handling of concrete mixture.

In construction practice, various methods are used to testing consistency, none of which is universal for the characterization and quality control of fresh concrete [4]. Despite the increasing knowledge of the rheological behaviour of concrete, slump measurement remains the world predominantly used method for evaluating the workability of fresh concrete, because it is simple, fast, inexpensive and convenient to test even on construction site [14, 15, 16].

According to EN 12812:2008 "Falsework – Performance requirements and general design" [17], for lateral pressure calculation of unhardened concrete on the formwork, one of the following documents is used: DIN 18218:2010 "Pressure of fresh concrete on vertical formwork" [18]; CIRIA Report 108 "Concrete pressure on formwork" [19]; Manual de Technologie: Coffrage, CIB-FIB-CEB 27-98-83 [20] or national annex. The lack of national annex in Bulgaria makes necessary to adopt some of the previous three normative documents for practical use.

The most used method for determining the horizontal pressure on formwork for vertical structural elements in European construction practice is the method described in DIN 18218 "Pressure of fresh concrete on vertical formwork" is [21, 22, 23, 24]. The values of horizontal pressure, according to the mentioned standard, are calculated by formulas referring to a concrete mixture of different consistency, expressed by flow classes from F1 to F6, according to EN 206:2013+A2:2021 [25] and measured according to the requirements of EN 12350-5:2019 "Testing fresh concrete. Part 5: Flow table test" [26]. Traditionally, in Bulgarian conditions, the consistency of concrete mixture is mainly tested by slump method – see EN 12350-2:2019 "Testing fresh concrete. Part 2: Slump test" [27]. Therefore, the direct use of the mentioned formulas by designers and contractors of the formwork in Bulgaria is practically impossible or difficult to implement in most cases.

In order to successful implementation of DIN 18218 in Bulgaria as well, it is necessary to analyse the relationship between the consistency determined by the slump test and the flow table test, and to specify the potential areas of application of the formulas from this standard, depending on slump class of concrete mixture.

2. MATERIALS AND METHODS

The determination of consistency was carried out by both methods in parallel, on the same concrete mixtures. The concrete mixes were produced in a certified concrete batching plant and tested on site. At the first stage of the test, the consistency was determined by slump method, according to EN 12350-2 [27], and immediately after that, the same concrete mixture was tested by flow table method – EN 12350-5 [26].

2.1. Measuring the consistency using the slump method

The slump test is the most well-known and world widely used method for characterising the workability of fresh concrete. This way of measuring consistency can be applied directly on construction sites to quickly determine whether a batch of concrete should be accepted or rejected when a designed slump class is set for the fresh concrete (Fig. 1).

The main characteristics of the measurement by slump test are the following:

- suitable for concrete mixtures with medium and high degree of workability i.e. measured slump from 5 to 21 cm;
- it measures the mobility of concrete mixture under the action of its own weight after standard compaction (a function of the yield stress);
- sensitive to small changes in effective water content;
- easy measurement procedure, suitable for application both in laboratory conditions and on construction site;
- highly dependent on the operator.

The test results are only valid when true slump occurs, i.e. when the concrete remains substantially intact and symmetrical. When the specimen is sheared or completely collapsed, a new test should be made. If during two consecutive tests an incorrect slump occurs, then the concrete mixture does not have the necessary plasticity and cohesiveness to carry out the slump test [27].

The slump method is suited for consistency measurement of plastic concrete, which correspond to slump values between 50 mm and 210 mm, outside this range, the slump test can be inaccurate [27]. In these cases, other methods of determining the consistency should be used such as VeBe or flow table method.

2.2. Measuring the consistency using the flow table method

Fig. 1. Measuring the consistency of concrete mixtures by the slump method according to EN 12350-2

The flow table method is applicable to a wide range of workability of fresh concrete and is particularly suitable for highly mobile mixtures whose samples disintegrate when measuring consistency by the slump method. This method is characterised by the following features:

- suitable for concrete mixtures with a high and very high degree of workability;
- it measures the effect of a standard amount of work (jolting) on the spreading of the mixture;
- it gives some indication of tendency of concrete mixture to segregate;
- a rather simplified measurement procedure, but like the slump method, it depends on the operator.

