PARAMETERS FOR SELF-COMPACTING CONCRETE MORTAR PHASE

Miguel Nepomuceno and Luiz Oliveira

Synopsis: This paper reports an experimental study on the mortar phase for self-compacting concrete. A series of mortars were produced with similar flow properties, measured by spread and v-funnel tests, adequate to produce self-compacting concrete. The water content and the modified carboxylic superplasticizer dosage were determined experimentally for each mortar. Different percentages of cement replacement materials were used in binary blends, each one combining one of the two types of cement with one of the three mineral additions selected: limestone powder, granite filler and fly ash. Each of the binary blends of powders was combined in five different proportions in volume with the fine aggregate (Vp/Vs). Mortars were tested for compressive strength at 28 days age and this value was related to the water/cement ratio, the percentage of replacement materials, and Vp/Vs parameter. The analysis revealed the possibility of establishing adequate mortar parameters to obtain simultaneously the self-compactability and the required compressive strength of self-compacting concrete.

Keywords: mortar, compressive strength; fresh-properties; mineral fillers; self-compacting concrete; spread test; v-funnel test

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INTRODUCTION

The development of self-compacting concrete and the first mixture design method, namely the method proposed by Okamura, Maekawa and Ozawa, later on improved by the contribution of Ouchi et al. [1, 2, 3, 4], represent an important step for concrete technology. Furthermore, the guidelines proposed by the JSCE [1, 2] establish the basis to generalize its use.

The method proposed by Okamura was developed for general application and is supported by great simplicity of procedures. However, this method is considered as being conservative and, in general, it leads to a self-compacting concrete mixture with higher volumes of paste in comparison with an optimized mixture [5]. Afterwards, the general tendency was to focus on optimizing mixtures proportions, aiming to reduce dosage of paste. The research works developed by Petersson et al. [6, 7], Van Bui and Tangtermsirikul [8], Van Bui and Denis Montgomery [9], Sedran and Larrard [5] should also be recognized.

As a result of the analysis done, the possibility to outline a different approach was considered. The new proposal is supported by tests on the mortar phase as proposed by Okamura research group [1, 2, 3, 4]. Furthermore, based on bibliographic review, an interval of variation was defined for the parameters that characterize the flow behavior of mortars (Gm, Rm), in such a way that it leads to self-compacting concrete. The Gm parameter is measured on mortar spread test and Rm is measured on a v-funnel test. New parameters were introduced to quantify the fine aggregate in mortars (Vp/Vs, where Vp is the volume of powder and Vs is the volume of sand) and to quantify the coarse aggregate in concretes (Vm/Vg, where Vm is the volume of mortar excluding air and Vg is the volume of coarse aggregate). Finally, parameters that evaluate mortar and concrete compressive strength were analyzed.

The values assumed for the parameters Vp/Vs and Vm/Vg should vary in such a way that the corresponding volumes of fine and coarse aggregates in concrete mixtures vary below and above those proposed by Okamura et al. [1, 2, 3, 4]. However, varying the volumes of fine and coarse aggregates introduces the additional necessity to evaluate the fresh properties of mortars that leads to self-compacting concrete.

Studies on mortar and concrete were made using binary blends of powder materials which combine two types of cements and three mineral additions: limestone powder, fly ash and granite filler from a by-product of industry. The described project was concluded [10] and confirms that the fresh properties defined for mortar phase are adequate to produce self-compacting concretes. However, the results presented in this paper represent only the first step of the project concerning the mortar phase.

EXPERIMENTAL PROGRAM

Materials used

The cements used include a normal portland cement (CEM I 42.5R) with a specific gravity of 3.14 and a calcareous portland cement (CEM II/B-L32.5N), with a specific gravity of 3.04. The mineral additions include a limestone powder with a specific gravity of 2.72, granite filler with a specific gravity of 2.65 and a fly ash with specific gravity of 2.38.

A modified polycarboxylic based superplasticizer was used and supplied in liquid form and with a density of 1.05. The fine aggregate grading curve results from the combination of two sands. The proportion in absolute volume of the two sands was 40% of Sand 01 and 60% of Sand 05. Sand 01 was produced from crushed granite with very fine particles and a specific gravity of 2.59 and a fineness modulus of 1.49. Sand 05 was river sand with a specific gravity of 2.61 and a fineness modulus of 2.71. The proportions in absolute volume between the two sands were kept constant during all the research work. Those proportions were determined experimentally to obtain the maximum compactness. The combined grading curve is shown in Fig. 1.

Mix proportions of the powder materials

Different combinations of powder materials were established incorporating the two cements and the three additions selected, as shown in Table 1. Each of the mixtures of powder materials produced is identified by an abbreviation that express the dosage of each of the constituent material, expressed in percentage of the total absolute volume of powder materials. For example, the abbreviation (80C2+20FC) represents a mixture of powder materials that combine 80% of cement type CEM II/B-L32.5N and 20% of limestone powder, in terms of the absolute volume. The other abbreviations have the following interpretation: C1 means cement type CEM I 42.5R; FG means granite filler and CV means fly ash.

Studies in mortars

Parameters used for mortar mix design include the proportions of powder materials, Vp/Vs (ratio, in absolute volume, between the powder materials and the fine aggregates), Vw/Vp (ratio, in absolute volume, between the water and the powder materials), Sp/p% (ratio, in percentage, between the mass of the superplasticizer and the mass of the powder materials). For mortar mix design, the volume of voids and the contribution of powders from fine aggregates were not considered.

Fresh properties of mortars were evaluated by the mean value of two perpendicular flow diameters in the spread test and by the flow time in the v-funnel test. The results were expressed in terms of relative flow area (Gm) and the relative flow velocity (Rm). The spread cone and the v-funnel used have the internal dimensions shown in Fig. 2. The relative flow area was calculated according to the Eq. (1), whiles the relative flow velocity was calculated according to Eq. (2). The abbreviations shown in the Eqs. (1) and (2) have the following interpretation: Dm is the mean value of the two perpendicular diameters, in mm; D_0 is the initial diameter of the base of the cone, in mm, and t represents the time of flow in the v-funnel, measured in seconds.

$$\mathrm{Gm} = \left(\frac{\mathrm{Dm}}{\mathrm{D}_0}\right)^2 - 1 \tag{1}$$

$$\mathrm{Rm} = \frac{10}{\mathrm{t}} \tag{2}$$

The mixing sequence is shown in Fig. 3. Batches of 1.6 liters were produced and the introduction of the superplasticizer occurred without interruption of the paddle movement. Mortars were produced combining each mixture of powder materials shown in Table 1, with different values of the Vp/Vs. The Vp/Vs varied from 0.60 to 0.80. On average, for each combination of powder materials and Vp/Vs, three mortars were produced, varying the Vw/Vp and Sp/p% until required fresh properties were obtained. The experimental procedure is shown schematically on Figs 4 and 5. Figure 4 shows that for Sp/p% constant, the increase of Vw/Vp produces a linear translation of (Gm, Rm) values. Figure 5 shows the variation of the (Gm, Rm) values when the Vw/Vp remains constant and Sp/p% increases.

