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Data analysis of an autogenous shrinkage database of concrete with ground granulated blast-furnace slag

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Abstract:
Until recently, it was assumed that autogenous shrinkage in ordinary types of concrete is quite small, but in recent years there have been indications that it can be larger than previously thought.

In this study data from practice of a large number of autogenous shrinkage measurements was collected and analysed to determine the magnitude of autogenous shrinkage and to gain insight in influencing factors. The database contains mainly concrete with ground granulated blast-furnace slag (GGBFS) cement and a water-to-binder (w/b) ratio of 0.45 – 0.50. The measurements were carried out for construction projects.

In the data analysis it was found that autogenous shrinkage of more than -0.1 mm/m can occur for ordinary GGBFS concrete with a w/b ratio ≥ 0.45. It was found that the variation in autogenous shrinkage in practice is considerable. The strongest correlations that were found in the database relate to the aggregates and not to the w/b ratio or concrete strength as was expected from literature. That not more or stronger relations were found is probably caused by the number of missing values (incomplete variables) in the database, that arose because not all data was collected in the same way.

In this paper we present the insights that the analysis of the autogenous shrinkage database gave. We also support the development of a standardised and widely adopted concrete data model that is suited for scientific research as well as for data from practice, and will facilitate and promote the use of state-of-the-art data techniques in concrete research.

Keywords: Autogenous shrinkage, data analysis, data mining, ground granulated blast-furnace slag, database, concrete data model

1 Introduction

Autogenous shrinkage occurs in concrete when cement hydrates and is linked to self-desiccation in the pore structure as it develops. It is the phenomenon of shrinkage at a constant temperature, without any loss or ingress of substances or application of an external force [1][2]. In ordinary types of concrete the autogenous shrinkage is thought to be small, always less than -0.1 mm/m when the water-to-binder (w/b) ratio is larger than 0.45 [3]. In concrete with ground-granulated blast-furnace slag (GGBFS) cement autogenous shrinkage is found to be higher and takes place over a longer period of time than in concrete with ordinary Portland cement [1]. In most studies where autogenous shrinkage of concrete with GGBFS was investigated, the w/b ratios were smaller than 0.45 [4][5][6]. The comprehensive database on creep and shrinkage of concrete by the Northwestern University [7], gives no records for autogenous shrinkage of concrete with slag and w/b ratios higher than 0.40. Lu [8] reports autogenous shrinkage values at day 28 of -0.14 mm/m and -0.12 mm/m for blast furnace slag concrete with a w/b ratio of 0.44 and 0.5 respectively.

In recent years there have been indications in construction practice that autogenous shrinkage in ordinary concrete can be larger than previously thought. The Dutch institute CROW for infrastructure, public space, traffic & transport, and work & safety has listed a number of projects where the measured crack width in concrete structures with restrained deformations exceeded the calculated crack width considerably [9]. It was suspected that autogenous shrinkage played a role in the excessive cracking, despite ordinary w/b ratios ($\geq$ 0.45) were applied.

In this study a large number of autogenous shrinkage measurements was collected, that were carried out for construction projects in the Netherlands. The data is brought together in an autogenous shrinkage database and analysed. The variations in parameters within the database are not preconceived and controlled by researchers, but a sample of variations that occur in practice. This method can be seen as data mining.

The aim of this study was primarily to investigate the variation in autogenous shrinkage in concrete in practice. Secondly, it was investigated which correlations could be found between variables in the database and autogenous shrinkage and how this relates to the influencing factors that are known from literature.

2 Description of the database

A research group of Stutech, a Dutch study association for professionals in concrete technology, collected data from two commercial research institutes in the Netherlands from autogenous shrinkage tests that were carried out in the period 2016 - 2018 on concrete that was applied in construction projects. The data was made available retrospectively with the consent of the clients of the tests. All tests were carried out according to the same testing protocol [10]. According to this protocol the autogenous shrinkage is measured on sealed samples of 100 mm x 100 mm x 400 mm. Measurements were done from day 1 on a number of time steps, typically at day 2, 3, 7, 14, 28, 56 and 91.