The sequence of steps in measuring the consistency of concrete mixture by this method (Fig. 2) is as follows [26]:

- The conical mould is filled with concrete mixture in two equal layers, each layer being compacted by tamping 10 times lightly with a wooden rammer (tamping bar). After 30 seconds of wait, the cone is raised vertically allowing the concrete to flow out and spread out a little on the flow table;
- The table top is then raised till it reaches the upper stop and allowed to

drop freely 15 times (drops). This causes the concrete to spread further, in a roughly circular shape;
- The maximum diameters of spread of concrete mixture in both directions – d_1 and d_2 are measured, thus determining the flow, $f = (d_1 + d_2)/2$, as an average.

Fig. 2. Measuring the consistency of concrete mixture by means of the flow table method according to EN 12350-5

It is checked whether there is segregation of the concrete. The cement paste may separate from the coarse aggregate and form a segregation border that extends from several millimetres to 2–3 centimetres around the spreaded fresh concrete. The presence of segregation is recorded in the test report and the test is marked as unsatisfactory.

Due to cement hydration and possible moisture loss, the consistency of concrete mix decreases in time. Therefore, in order to obtain comparable results, the tests on different samples should be carried out in a short time interval after mixing.

The flow table test is sensitive to changes in the consistency of concrete, which corresponds to flow values between 340 mm and 620 mm. Beyond these extremes, the flow table test may be unsuitable and other methods of determining the consistency should be considered [26].

The classification of concrete mixture by consistency, measured by the two considered methods, is presented in Table 1.

Table 1. Consistency classes of concrete mixture according to EN 206

Slump		Flow diameter		
Class	Numerical Values (mm)	Class	Numerical Values (mm)	Physical description
S1	10 to 40	F1	≤ 340	stiff
S2	50 to 90	F2	350 to 410	plastic
S3	100 to 150	F3	420 to 480	soft
S4	160 to 210	F4	490 to 550	very soft
S5	≥ 220	F5	560 to 620	flowable
–	–	F6	≥ 630	highly flowable

3. RESULTS AND DISCUSSIONS

3.1. Test results

The experiment was conducted by testing 53 concrete mixes, widely used in construction, having a high-range water reducing chemical admixture (superplasticizer) with dosage of $0.4 \div 0.6\%$ by the cement mass. The results are presented in Table 2.

3.2. Analysis of the results

Based on the obtained consistency data given in Table 2, the workability expressed by the rheological behaviour of concrete mixtures was investigated. Thus additional qualitative information about the mobility of fresh concrete was received through processing of reported values of the slump, and application of empirical equations and graphical representation of dependencies (Fig. 3).

The slump is known to be affected by both yield stress (ultimate shear stress) and, to a lesser extent, plastic viscosity [28, 29, etc.]. Over the years, empirical equations have been developed for calculating yield stress in relation to the measured slump of concrete mixture, based on either analytical or experimental analyses. Since different rheometers/viscometers measure different absolute values for the yield stress of identical concrete samples (with the same slump), the empirical equations are highly dependent on the specific device used to measure yield stress.

When measuring the slump in various experimental studies, it was found that the speed of movement is small and the concrete mixture is at rest, i.e. the rate of shear strain is zero or near zero value throughout the test, and therefore

Table 2. Tests to determine the consistency of real (production) mixes of normal concrete with a superplasticizer