Admissible range for Gm and Rm is shown in Fig. 6. The values of Gm are between 5.3 and 5.9 and the values of Rm are between 1.14 and 1.30 s^{-1}, which correspond, respectively, to a flow diameter Dm between 251 and 263 mm and v-funnel time t between 7.69 e 8.77 s. Subsequent studies have revealed that those properties for mortars are adequate to produce concretes with values of Gc between 8 and 11.25 and values of Rc between 0.5 and 1.0 s^{-1}, which correspond, respectively, to the flow diameter Dm between 600 and 700 mm and v-funnel time t between 10 and 20 s.

For each of the mortars that satisfied the required fresh properties four cubic specimens of 50 mm side were molded for compressive strength tests. The cubes were cured in water at 20 ± 2^0C. At 28 days, those cubes were tested for compressive strength perpendicular to the cast direction and using a loading rate of 1.5 kN/s.

EXPERIMENTAL RESULTS AND DISCUSSION

Analysis of mixture proportions

The plots presented in Fig. 7 and Fig. 8 show the required amount of water for mortar mixtures that incorporate CEM II/B-L32.5N and CEM I 42.5R, respectively. Those plots show that mortars in which powder proportions include only cement and those in which this cement is partially replaced by granite filler, have the higher water requirements, and clearly detached from the other mortars in which cement was partially replaced by limestone powder or fly ash. On the other hand, the dosage of water tends to decrease with the increase of percentage of cement replacement by the addition, when this addition is limestone powder or fly ash. For the mortars that incorporate granite filler, the results seems to indicate that the dosage of water didn’t vary with cement replacement percentage and, in all cases, it was almost equivalent to the dosage of water used in the reference mix with only cement.

The plots presented in Fig. 9 and Fig. 10 show, respectively, the dosage of superplasticizer for mixtures that incorporate CEM II/B-L32.5N and CEM I 42.5R.

Those figures show that the higher amounts of superplasticizer always occurs for reference mortars which include only cement. When comparing the mortars with the same cement and the same percentage of cement replacement, the mean value of superplasticizer dosage is similar for all the three additions used.

Comparing the mortars that incorporate the same types of cement and addition, presented in Fig. 9 and Fig. 10, they show clearly that the amount of superplasticizer in those mortars decreases with the increase of percentage of cement replacement by the addition. This fact indicates, as expected, a clear tendency for an increase of superplasticizer with an increase in dosage of cement.

Relationship between mix design parameters

The plot presented in Fig. 11 shows the relationship between the parameters Vp/Vs and the Vw/Vp. It is observed that, for mortars with the same powder proportions, the increase of Vp/Vs leads to lower volumetric ratio between the water content and the dosage of powder materials (Vw/Vp). This happens because the amount of powder materials (Vp) increase with the increase of Vp/Vs, while the dosage of water remains almost constant for mortars with the same powder proportions.

In Fig. 11, it is also observed that, for mortars with the same value of Vp/Vs and the same types of cement and addition, the ratio Vw/Vp decreases with the increase of the percentage of cement replacement by the addition. Effectively, for a same value of Vp/Vs the dosage of powder materials (Vp) remains almost constant. On the other hand, when the percentage of cement replacement is increased, a reduction of the amount of water occurs. In this condition, the increase of the percentage of cement replacement leads to a reduction on the Vw/Vp ratio. However, a reduction of Vw/Vp ratio didn’t correspond to an increase of the mortar compressive strength, but the opposite. This happens because the reduction of the amount of cement, as a consequence of the increase of the percentage of cement replacement by the addition, is always higher, in absolute value, compared with the reduction of water dosage, which increases the W/C ratio and, as a result decreases mortar compressive strength.

The plot presented in Fig. 12 shows the relationship between Vw/Vp and the Sp/p%. It is observed that, for mortars with the same binary mixture of powder, the dosage of the superplasticizer, expressed in terms of Sp/p%, didn’t change significantly with variation of Vw/Vp. In mortars with the same types of cement and addition, the dosage of the superplasticizer, expressed in terms of Sp/p%, tends to decrease when the percentage of cement replacement by the addition increases.

Parameters correlated with mortar compressive strength

The relationship between the mortar compressive strength at 28 days age (fm,28) and the Vp/Vs parameter is shown in Fig. 13. It can be observed that the range of mortar compressive strength is between 25 MPa and 95 MPa. For mortars with the same combination of powder materials, the compressive strength varied about 10 MPa, when Vp/Vs varied from 0.60 to 0.80. This confirms the initial hypothesis that, besides the powder proportions, the Vp/Vs parameter contributes to the control of mortar compressive strength. The results shown that this relationship clearly exists for each one of the mortars that incorporate the same type of powder association.

Figure 14 shows two equations relating the compressive strength and the W/C ratio, expressed in terms of mass. Equation 1 of Fig. 14 includes all the mixtures that incorporate the cement type CEM I 42.5R, while Eq. 2 of Fig. 14 includes all the mixtures that incorporate the cement type CEM II/B-L32.5N. As expected, the mortar compressive strength decreases with the increase of W/C ratio. Figure 14 indicates a general relationship for each type of the cement used.

One of the mortar mixture parameters initially assumed to allow the control of mortar compressive strength was the combination of powder materials. This combination of powder materials can be expressed by the unit percentage of cement replacement by the addition in absolute volume ($f_{Ad.}$). On the other hand, the results presented on this paper have shown that Vp/Vs parameter also influences the mortar compressive strength for each combination of powder materials. Furthermore, it was shown that mortar compressive strength can be correlated with the W/C ratio for each type of cement. As a consequence of the analysis done it is possible to establish the relationship between the percentage of cement replacement by the addition ($f_{Ad.}$), the W/C ratio and the Vp/Vs parameter. This analysis is shown in Fig. 15 to Fig. 20.

The analysis of binary mixtures has shown the possibility to establish the relationship between the W/C ratio and the percentage of cement replacement by the addition, for the selected Vp/Vs of the mortar and a certain type of cement and addition previously defined. The results presented from Fig. 15 to Fig. 20 can be used together with the relationship between compressive strength and W/C ratio (Fig. 14) to estimate all the mixture parameters of any mortar that includes the materials analyzed in this research work. It is believed that, even if a different polycarboxylic based superplasticizer is used, the variations produced on water content will be not so large so as to significantly affect the W/C ratio presented in this research work.

CONCLUSIONS

The following conclusions can be drawn based on the results of this experimental investigation for the mortar mixtures and procedures used:

The Vp/Vs is an important parameter for the mix design by making it possible to control the powder materials volumes and mortar fine aggregates ratio, independent of the water and superplasticizer quantities for each proportions of powder materials.

For mortars with the same powder proportions, the increase of the Vp/Vs leads to a lower volumetric ratio between the water content and the powder materials Vw/Vp. Comparing mortars with the same value of Vp/Vs and the same types of cement and addition, the ratio Vw/Vp decreases with the increase of the percentage of cement replacement by the addition.

For mortars with the same powder proportions, the dosage of the superplasticizer, expressed in terms of Sp/p%, doesn’t change significantly with variation of Vw/Vp.

