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Why do HPC and SCC require a longer mixing time?

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Abstract

The industrial production of superplasticized concrete is slowed down because of the long mixing time often necessary for these materials. The aim of the study presented here was to find out the mix-design peculiarities of high-performance concrete (HPC) and self-consolidating concrete (SCC) that could be responsible for the long mixing time.

To compare the behaviour of various mixes, a mathematical model is proposed to fit the power consumption curve of the mixer and to choose a criterion to determine the stabilisation time of the curve.

The parameters studied were the paste content, its components (silica fume, limestone filler, etc.), the high-range water reducing admixture (HRWRA) type and dosage and the water/cement (w/c) ratio. The comparison of stabilisation time for 36 different HPC and SCC mixes allowed to highlight the major influence of w/c ratio, on the stabilisation time. The higher the w/c ratio, the lower the stabilisation time. It also appears that fine content, HRWRA dosage and the use of silica fume have significant effects on the time necessary to homogenise the material. This result can also be expressed by using the actual and maximum solid content concepts, which are dependent on all the mix-design parameters.

These results were quantified, for our experimental conditions, through two models which are proposed in this paper. An empirical one using the components' amount and the other, the actual and maximum solid content of the concrete.

The validation of such a model with other sets of data obtained with different materials and mixers could lead to its use in mix-design software programs; thus, it would become possible to take the mixing time into account at the laboratory step of mix design.

Keywords: High-performance concrete; Mixing; Mixture-proportioning; Rheology; High-range water reducer

1. Introduction

During the last 20 years, high-performance concrete (HPC) and self-consolidating concrete (SCC) have become more and more commonly used. But the expansion of these new materials is slowed down by difficulties of industrial production. The mixing time is one of the problems highlighted by ready-mix concrete firms. Indeed, mixing time often reaches 2 min for SCC produced in concrete plants and 5 min for some HPC, while, in France, ordinary concrete is mixed for 35 s. The solution to this problem is researched by the authors within the mix-design peculiarities of those concretes. Indeed, the components are not anymore the four basic materials (cement, water, sand and coarse aggregate), but, to reach the mechanical and rheological properties, high-range water reducing admixture (HRWRA), silica fume or filler materials are used for controlling the packing density of HPC and SCC. This paper presents the parameters that can explain the long mixing time of new generation concretes by observing the stabilisation time of mixer power consumption for 40 different mix designs.

2. Experimental program

To understand why HPC and SCC require a longer mixing time, it is necessary to study the influence on mixing time of the mix design. Most of these concretes have a higher paste volume (30–40%), a lower water/cement (w/c) ratio, use silica fume, and a high HRWRA dosage.

An experimental program was set up to study the influence of these parameters on the mixing time. The selection of parameters came from industrial experience and published literature [1,4].

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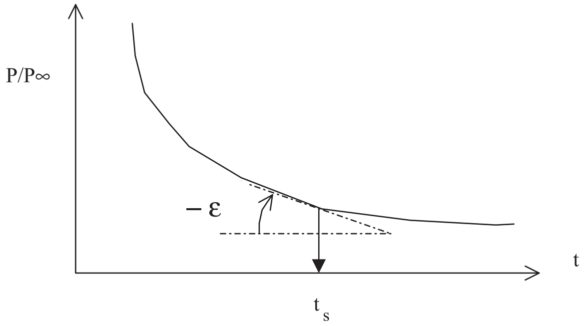

Fig. 1. Definition of the stabilisation time.

2.1. Fine particles content

The time necessary to reach a uniform dispersion of a granular material into a mix is assumed to be related to the mean diameter of the material considered [1]. This implicates that the repartition of coarse aggregates is reached faster than the repartition of sand or fine particles. Thus, as SCC and HPC contain more fine particles than ordinary concrete, high mixing time should be necessary. The fine particles content, for this study, was fixed to either 425 or 550 kg/m^3.