Sample No.	Determination of concrete consistency						Compressive strength class of concrete
	EN 12350-2		EN 12350-5				
	Slump s, [mm]	Class	Diam. of flow d_1, [mm]	Diam. of flow d_2, [mm]	Aver. diam. of flow (spread) f, [mm]	Class	
1	210	S4	580	510	545	F4	C20/25
2	20	S1	405	345	375	F2	C12/15
3	200	S4	620	580	600	F5	C20/25
4	25	S1	310	360	335	F1	C12/15
5	80	S2	470	420	445	F3	C12/15
6	15	S1	345	325	335	F1	C12/15
7	200	S4	600	510	555	F4	C30/37
8	150	S3	500	460	480	F3	C20/25
9	165	S4	620	550	585	F5	C20/25
10	210	S4	570	530	550	F4	C20/25
11	205	S4	560	470	515	F4	C30/37
12	150	S3	490	430	460	F3	C30/37
13	220	S5	550	570	560	F5	C30/37
14	195	S4	460	490	475	F3	C30/37
15	180	S4	460	500	480	F3	C30/37
16	210	S4	445	570	510	F4	C30/37
17	140	S3	440	400	420	F3	C30/37
18	200	S4	620	525	575	F5	C30/37
19	215	S4	580	540	560	F5	C30/37
20	190	S4	475	505	490	F4	C30/37
21	200	S4	580	480	530	F4	C20/25
22	230	S5	610	580	595	F5	C20/25
23	205	S4	590	510	550	F4	C20/25
24	180	S4	550	470	510	F4	C20/25
25	205	S4	560	570	565	F5	C25/30
26	190	S4	490	540	515	F4	C25/30
27	145	S3	500	470	485	F3	C20/25
28	155	S3	505	435	470	F3	C20/25
29	195	S4	500	510	505	F4	C25/30
30	225	S5	510	610	560	F5	C20/25
31	210	S4	590	600	595	F5	C20/25
32	185	S4	570	600	585	F5	C30/37
33	220	S5	570	580	575	F5	C20/25
34	215	S4	620	600	610	F5	C20/25

Sample No.	Determination of concrete consistency							Compressive strength class of concrete
	EN 12350-2		EN 12350-5					
	Slump s, [mm]	Class	Diam. of flow d_1, [mm]	Diam. of flow d_2, [mm]	Aver. diam. of flow (spread) f, [mm]	Class		
35	200	S4	580	550	565	F5		C20/25
36	210	S4	600	570	585	F5		C20/25
37	175	S4	510	550	530	F4		C25/30
38	180	S4	570	555	565	F5		C25/30
39	215	S4	545	495	520	F4		C35/45
40	200	S4	490	490	490	F4		C35/45
41	200	S4	485	480	485	F3		C35/45
42	185	S4	470	470	470	F3		C35/45
43	180	S4	475	440	460	F3		C35/45
44	190	S4	430	415	425	F3		C35/45
45	70	S2	350	345	350	F2		C25/30
46	60	S2	375	340	360	F2		C25/30
47	65	S2	360	345	355	F2		C25/30
48	160	S4	435	445	440	F3		C20/25
49	145	S3	465	490	475	F3		C20/25
50	155	S3	465	495	480	F3		C20/25
51	205	S4	545	525	535	F4		C35/45
52	195	S4	530	520	525	F4		C35/45
53	200	S4	550	525	540	F4		C35/45

a relationship between the slump and the yield stress might be expected [13, 14].

Based on computer analyses and finite element simulations of concrete slump tests, Hu et al. [30] developed an expression for calculating yield stress τ_0 from the measured slump s and bulk density $\rho = 2350$ kg/m^3 of the concrete mixture, then these results were confirmed by actual measurement with the BTRHEOM rheometer, namely:

$$\tau_0 = \frac{rho}{270} . (300 - s)\,, \quad [\mathrm{Pa}]. \tag{1}$$

Based on additional experimental measurements with the BTRHEOM rheometer, Ferraris and de Larrard [15] altered the equation from the previous study and proposed the following empirical relationship:

$$\tau_0 = \frac{\rho}{347} . (300 - s) + 212 \quad [\mathrm{Pa}]. \tag{2}$$

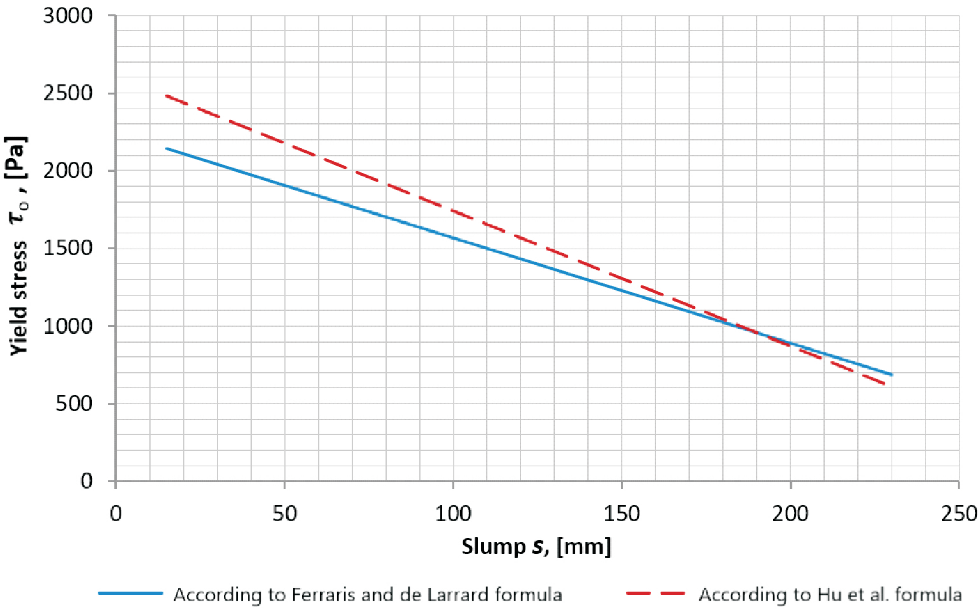

Fig. 3. Comparison of graphs expressing relationship between slump and yield stress for the concrete mixtures in this study

Although the two graphs in Fig. 3, built using the above expressions and the experimentally obtained data in Table 2, almost overlap, they increasingly deviate from each other at a lower degree of workability of concrete mixture. From the graphs presented, the yield stress τ_0 for the corresponding slump can be determined. After overcoming τ_0, the concrete mixture flows like a viscous liquid. Increasing or decreasing the water content changes both the yield stress and the plastic viscosity (while chemical additives reduce the yield stress at nearly constant plastic viscosity).

Within the present study, a relationship was determined between the results obtained in the consistency test carried out as per the slump method and the flow table method. The relationship, accepted for the needs of the study is linear and the regression equation and the coefficient of determination are presented in Fig. 4. It is assumed that the initial horizontal spread (flow), before jolting, correlates better with the slump of concrete mixture [31].

The analysis of the results and the graph presented in Fig. 4 show that there is a clear correlation between the slump and the flow diameter. The calculated correlation coefficient is $R = \sqrt{R^2} = \sqrt{0.735} = 0.86$, i.e. the slump and the flow are highly correlated variables having a linear relationship between them. And since the correlation coefficient R is with a positive sign, it can be said

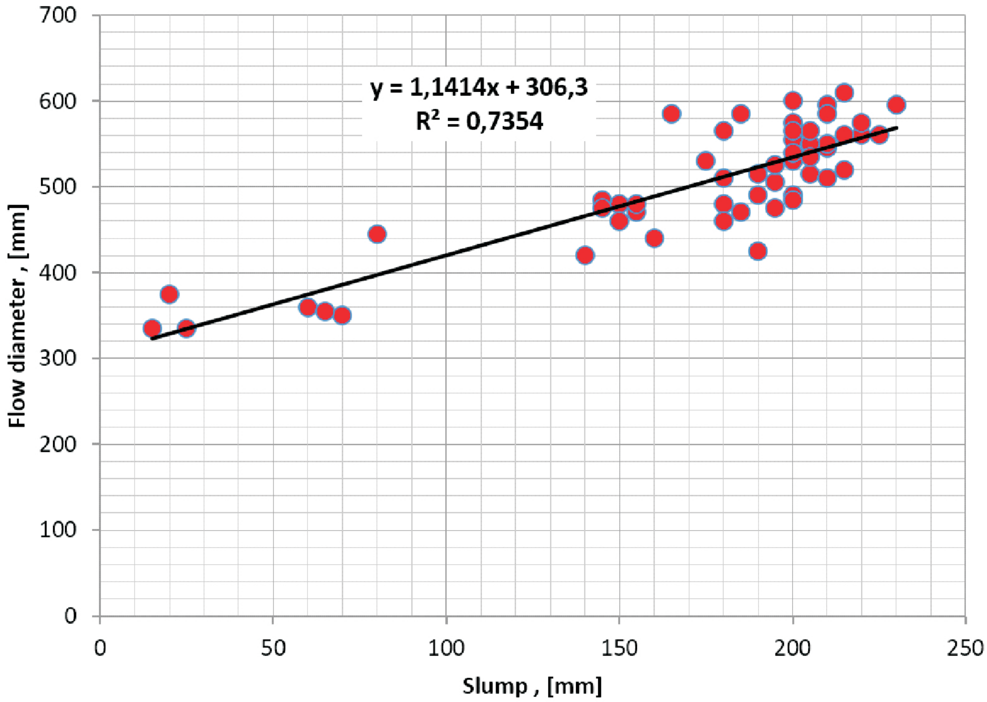

Fig. 4. Relationship between the consistency values measured by the slump method and the flow table method for mixes of normal concrete with chemical additive

that there is a direct relationship between the two variables – as the slump increases, the flow diameter also increases.