Mixtures with the same Vp/Vs values and the same types of cement and addition have shown that the dosage of the superplasticizer, expressed by Sp/p%, tends to decrease when the percentage of cement replacement by the addition increases.

The comparative analysis of mortars doesn't reveal a general relationship between the analyzed parameters Vp/Vs, Vw/Vp and Sp/p%. However, it can be useful to preview trial mixtures behavior in laboratory to obtain the required fresh properties.

Good agreement was observed, for each powder association mortar, between the mortar compressive strength and the Vp/Vs parameter. The mortar compressive strength increases as Vp/Vs ratio increases.

As expected the compressive strength decreases with the increase of W/C ratio for mortars with the same type of cement.

For binary mixtures incorporating a certain type of cement and addition, it is possible to find a good correlation between the W/C ratio and the percentage of cement replacement by the addition when the Vp/Vs is constant.

It can be concluded that, after having selected the type of powder materials to be used and the required mortar compressive strength, it is possible to estimate the adequate W/C ratio. Moreover, from W/C ratio and Vp/Vs, it is possible to estimate the required percentage of the cement replacement by the addition.

REFERENCES

[1] DOMONE, P.," Mix Design", in Self-Compacting Concrete: State-of-the-Art Report of RILEM Technical Committee 174-SCC, RILEM Publications S.A.R.L., ISBN: 2-912143-23-3, 2000, p. 49-65.

[2] NAWA, T. ; IZUMI, T. ; EDAMATSU, Y., "State-of-the-art Report on Materials and Design of Self-Compacting Concrete", in International Workshop on Self-Compacting Concrete, Japan Society of Civil Engineers, Japan, August, 1998, p. 160-190.

[3] OKAMURA, H.; OZAWA, K.; OUCHI, M., "Self-Compacting Concrete", in Structural Concrete: Journal of the fib, vol.1, No. 1, Thomas Telford Ltd, March 2000, p. 3-17.

[4] OUCHI, M.; HIBINO, M.; OZAWA, K.; OKAMURA, H., "A Rational Mix-Design Method for Mortar in Self-Compacting Concrete", in Proceedings of the Sixth East-Asia-Pacific Conference on Structural Engineering & Construction, Taipei, Taiwan, 1998, p. 1307-1312

[5] SEDRAN, T.; LARRARD, F., "Optimization of Self-Compacting Concrete Thanks to Packing Model", in Proc. of the 1st Intern. RILEM Symposium on SCC, Sweden, ISBN: 2-912143-09-8, Sept. 1999, p. 321-332.

[6] PETERSSON, O.; BILLBERG, P., "Investigation on Blocking of Self-Compacting Concrete with Different Maximum Aggregate Size and Use of Viscosity Agent Instead of Filler", in Proceedings of the 1st International RILEM Symposium on SCC, Sweden, Sept. 1999, p. 333-344.

[7] PETERSSON, O.; BILLBERG, P; BUI, V. K., "A Model for Self-Compacting Concrete", in Proc. of RILEM Intern. Conf. on Production Methods and Workability of Fresh Concrete, Paisley, June 1996, Ed. Bartos PJM, Marrs DL, and Cleland DJ, E&FN Spon; London, p 484-492.

[8] TANGTERMSIRIKUL, S.; BUI, V. K., “Blocking Criteria for Aggregate Phase of Self-Compacting High-Performance Concrete”, in Proceedings of Regional Symposium on Infrastructure Development in Civil Thailand Engineering, December, 1995, Bangkok, p. 58-69.

[9] BUI, V. K.; MONTGOMERY, D., “Mixture Proportioning Method for Self-Compacting High Performance Concrete with Minimum Paste Volume”, in Proceedings of the 1st International RILEM Symposium on SCC, Sweden, ISBN: 2-912143-09-8, Sept. 1999, p. 373-384.

[10] NEPOMUCENO, Miguel, “Methodology for self-compacting concrete mix-design”, in PhD thesis, Covilhã, UBI, Portugal, March, 2006.

[11] DOMONE, P.L.J.; JIN, J., “Properties of Mortar for Self-compacting Concrete”, in Proceedings of the 1st International RILEM Symposium on SCC, Sweden, ISBN: 2-912143-09-8, Sept. 1999, p. 109-120.

TABLES

Table 1 – Volume fractions in binary blends of powders

Materials ► Mixtures ▼			Cement		Addition		
			CEM I 42.5R (**C1**) δ_{C1} = 3140 kg/m^3	CEM II/B L32.5N (**C2**) δ_{C1} = 3040 kg/m^3	Fly ash (**CV**) δ_{CV} = 2380 kg/m^3	Limestone powder (**FC**) δ_{FC} = 2720 kg/m^3	Granite filler (**FG**) δ_{FG} = 2650 kg/m^3
Ref.	1	100C2	---	fc2= 1.00	---	---	---
Binary mixtures	2	80C2+20FC	---	fc2= 0.80	---	ffc= 0.20	---
	3	80C2+20FG	---	fc2= 0.80	---	---	ffg= 0.20
	4	80C2+20CV	---	fc2= 0.80	fcv= 0.20	---	---
	14	60C2+40FC	---	fc2= 0.60	---	ffc= 0.40	---
	15	50C2+50FC	---	fc2= 0.50	---	ffc= 0.50	---
Ref.	5	100C1	fc1= 1.00	---	---	---	---
Binary mixtures	6	70C1+30FC	fc1= 0.70	---	---	ffc= 0.30	---
	7	70C1+30FG	fc1= 0.70	---	---	---	ffg= 0.30
	8	70C1+30CV	fc1= 0.70	---	fcv= 0.30	---	---
	9	60C1+40FC	fc1= 0.60	---	---	ffc= 0.40	---
	10	60C1+40FG	fc1= 0.60	---	---	---	ffg= 0.40
	11	60C1+40CV	fc1= 0.60	---	fcv= 0.40	---	---
	12	50C1+50FC	fc1= 0.50	---	---	ffc= 0.50	---
	13	40C1+60FC	fc1= 0.40	---	---	ffc= 0.60	---

FIGURES

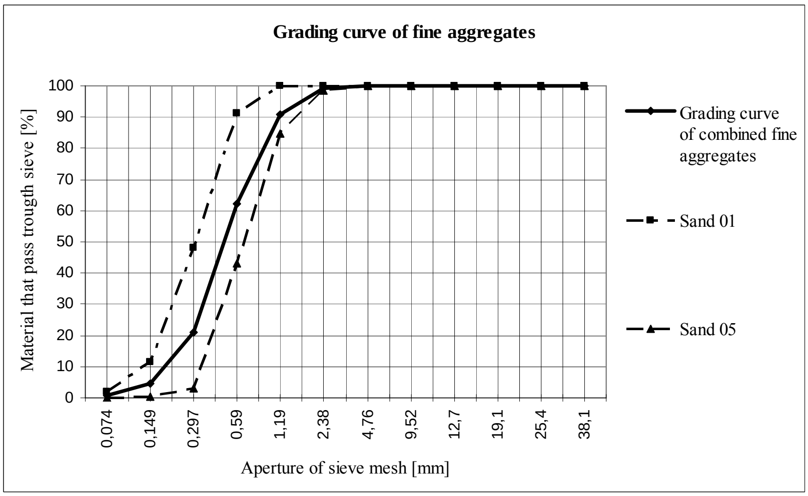
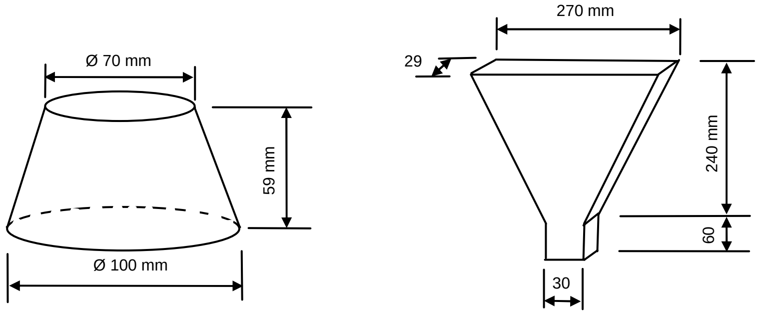