2.2. Paste composition

The second parameter studied is the paste composition. In SCC and HPC, supplementary cementitious materials (SCMs) are often used. Therefore, the effect of silica fume and limestone filler have been studied.

The dosage of silica fume is set between 0% and 8% of the mass of cement. Three different forms of silica fume have been chosen:

(i) undensified,
(ii) densified (by a pneumatic process) and
(iii) premixed and crushed with cement.

The influence of filler material has been studied by comparing SCC with 0% or 30% of limestone filler by mass of cement.

2.3. HRWRA type and content

Finally, the use of various HRWRAs at various dosages is one of the peculiarities of SCC and HPC. Two different molecules have been used in this program: polycarboxylic type and melamine type. The first one is a more commonly used molecule which acts by steric effect, while melamine molecules, which have an electric repulsion effect, have been used for a longer time. The content of HRWRA in this experimental program is 40% or 100% of the saturation dosage [3].

2.4. Granular skeleton

The size distribution of aggregate (diameter over 80 μm) is the same for all mixes. It has been determined by optimisation of the packing density using the Compressible Packing Model [2]. The gravel/sand ratio obtained for the maximum packing density is 1.18.

The coarse aggregates are crushed materials of two granular fractions: 5–12.5 and 10–16 mm. The sand is a river natural sand with particles from 80 μm to 4 mm.

2.5. Mixtures and procedures

The 36 mixes designed were then batched on a 330-l vertical orbital mixer set up in an experimental, full-scale concrete plant. During mixing, the power consumption of the mixer was recorded. All mixtures were designed to display a slump value of 20 ± 4 cm for HPC mixes and a slump flow of 60 ± 5 cm for SCC mixes. Detailed mix design and properties of mixtures are summarised in Appendix A [5].

3. Definition of stabilisation time

For industrial production of concrete, the power consumption curve versus time is often recorded to determine the time for emptying the mixer. As a general rule, concrete is discharged when the stabilisation time [5,6] is reached. It is defined as the time at which the power–time curve reaches

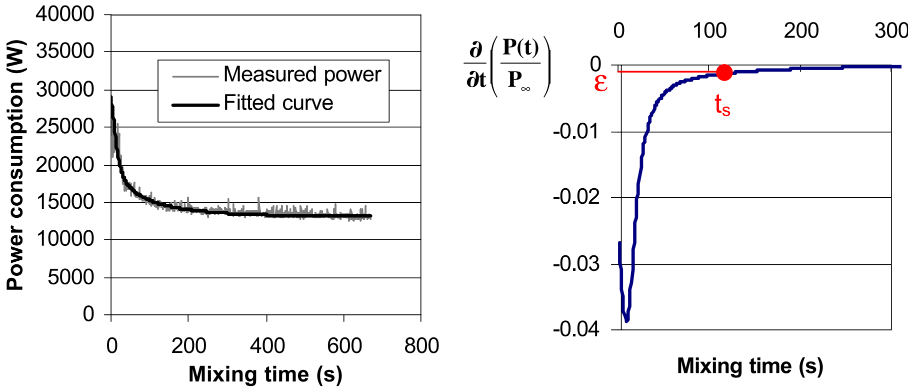

Fig. 2. Power consumption curve fitting and calculation of stabilisation time t_s.