More than 80% of the 53 samples tested have a slump more than 150 mm and an average flow diameter of more than 450 mm. This shows that concrete mixtures with higher slump and flow values were used, so they can be defined as "more mobile", and which in its turn implies easier and faster placement in the formwork and the need for minimal vibration, for compaction purposes only.

Previous studies published in three sources are summarized in [1]: (Cement and Concrete Association, Superplasticizing admixtures in concrete: Report of Working Party [32]; Mor A. and Ravina D., The DIN flow table [33]; Domone P.L., The slump flow test for high workability concrete [34]).

Fig. 5 compares the results of the present author's study conducted (data indicated in red) and the summarized results given in [1].

The relationships between the slump and flow table results in Fig. 5 are presented in the following manner: two of them indicate an S-shaped form

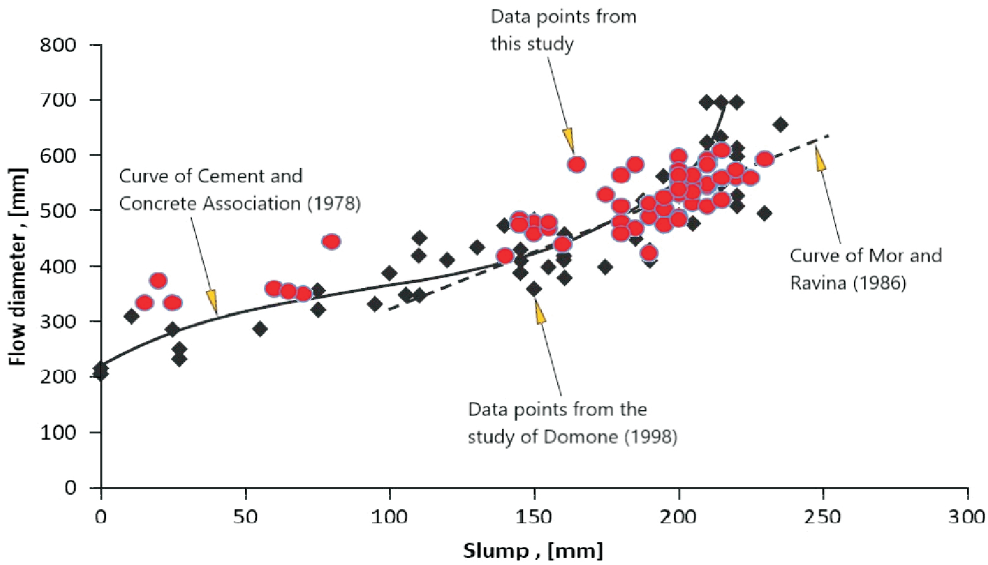

Fig. 5. Comparison of different studies presenting relationships between consistency by slump method and flow table method

of correlation showing a significant increase of the flow diameter at higher slumps, and the other two are expressed by a linear correlation. The scatter in the results is such that both forms of relationship between consistency by slump method and by flow table method could be accepted.

After analysing the results of considered studies, the relationship between values of the slump and the flow diameter is obvious – with an increase in the consistency determined by the slump method, there is also an increase in the consistency determined by the flow table method. When examining the presented results in detail, it can be found that in the slump interval from 100 mm to 170 mm, a relatively smooth increase in the values of the correlated variables is observed. However, when increasing the slump above 170 mm, there is a sharp increase in the flow diameter compared to the results obtained by the slump method.

Stated above gives reason to look for a specific relationship between the flow classes from F1 to F6 according to EN 12350-5 and the slump according to EN 12350-2, and this would make it possible to determine the applicability of the formulas specified in DIN 18218 (regarding the value of the horizontal/lateral pressure of concrete mixture on vertical formwork).

Based on the analyses carried out, it can be summarised that there are practically no significant differences in the values of flow diameter at the corresponding slump between the examined studies, including compared to the author's study, from which a comparison of the consistency classes measured according to EN 12350-2 and EN 12350-5 can be made – Fig. 6.