Fig. 1 – Grading curves of fine aggregates



Spread test V-funnel test

Fig. 2 – Dimensions of spread and V-funnel tests

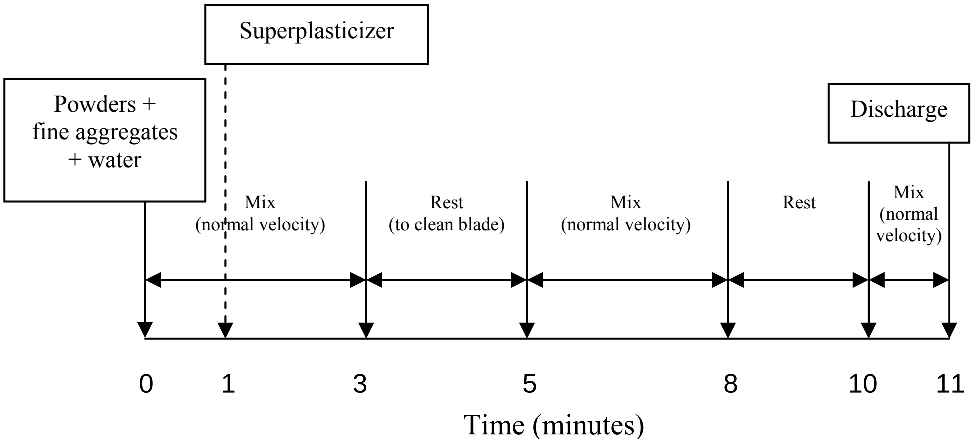


Fig. 3 – Mixing sequence used to produce mortars

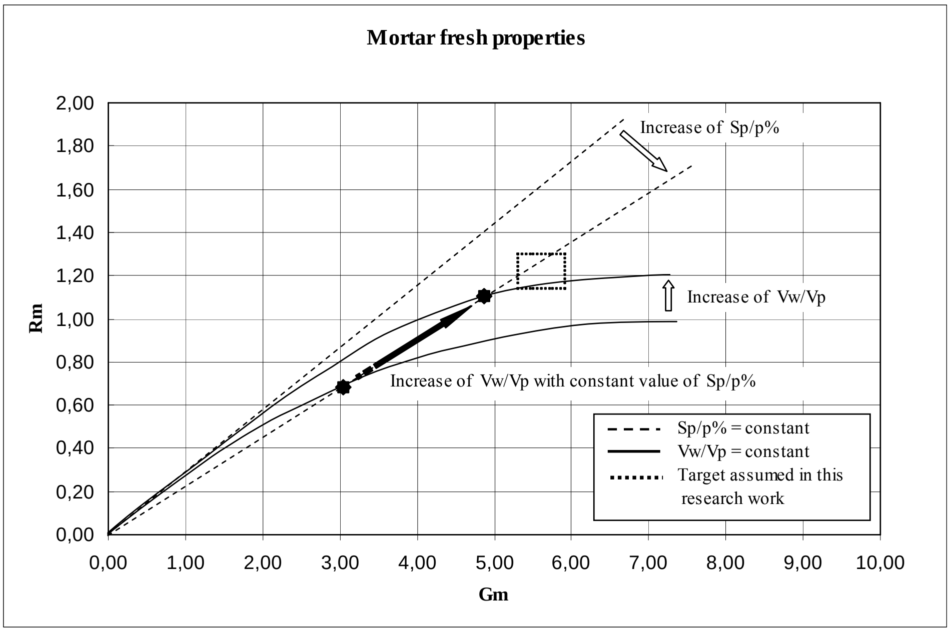


Fig. 4 – Mortar fresh properties when Vw/Vp increases with Sp/p% constant

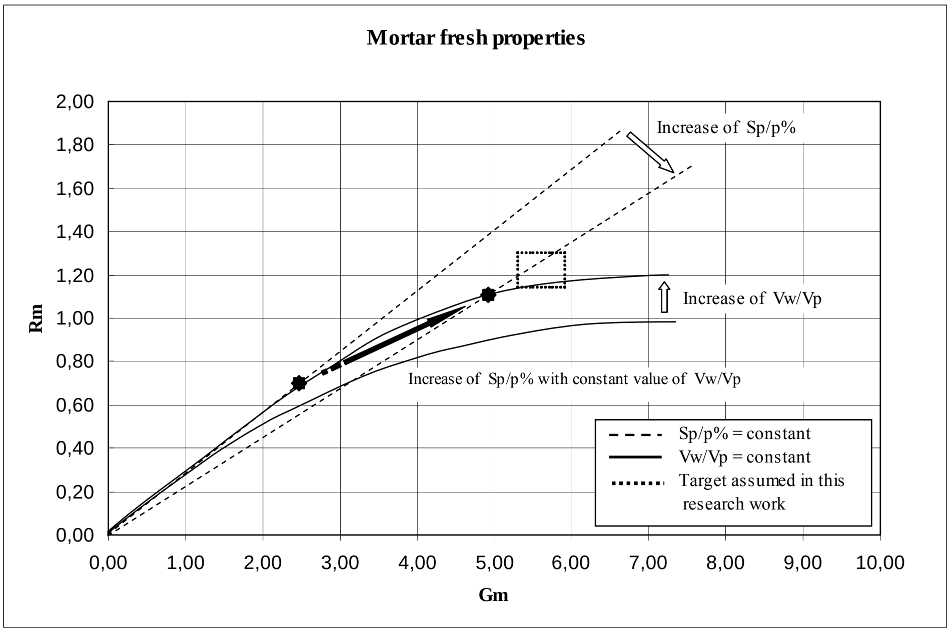


Fig. 5 – Mortar fresh properties when Sp/p% increases with Vw/Vp constant

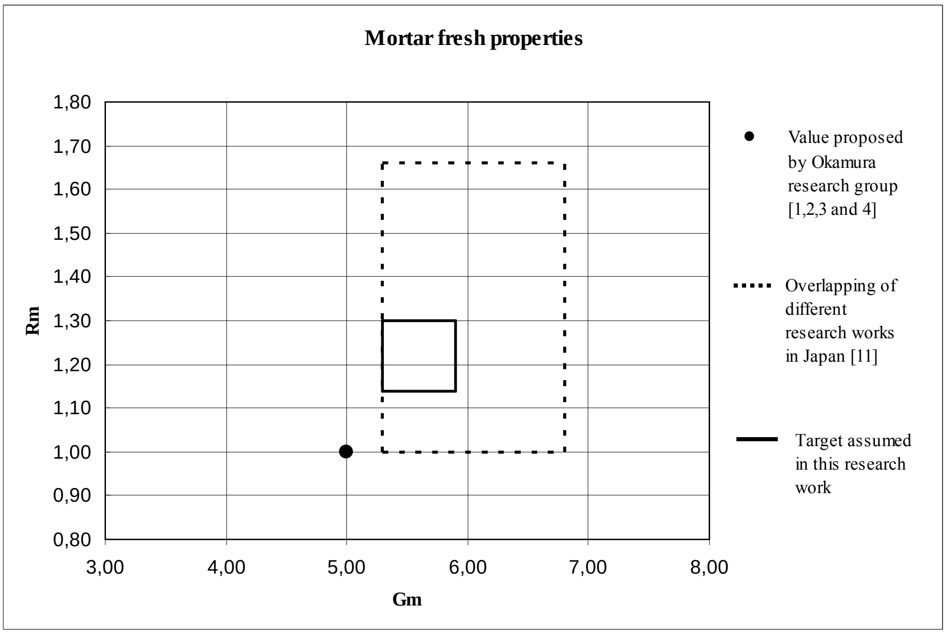