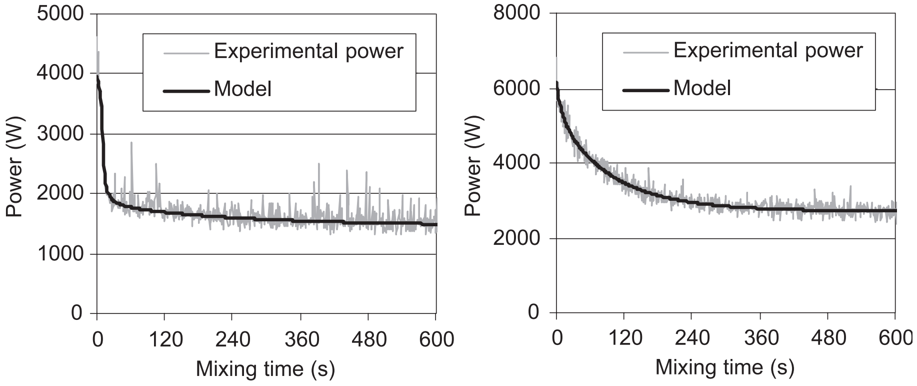

Fig. 3. Examples of power curves fitted with Eq. (1) (with two different concrete recipes).

the asymptote. For the present study, a visual determination of stabilisation time lacks objectivity to analyse the concrete behaviour. Therefore, the following method was adopted: the power–time curves is fitted with Eq. (1), and stabilisation time is taken as the time where the derivative of the power function (normalized by the constant P_∞), is equal to a constant called ε (see Fig. 1). The fitting equation is the following:

$$P(t) = P_\infty + P_\mathrm{d} e^{\left(\frac{-t}{t_\mathrm{d}}\right)} + \frac{2P_\mathrm{m}}{\pi}\left(\mathrm{Arctan}\left(\frac{t_\mathrm{a} - t}{t_\mathrm{m}}\right) + \frac{\pi}{2}\right) \qquad (1)$$

where $P(t)$ is the power consumed by the mixer, as a function of time t (see Fig. 2). P_∞ is the power consumed after stabilisation of the curve, P_d and P_m are adjusted coefficients, t_d, t_a and t_m are time coefficients

$$t_\mathrm{s} \text{ so that} \left|\frac{\partial}{\partial t}\left(\frac{P(t_\mathrm{s})}{P_\infty}\right)\right| = \varepsilon \qquad (2)$$

where t_s is the stabilisation time of power curve. ε is fixed to get a minimum value of 35 s for t_s among the mixtures considered. As a matter of fact, this time is the minimum mixing time required by French standard NF P 18-305.

Two examples are given in Fig. 3 to show how the power–time curve can be fitted by Eq. (1).

4. Results and discussions

Using the method highlighted here, we can examine the influence of various mix-design parameters on t_s. An attempt is then made to develop a relationship between t_s and the mix-design parameters using two models.

4.1. Stabilisation time of power consumption curve versus mix design

Fig. 4 shows the stabilisation time t_s as a function of w/c ratio, for several groups of mixes containing polycarboxylic HRWRA and having the same binder content and workability. The first observation is that stabilisation time increases when w/c ratio decreases within each group. We can notice the plots fall into two groups depending on the fine element content of the mix. In these experiments, the highest fine content leads to the lowest stabilisation time. Moreover, it seems that HRWRA dosage slightly changes the slope of the curve.

By making the same analysis for mixes with melamine HRWRA, the same tendencies are found, although less systematically (see Section 4.2).

Another observation deals with the comparison of stabilisation time for concretes with and without silica fume. It appears that the mixing time is significantly reduced (by 40%) for the mixes containing silica fume (Fig. 5). Moreover, if we compare the stabilisation time for the different types of silica fume, no significant difference appears between undensified and densified, while blended silica fume leads to slightly higher stabilisation times.

Also in Fig. 5, the influence of the HRWRA type can be studied by comparing mean values of stabilisation time for mixes designed with melamine and polycarboxylic types. Concretes designed with polycarboxylic HRWRA display