The autogenous shrinkage database was set up according to the tidy data format [11]. According to the tidy data semantics a dataset is a collection of values, being numbers (quantitative) or strings (qualitative). A variable contains all values that measure the same underlying attribute across units. An observation contains all values measured on the same unit across attributes. In the autogenous shrinkage database the unit is an autogenous shrinkage test for one concrete composition containing multiple, generally three, samples. An observation consists of data of the concrete composition, concrete characteristics, testing conditions and autogenous shrinkage data of the samples. The database contains 114 observations in total. A typical example of autogenous shrinkage data from one observation can be seen in **Fig. 1**. For the data analysis the autogenous shrinkage data from one observation is aggregated to one value by taking the mean autogenous shrinkage at a certain time step, mostly 91 days. The variations between the samples in one observation is generally small. The mean standard deviation for the three samples is 0.01 mm/m.

In the database autogenous shrinkage is expressed in mm/m. Besides autogenous shrinkage also autogenous expansion occurs. Although autogenous deformation may be used as a more general term, autogenous shrinkage is more common and therefore used in the database as well. To define the direction of the deformation a negative value is used for autogenous shrinkage and a positive value for autogenous expansion.

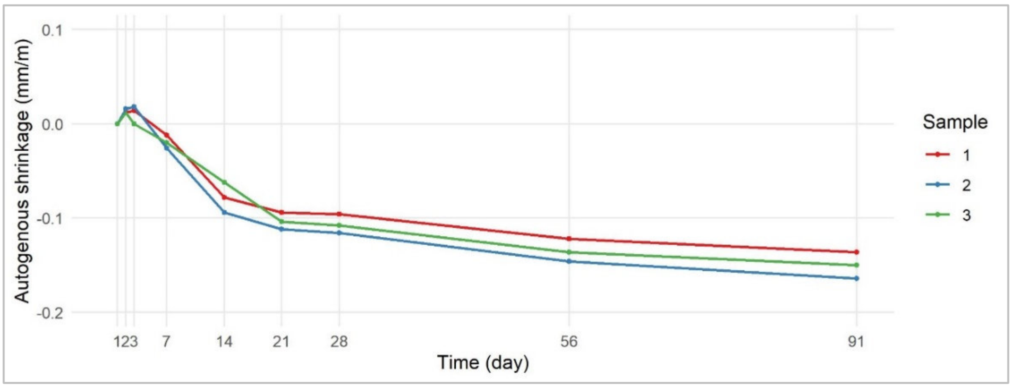

Fig. 1 An example of autogenous shrinkage data of three samples from one observation.

The database is thoroughly checked and verified before the data analysis is started. Outliers in the data are investigated. Samples with more than +/- 0.04% mass difference during testing are ruled out, because it is seen as a measurement error or the sealing of the sample did not function. Also observations where the behaviour of the samples is not equal, due to a difference in direction (shrinkage or expansion) during the test, are ruled out. After the verification 110 of 114 observations were approved for data analysis.

In total 153 variables, numerical, Boolean (True/False) and categorical, were part of the database. An impression of the variables can be seen in **Table.1**. To give an impression of the values for categorical and Boolean variables the (most) common values and the numbers of occurrence are given. For numerical variables the five-number summary is given with the minimum value (min), the first quartile (q1), the median (m), the third quartile (q3) and maximum value (max).

The database contains mainly concrete with GGBFS cement and a w/b ratio of 0.45 – 0.50, what is seen as ordinary concrete in the Netherlands. Most of the concrete is made with river dredged round aggregates, a smaller part contains light weight aggregates or recycled concrete aggregate.

During testing not all variables were registered, or registered in the same way. In addition some clients of the tests, the owners of the data, did not agree to reveal all data of the concrete composition. Although many efforts have been taken to retrieve as much data as possible and fill the database as completely as possible, the number of missing values (incomplete variables) in the database is considerable. In **Table.1** the number of missing values can be seen for the listed variables.

Table.1 Impression of variables in the autogenous shrinkage database.