Fig. 6 – Admissible interval of variation for fresh properties of mortars

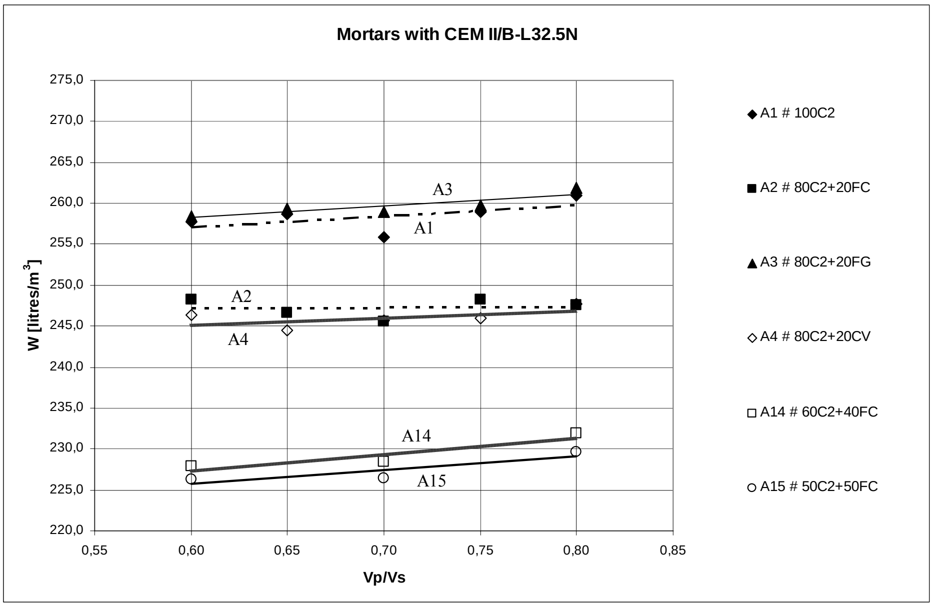


Fig. 7 – Variation of water content of mortars as a function of Vp/Vs for CEM II/B-L32.5N

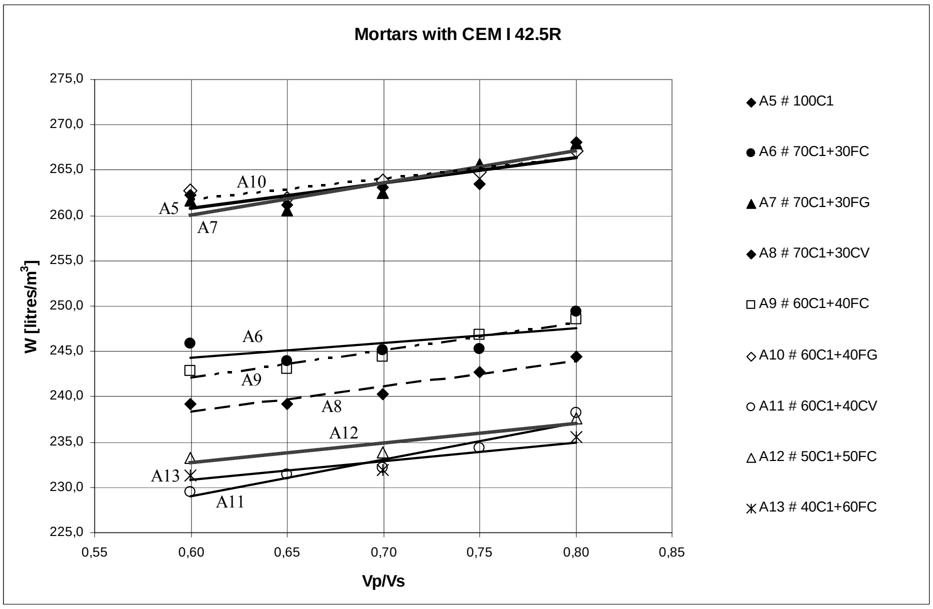


Fig. 8 – Variation of water content of mortars as a function of Vp/Vs for CEM I 42.5R

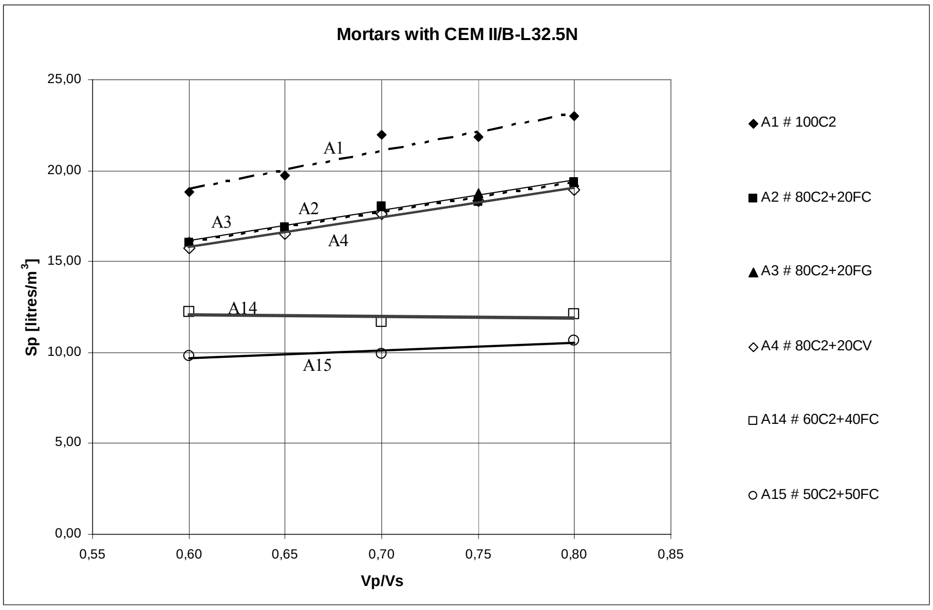


Fig. 9 – Variation of superplasticizer content as a function of Vp/Vs for CEM II/B-L32.5N