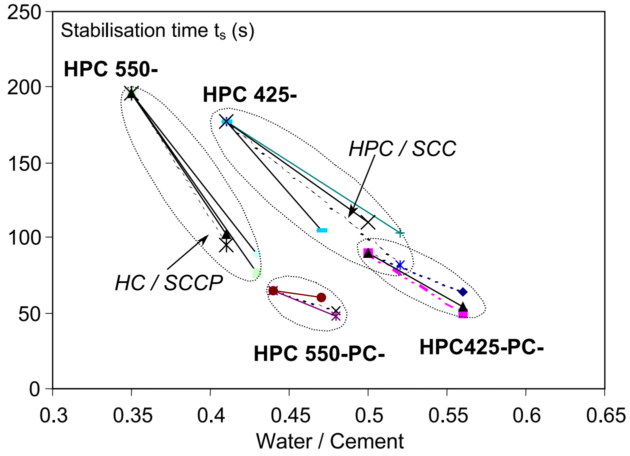

Fig. 4. Relationship between stabilisation time of power consumption and w/c ratio, for mixes with polycarboxylic HRWRA. HPC, high-performance concrete; SCC, self-consolidating concrete; 425 or 550, fine element content; PC, polycarboxylic; 0.4 and 1, superplastcizer amount in terms of saturation degree.

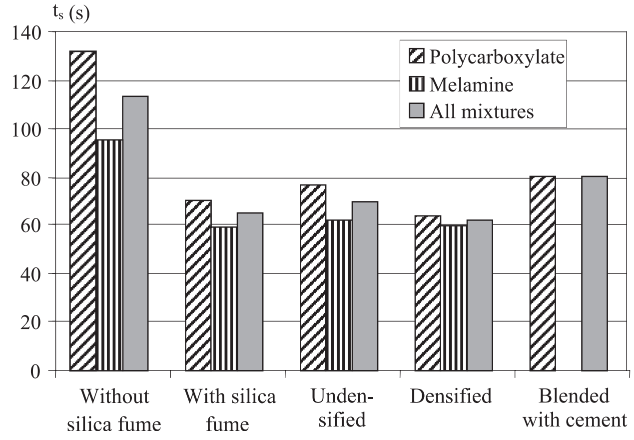

Fig. 5. Influence of silica fume on mixing time of concrete.

slightly longer stabilisation times than those which are designed with melamine HRWRA. But it is unclear whether this result is due to differences in the chemical nature of HRWRA, or to the concrete rheological behaviour. Hence, because the comparisons between both natures of HRWRA are made at fixed water/binder ratio, consistency differs from a product to the other one. This difference in consistency acts on the level of power consumed, which is accounted for in the calculation of stabilisation time (see Eq. (2)).

4.2. Analysing influences by a linear model

The relationship we have observed between stabilisation time, w/c ratio and fine content leads to try to separate the effects of water and fine content. Moreover, the small difference due to HRWRA dosage is to be taken into account. The following linear model is proposed to understand the influence of each parameter:

$$t_s = T_0 + a_w W + a_c C + a_{sp} SP \qquad (3)$$

where t_s is the stabilisation time of power consumption curve (s); W is the water content (l/m^3); C is the cement content (kg/m^3); SP is the HRWRA content (kg/m^3); T_0, a_w, a_c, a_{sp} are the coefficients of the model.

Table 1
Values of coefficients used in Eq. (3) to fit experimental stabilisation time results

HRWRA	Polycarboxylic	Melamin
T_0	392	110
a_w	− 2.09	− 0.91
a_c	0.351	0.325
a_{sp}	− 9.82	− 3.48
Mean error (s)	14.54	17.57
Correlation	0.92	0.68
Mean of aE (s)	− 454	− 169
Mean of $a_c C$ (s)	165	165
Mean of a_{sp}SP (s)	− 10	− 14

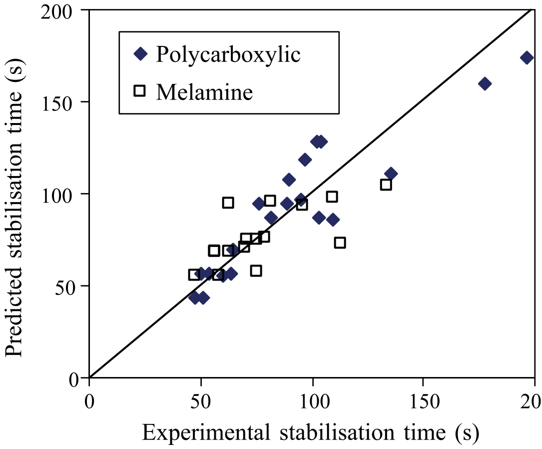

Fig. 6. Comparison between predicted (Eq. (3)) and experimental values of stabilisation time.