Variable	**Type**	**Missing values**	**Impression of values**
Concrete composition known	Categorical	0	Yes (68), Partly (16), No (26)
Cement type	Categorical	39	CEM III/B 42,5 N (39), CEM III/B 42,5 L (17), CEM III/A 42,5 N (4), Other CEM III (2), CEM I 52,5 N (3), Other CEM I (3) Mix CEM III and CEM I (3)
Cement content (kg/m³)	Numerical	26	min=290, q1=325, m=340, q3=340, max=450
Portland clinker content (kg/m³)	Numerical	42	min=41, q1=85, m=99, q3=102, max=340
Ground granulated slag content (kg/m³)	Numerical	42	min=0, q1=224, m=238, q3=256, max=360
Water-binder-ratio	Numerical	26	min=0,31, q1=0,45, m=0,46, q3=0,5, max=0,55
Fine aggregate content (kg/m³)	Numerical	26	min=547, q1=706, m=791, q3=903, max=1076
Coarse aggregate average density (kg/m³)	Numerical	61	min=2150, q1=2650, m=2650, q3=2650, max=2710
Coarse aggregate content (kg/m³)	Numerical	26	min=582, q1=952, m=1050, q3=1168, max=1306
Water absorption (kg/m³)	Numerical	67	min=6, q1=7, m=7, q3=19, max=115
28-days cubic strength (N/mm²)	Numerical	80	min=28, q1=46, m=50, q3=53, max=70
Contains air entraining agent	Boolean	19	True (4), False (87)
Contains fly ash	Boolean	42	True (6), False (62)
Contains light weight aggregates	Boolean	19	True (5), False (86)
Contains limestone	Boolean	19	True (9), False (82)
Contains limestone powder	Boolean	42	True (2), False (66)
Contains plasticizer	Boolean	19	True (28), False (63)

Contains recycled concrete aggregate	Boolean	19	True (16), False (75)
Contains retarder	Boolean	19	True (3), False (88)
Contains river dredged round aggregate	Boolean	19	True (82), False (9)
Contains shrinkage reducing agent	Boolean	19	True (4), False (87)
Contains superplasticizer	Boolean	19	True (24), False (67)

Although the database contains mainly ordinary concrete with GGBFS cement and a w/b ratio of 0.45 – 0.50, many observations have some kind of special characteristic, like containing light weight aggregate, containing recycled concrete aggregate, the use of shrinkage reducing agent or a w/b ratio < 0.45. To investigate the variation in similar GGBFS concrete, a subset of similar GGBFS concrete of observations without any special characteristic is identified within the database. The subset is defined as observations containing only cement of type CEMIII/B 42.5 N or CEMIII/B 42.5 L, a w/b ratio of 0.45-0.50, only river dredged round aggregate and no special admixtures or fillers. The subset contains 23 of the 110 observations.

3 Results

3.1 Variation of autogenous shrinkage in the database

The median of autogenous shrinkage is -0.007 mm/m at day 2 and increases to -0.093 mm/m at day 91. The variation increases also over time. The distance between the first quartile and third quartile (the height of the box in a boxplot) increases from 0.05 at day 2 to 0.15 at day 91. If the outliers are neglected, the autogenous shrinkage at day 91 varies from -0.3 mm/m (shrinkage) to 0.1 mm/m (expansion).

For the subset with similar GGBFS concrete the median of the autogenous shrinkage increases from 0.000 mm/m at day 2 to -0.076 mm/m at day 91. The distance between the first quartile and third quartile increases from 0.06 at day 2 to 0.11 at day 91. For the subset the autogenous shrinkage at day 91 varies from -0.2 mm/m to 0.0 mm/m. Boxplots of autogenous shrinkage of all observations and of the subset with similar GGBFS concrete can be seen in **Fig.2**.