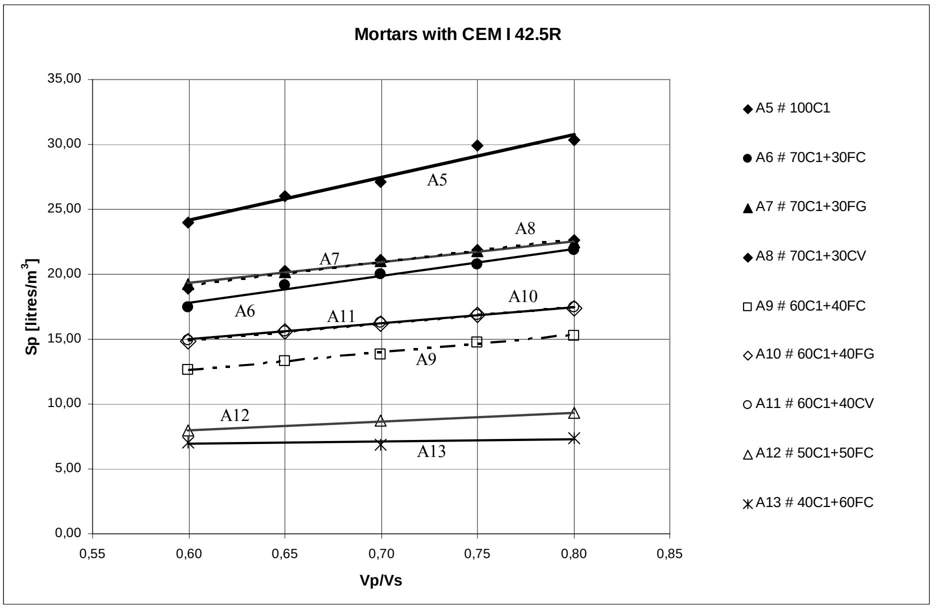


Fig. 10 – Variation of superplasticizer content as a function of Vp/Vs for CEM I 42.5R