After an optimization consisting in minimizing the mean error of the model, the results obtained are displayed in Fig. 6 and Table 1. The model is quite satisfactory for polycarboxylic HRWRA but not really satisfying for melamine. Therefore, it seems necessary to find an explanation of the effects of the different parameters to have a more accurate model, valid for both HRWRA types.

Most of the differences between experimental and predicted stabilisation time values can be explained by the lack of precision when weighing constituents on a full-scale plant, but this cannot explain everything. This means that the parameters considered in this model are not the only ones that can affect the mixing time. Thus, it is necessary to look for the physical parameters of the concrete which are behind the changes of mix-design parameters.

4.3. Stabilisation time of power versus packing parameters

de Larrard [2] has shown that packing concepts can be used successfully to model various fresh concrete properties. Among those concepts, the actual solid content ϕ is the sum

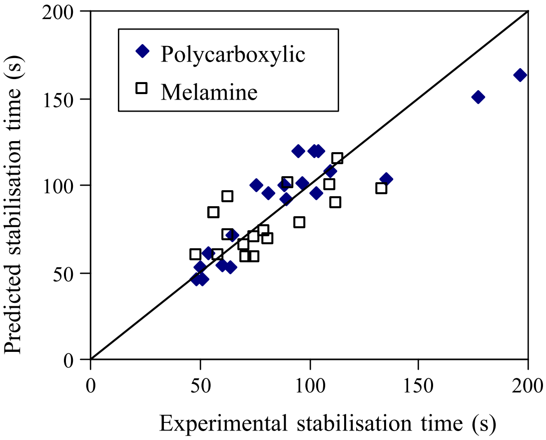

Fig. 7. Comparison between predicted (Eq. (4)) and experimental values of stabilisation time.

of all solid per unit volume, whereas the maximum solid content ϕ^* is the maximum solid concentration which could be obtained with a compaction index equal to 9 for given proportion of dry constituents. The compaction index describes the compaction energy used to place the granular mixture.

Using these definitions, a relation exists between mixture composition and the packing parameters of concrete. For instance, an increase in water content, for given proportions of other constituents, will lead to a decrease of actual solid content while the maximum solid content remains constant. The relative solid concentration of concrete ϕ/ϕ^* will then be reduced. In the same way, replacing part of the cement by silica fume increases the maximum solid content, but does not change the actual solid content (if the replacement is performed on a volume basis). This leads to a decrease of the relative solid concentration.

Thus, the influence of the various parameters we have studied on stabilisation time can be related to the concrete packing parameters following Eq. (4):

$$T_s = T_m + A\frac{\phi}{\left(\phi^* - B_i\dfrac{\mathrm{Sp}}{\mathrm{Sp}^*}\right)} \tag{4}$$

where T_s is the stabilisation time; ϕ is the actual solid content; ϕ^* is the maximum solid content; Sp/Sp* is the relative HRWRA dosage (Sp is the actual dosage and Sp* is the saturation dosage; Ref. [3]); B_i is a coefficient function of the HRWRA type, expressing the difference in fine elements dispersion obtained with different molecules; T_m and A are constants.

Fig. 7 and Table 2 show the comparison between actual and theoretical data, after a numerical optimization.

Comparing the two models reveals that both have comparable precisions, but the latter seems more physical. Furthermore, as it has been assessed that the ϕ/ϕ^* ratio is linked to plastic viscosity of fresh concrete [2], it could therefore be deduced that mixing time is likely to increase with this rheological parameter. This explains why HPC, which is known to display higher values of plastic viscosity, often requires long mixing times.