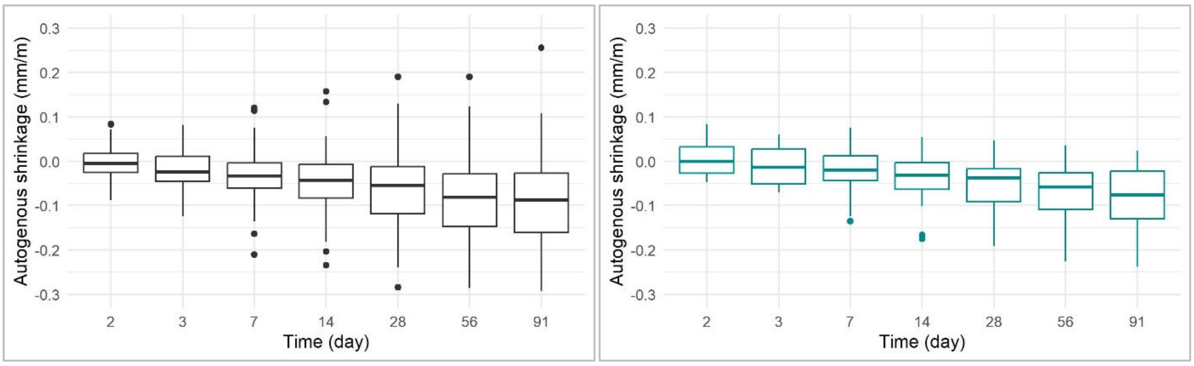

Fig.2 Boxplots of autogenous shrinkage over time, at day 2 until day 91 for all 110 observations (left) and for a subset of 23 observations with similar GGBFS concrete (right).

3.2 Correlations in the database

Correlations are investigated with the autogenous shrinkage at day 7, 28 and 91. Data points are considered as an outlier if they are more than 1.5 times the interquartile range from the median. In a boxplot those are the data points outside the whiskers. Outliers are not taken into account in the correlations.

Single correlations between autogenous shrinkage and other numerical variables were investigated using Pearson's correlation coefficient for a sample (Pearson's r) according to **Eq. (1)**.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (1)$$

in which n is sample size, x_i and y_i are individual sample points, $\bar{x}$ is the sample mean $\frac{1}{n}\sum_{i=1}^{n} x_i$ and $\bar{y}$ is the sample mean $\frac{1}{n}\sum_{i=1}^{n} y_i$.

A Pearson's r from 0.5 to 0.7 (or -0.5 to -0.7) is considered to be weak, from 0.7 to 0.9 (or -0.7 to -0.9) is considered to be moderate and from 0.9 to 1.0 (or -0.9 to -1.0) is considered to be strong.

Single correlations between autogenous shrinkage and Boolean variables were investigated with a two-sided permutation test for the mean difference with 10,000 permutations (random shuffles). This statistical method is used to assess whether there is a significant difference between two groups. It involves randomly shuffling the observations between the groups, recalculating the mean difference for each permutation, and comparing it to the observed mean difference. The p-value is then calculated as the proportion of permutations where the absolute mean difference is as extreme as or more extreme than the observed value. This approach provides a robust assessment of significance without assuming any specific distribution for the data.

For all investigated correlations the p-value is calculated as measure for the statistical significance. Only results under a significance level of 5% are regarded significant. If the p-value is higher than the significance level it cannot be ruled out that the correlation is based on coincidence. A significance level of 5% is commonly used and is found fitting to this study.

No strong correlations were found between autogenous shrinkage and other numerical variables, only some moderate or weak correlations. The two strongest correlations can be seen in **Fig.3**. The blue line is the fitted correlation, the grey band is the 0.95 confidence interval for the correlation. The strongest correlations are with the 'Coarse aggregate average density (kg/m³)' with Pearson's r = 0.70, p = 0.00 and 'Water absorption (kg/m³)' with Pearson's r = 0.58, p = 0.00.

'Coarse aggregate average density (kg/m³)' is the density of the coarse aggregates. If different coarse aggregates are used, the density is averaged by the mass. 'Water absorption (kg/m³)' is the amount of water that is absorbed by the aggregates.