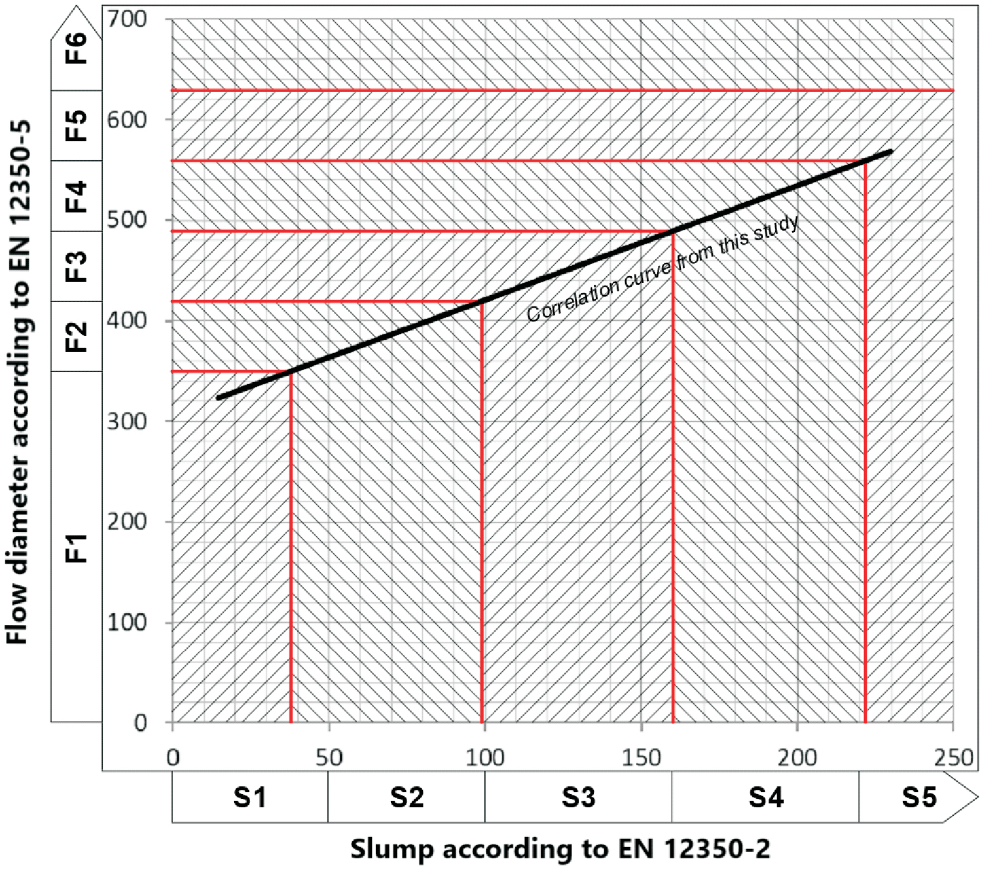

Fig. 6. Comparison of consistency classes measured according to EN 12350-2 and EN 12350-5

Analysing the results presented in Fig. 6 it can be concluded that in order to determine the value of the lateral pressure (horizontal load) of unhardened/plastic concrete on formwork according to DIN 18218:2010 the following formulas can be used:

- for slump from 10 mm to 40 mm – the formulas specified in DIN 18218 for class F1;
- for slump from 40 mm to 100 mm – the formulas specified in DIN 18218 for class F2;

- for slump from 100 mm to 160 mm – the formulas specified in DIN 18218 for class F3;
- for slump from 160 mm to 220 mm – the formulas specified in DIN 18218 for class F4;
- for slump greater than 220 mm – the formulas specified in DIN 18218 for class F5.

4. CONCLUSION

Taking into account the high value of the coefficient of determination (correlation, respectively), the data obtained for the consistency by slump method (EN 12350-2) could be used with some approximation to determine the lateral pressure of fresh concrete on vertical formwork in compliance with DIN 18218.

In the same time, it should be kept in mind that the relationships obtained refer only to the specific mixes tested in this study. In other words, this relationship cannot be accepted as universal, and it should be checked for each specific case – for example, for large batches of concrete mixture when concreting large-sized structural elements, at large concreting cycles, etc.

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