Table 2
Values of coefficients used in Eq. (4) to fit experimental stabilisation time results

Coefficient	Value
T_m (s)	− 920.8
A	1062.3
B_{PC}	0.04
B_{ML}	0
Mean error (s)	16.90

5. Conclusions

To understand why HPC and SCC are so long to mix, an experimental plan has been set up to study the influence of mix-design parameters, through 36 different mixes. The parameters that have been studied are the fine element content, the use of limestone filler or silica fume (in various forms) and the HRWRA type and dosage. To analyse the influence of those parameters on mixing time, it has been necessary to define a stabilisation time of power consumption which is recorded during mixing. An accurate empirical model is then proposed to fit the power curves.

A first linear, empirical model has been proposed, directly accounting for the mix-design ratios. Furthermore, it has been established that the mixing time of a given mix is linked to its actual and its maximum solid content. Those two concepts, defined by de Larrard [2], are related to mix design of concrete. An experimental model, based on those conclusions, is proposed to evaluate the stabilisation time of a concrete, for a given mixer. Such a model could be used in a mix-design software such as BetonLabPro 2 [7], which would provide a prediction of mixing time at the mix-design step.

In practice, the effect of packing density can be controlled by knowing the effect of some mix design data on this parameter. The mixing time can then be reduced by the following means:

- increasing the fine particle content, with a constant w/c ratio,
- increasing the total water amount (the compressive strength will be modified),
- optimising the granular skeleton will lead to a higher maximum solid content, for a constant total aggregate content and
- replacing part of the cement by silica fume will have the same effect (reduced packing density). The use of different forms of silica fume (undensified, densified or premixed) can also have a small effect on mixing time.

It would be interesting to check the validity of this semiempirical model with the help of another independent set of data, dealing with different materials and mixer. In case of success, a further step towards scientific concrete mix design would have been made through the research related in this article.

Acknowledgements

The collaboration in this project of “Béton de France/RMC” and “Liebherr France” companies is gratefully acknowledged.