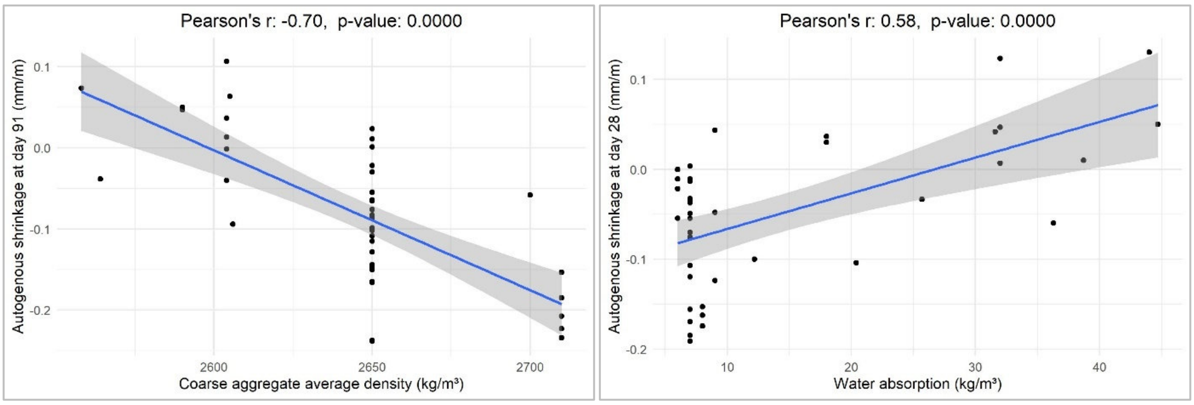

Fig.3 Correlations between autogenous shrinkage at day 91 and 'Coarse aggregate average density (kg/m³)' (left) and between autogenous shrinkage at day 28 and 'Water absorption (kg/m³)' (right).

Correlations between autogenous shrinkage and 'Water-binder-ratio' or '28-days cubic strength (N/mm²)' were found to be weak (low Pearson's r) and uncertain (high p-value), as can be seen in **Fig.4** and **Fig.5**, for all observations as well as for the subset of 23 observations with similar GGBFS concrete.

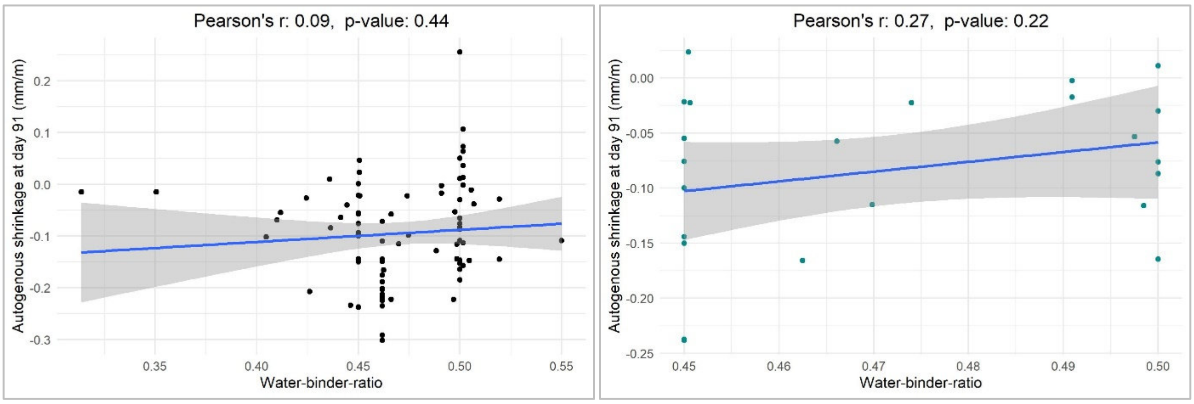

Fig.4 Correlations between autogenous shrinkage at day 91 and 'Water-binder-ratio' for all observations (left) and for the subset with similar GGBFS concrete (right).