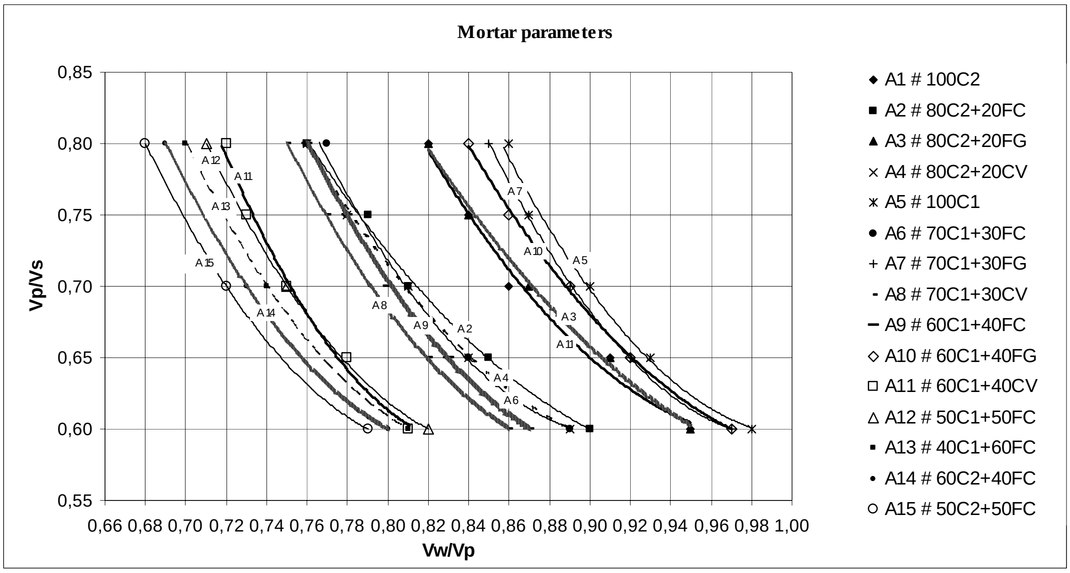


Fig. 11 – Relationship between Vp/Vs and Vw/Vp for the mortars produced

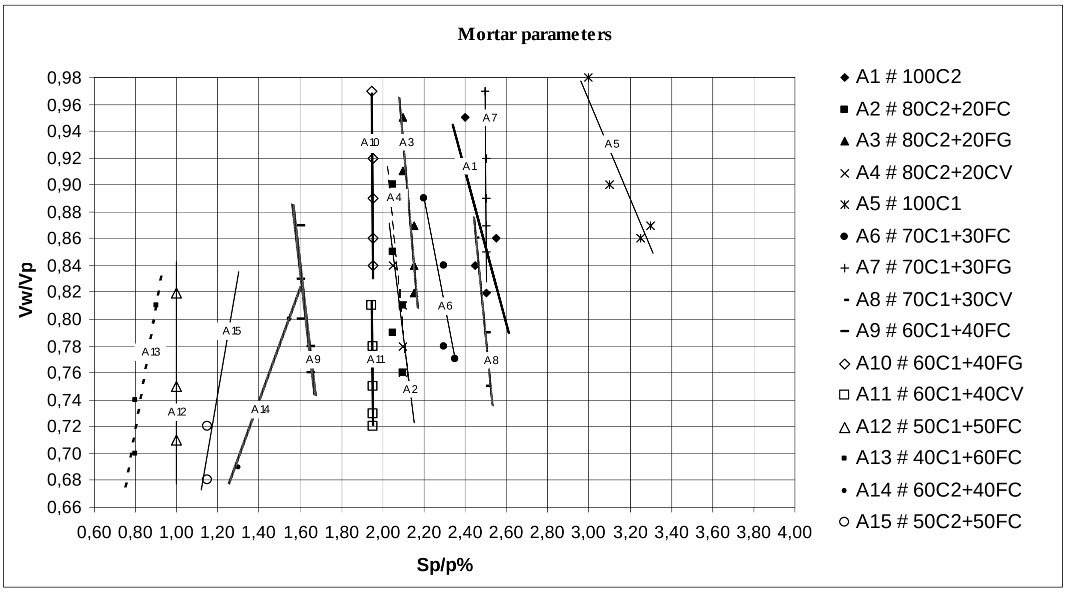


Fig. 12 – Relationship between Vw/Vp and Sp/p% for the mortars produced

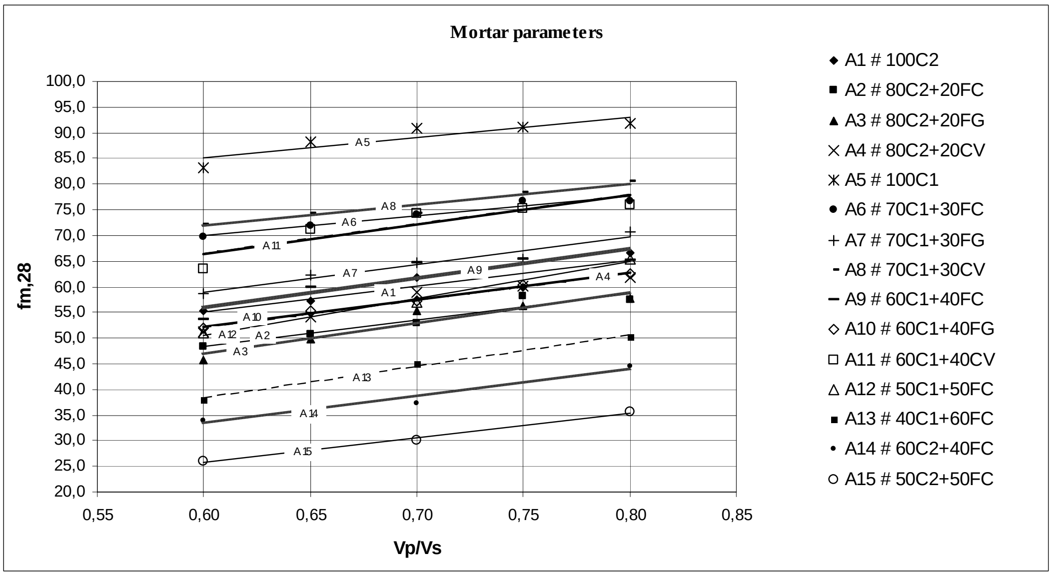


Fig. 13 – Relationship between fm,28 and Vp/Vs for the mortars produced

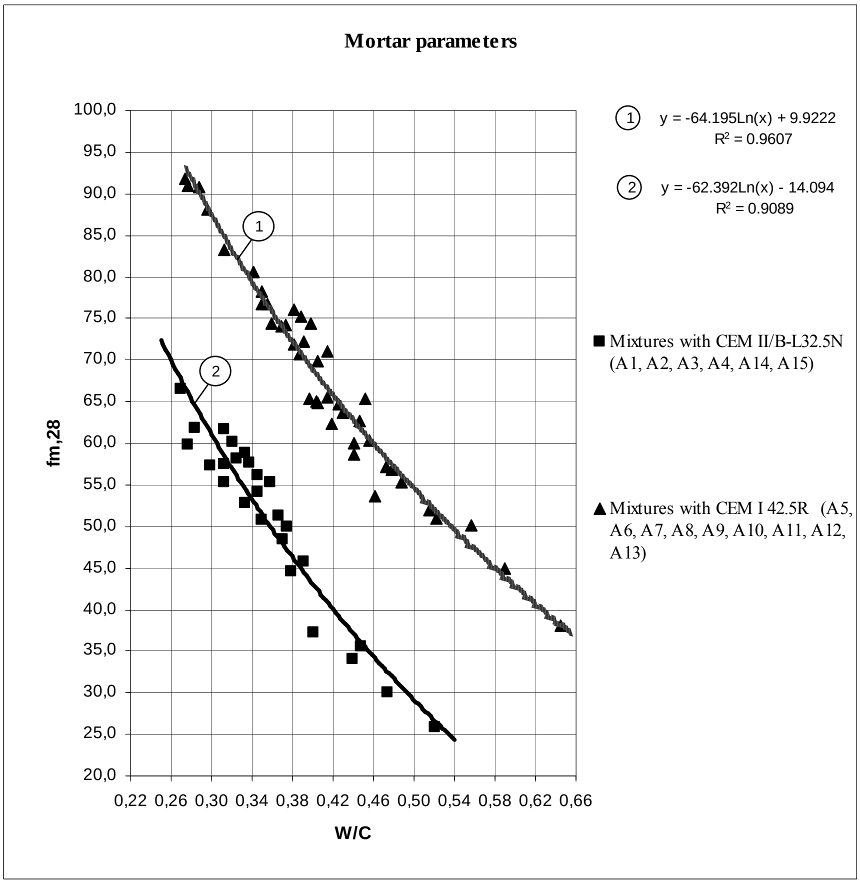


Fig. 14 – Relationship between fm,28 and W/C for the mortars produced

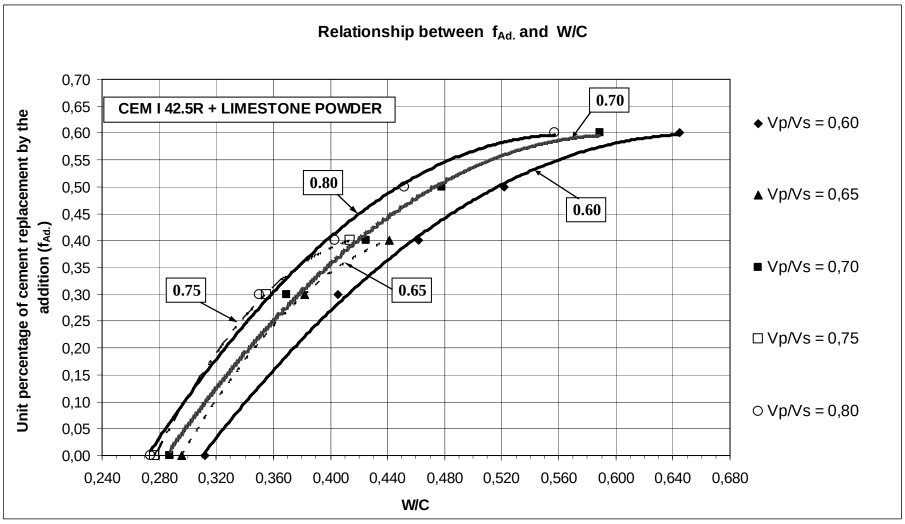


Fig. 15 – $f_{Ad.}$ versus W/C when using CEM I 42.5R and limestone powder