Appendix A. Mix design and stabilisation time for the 40 mixes

	Crushed aggregate, 5/16 mm (kg/m^3)	Natural sand, 0/4 mm (kg/m^3)	OPC CEM, 52.5 R (kg/m^3)	Limestone filler (kg/m^3)	Silica fume (kg/m^3)	HRWRA (kg/m^3)	Total water (kg/m^3)	w/c	Yield stress (Pa)	Plastic viscosity (Pa s)	Slump (cm)	Actual solid content	Maximum solid content	Stabilisation time (s)
HPC425-PC-0,4	901	766	430	0	0	2.6	206	0.47	385	23	23.5	0.7916	0.849	89.7
HPC425-PC-1	935	795	429	0	0	6.4	177	0.41	397	76	24.5	0.8212	0.856	177.3
HPC425-ND-PC-0,4	868	738	396	0	34	2.4	225	0.6	533	9	20	0.7725	0.862	63.62
HPC425-DP-PC-0,4	868	738	396	0	34	2.4	225	0.6	480	1	20	0.7725	0.862	50.06
HPC425-ND-PC-1	887	755	396	0	34	5.9	207	0.5	407	5	20	0.7905	0.869	103.3
HPC425-DP-PC-1	887	755	396	0	34	5.9	207	0.5	603	10	20	0.7905	0.869	81.35
HPC425-CJ-PC-0,4	868	738	396	0	34	2.4	225	0.6	284	4	25	0.7730	0.8542	54.24
HPC425-CJ-PC-1	912	776	394	0	34	5.9	187	0.5	424	11	21	0.8107	0.87	104.3
HPC550-CJ-PC0,4	782	666	512	0	45	3.1	244	0.5	291	11	26	0.7541	0.84	60.49
HPC550-CJ-PC-1	829	705	511	0	44	7.7	205	0.4	492	43	23	0.7928	0.852	102.2
HPC550-PC-0,4	814	692	558	0	0	3.3	230	0.4	162	18	25	0.7680	0.824	64.67
HPC550-PC-1	860	732	556	0	0	8.3	190	0.4	830	99	17	0.8074	0.834	196.1
HPC550-ND-PC-0,4	776	661	513	0	45	3.1	250	0.5	588	5	20	0.7475	0.84	51.11
HPC550-DP-PC-0,4	776	661	513	0	45	3.1	250	0.5	801	1	21	0.7476	0.84	47.98
HPC550-ND-PC-1	810	689	512	0	45	7.7	221	0.43	618	6	20	0.7764	0.851	88.66
HPC550-DP-PC-1	810	689	512	0	45	7.7	221	0.43	676	11	19	0.7763	0.851	76.14
SCC550-PC	813	691	558	0	0	8.4	227	0.4	467	16	–	0.7712	0.8295	94.91
SCC550-F-PC	809	689	391	168	0	5.9	223	0.6	127	30	–	0.7754	0.8435	135.6
SCC425-AV-PC	888	756	431	0	0	6.5	213	0.5	366	19	–	0.7853	0.853	109.5
SCC425-F-AV-PC	901	166	302	129	0	4.5	199	0.7	304	25	–	0.8000	0.864	97
HPC425-PC-1-S	927	788	429	0	0	6.4	182	0.4	401	108	21	0.8157	0.856	136.6
HPC425-PC-1-S2	1122	628	435	0	0	6.5	169	0.4	1679	236	9	0.8292	0.856	140.8
HPC425-ML-0,4	913	776	429	0	0	6.7	192	0.5	326	52	23	0.8056	0.861	62.58
HPC425-ML-1	933	793	427	0	0	17	168	0.4	592	60	20	0.8289	0.871	112.6
HPC425-ND-ML-0,4	904	769	395	0	34	6.2	195	0.5	554	32	20	0.8024	0.868	58.41
HPC425-DP-ML-0,4	904	769	395	0	34	6.2	195	0.5	550	24	20	0.8024	0.868	47.98
HPC425-ND-ML-1	934	795	393	0	34	15	163	0.4	534	60	20	0.8341	0.881	56.32
HPC425-DP-ML-1	934	795	393	0	34	15	163	0.4	530	58	19	0.8340	0.881	56.32
HPC550-ML-0,4	838	714	556	0	0	8.7	206	0.37	406	52	23	0.7915	0.84	95.96
HPC550-ML-1	860	732	552	0	0	21.6	176	0.34	671	95	20	0.8207	0.854	109.5
HPC550-ND-ML-0,4	823	700	511	0	44	8	211	0.4	487	17	23	0.7865	0.851	70.92
HPC550-DP-ML-0,4	823	700	511	0	44	8	211	0.4	508	14	21	0.7864	0.851	75.1
HPC550-ND-ML-1	865	736	508	0	44	20	167	0.4	644	46	20	0.8300	0.869	62.58
HPC550-DP-ML-1	865	736	508	0	44	20	167	0.4	1057	80	15	0.8296	0.8695	133.5
SCC550-ML	821	699	554	0	0	22	206	0.4	197	18	–	0.7911	0.851	69.88
SCC550-F-ML	838	713	388	166	0	15	191	0.5	269	56	–	0.8068	0.864	81.35
SCC425-AV-ML	911	775	428	0	0	17	185	0.5	85	24	–	0.8125	0.87	75.1
SCC425-F-AV-ML	924	786	300	129	0	12	174	0.6	227	43	–	0.8240	0.879	79.27
HPC425-ML-1-S	1138	637	429	0	0	17	149	0.4	1913	215	9	0.8489	0.87	113.7
HPC425-ML-1-S2	1123	629	430	0	0	17	160	0.4	410	170	21	0.8383	0.87	90.74

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