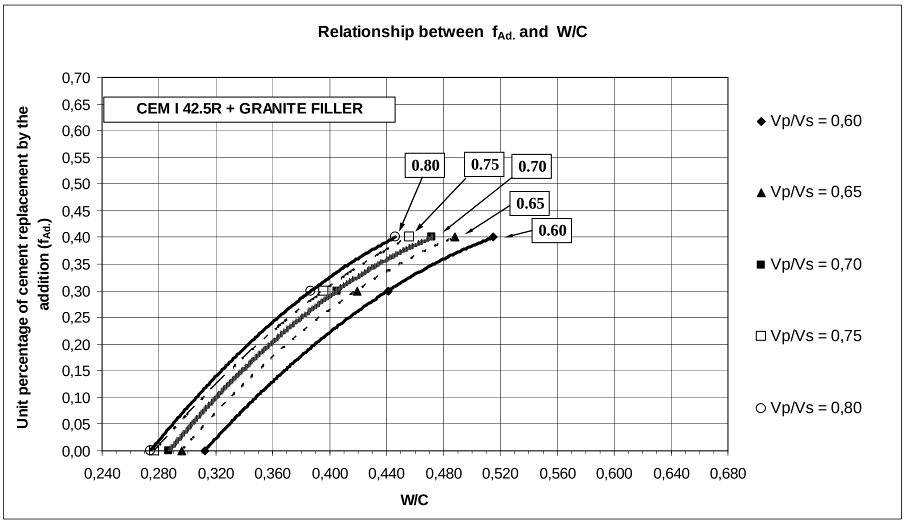


Fig. 16 – $f_{Ad.}$ versus W/C when using CEM I 42.5R and granite filler

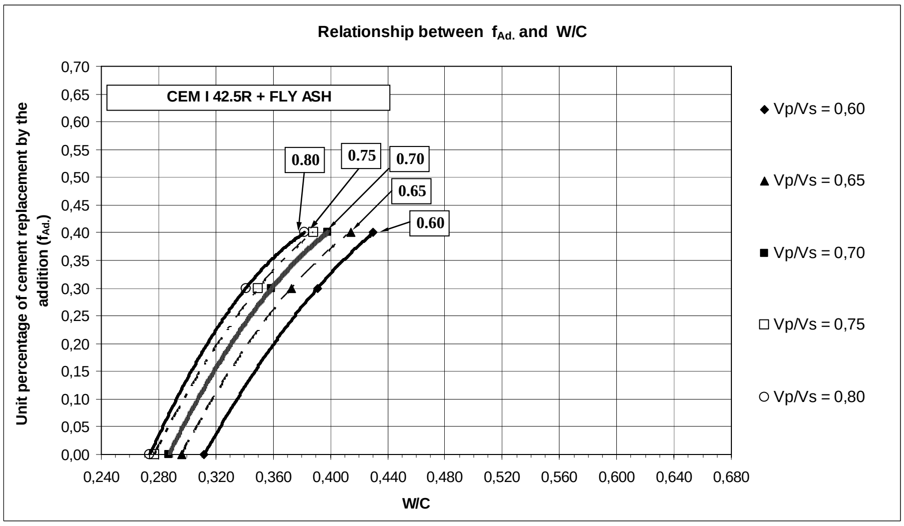


Fig. 17 – $f_{Ad.}$ versus W/C when using CEM I 42.5R and fly ash

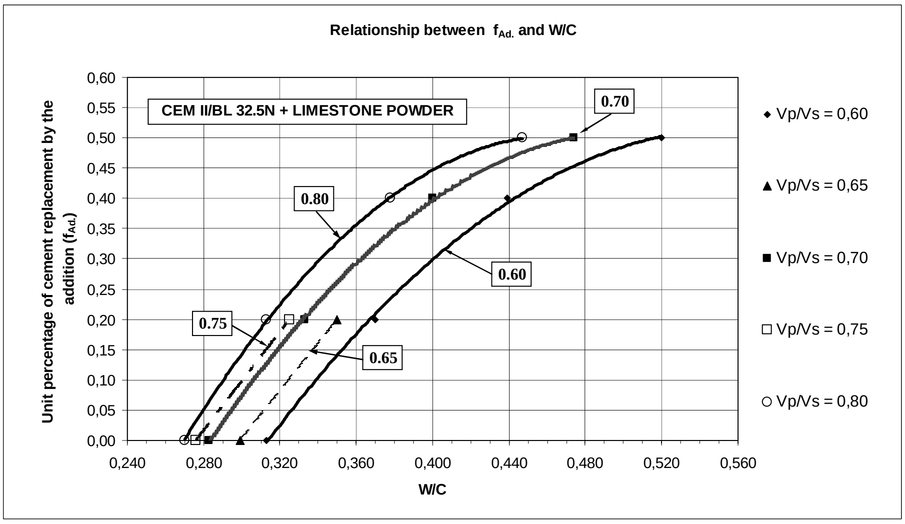


Fig. 18 – $f_{Ad.}$ versus W/C when using CEM II/B-L32.5N and limestone powder

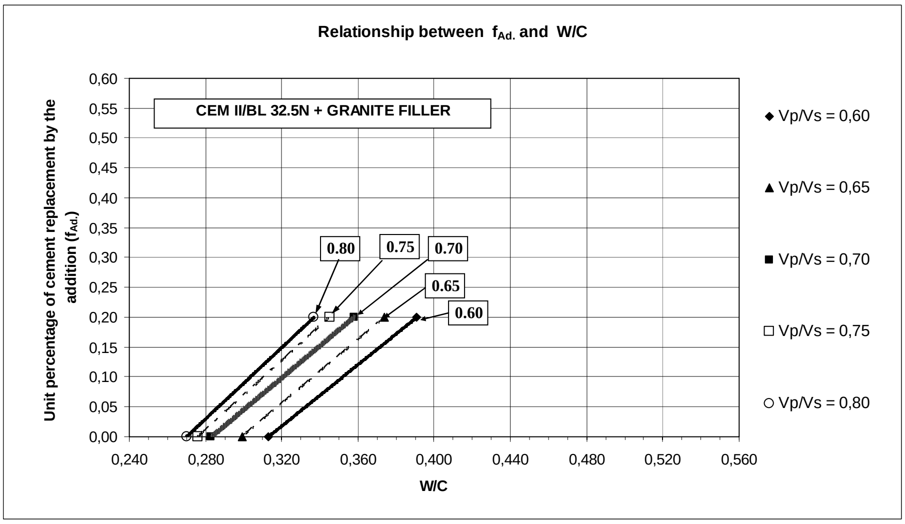


Fig. 19 – $f_{Ad.}$ versus W/C when using CEM II/B-L32.5N and granite filler

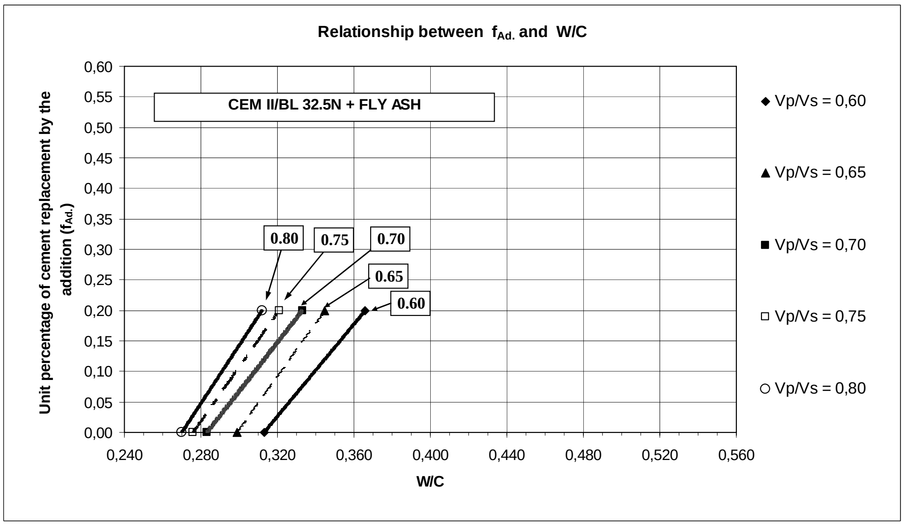


Fig. 20 – $f_{Ad.}$ versus W/C when using CEM II/B-L32.5N and fly ash