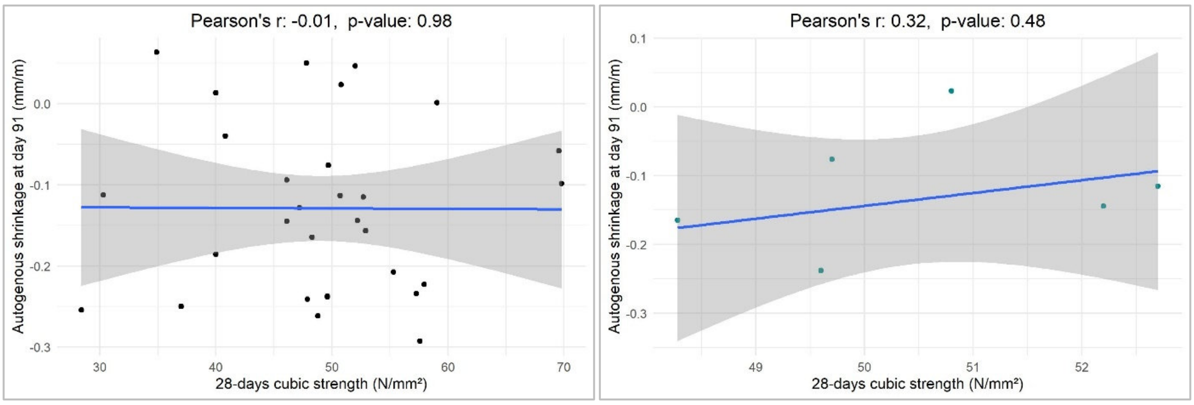

Fig.5 Correlations between autogenous shrinkage at day 91 and '28-days cubic strength (N/mm²)' for all observations (left) and for the subset with similar GGBFS concrete (right).

In the permutation tests there were two Boolean variables with a consistent p-value lower than 5% with autogenous shrinkage at day 7, 28 and 91. These are the Boolean variables 'Contains light weight aggregate' and' Contains recycled concrete aggregate'. The distribution of values of autogenous shrinkage at day 91 in the two groups (True/False) for these two variables can be seen in **Fig.6**. The red diamond is the mean autogenous shrinkage at day 91 for each group.

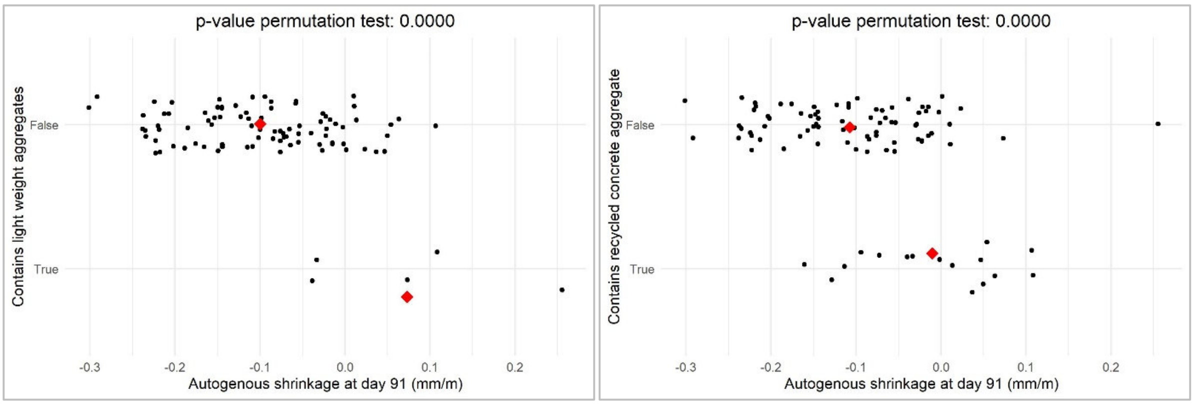

Fig.6 Correlation between autogenous shrinkage at day 91 and 'Contains light weight aggregate' (left) and 'Contains recycled concrete aggregate (right).

Lasso linear regression was used to investigate the correlation between autogenous shrinkage and multiple variables. In the lasso linear regression the loss function according to **Eq. (2)** is minimised.

$$Loss\ function\ = \sum(y_{actual} - y_{predicted})^2 + \alpha \sum|\beta| \qquad (2)$$

with y_{actual} is the actual value of autogenous shrinkage, $y_{predicted}$ is the value of autogenous shrinkage predicted by the linear regression model, α is a tuning parameter to influence the number of variables in the model and β are the coefficient(s) in the model. Numerical, Boolean and categorical variables were used in the lasso linear regressions. Boolean and categorical variables are converted into dummy/indicator variables with values 0 or 1. All variables are standardised by removing the mean and scaling to unit variance, in order to transform the variables to a similar scale to ensure that all variables contribute equally to the model.

In the lasso linear regressions R^2 was used as measure for the regression fit according to **Eq. (3).**

$$R^2 = 1 - \frac{\sum(y_{actual} - y_{predicted})^2}{\sum(y_{actual} - y_{mean})^2} \qquad (3)$$

in which y_{mean} is the mean autogenous shrinkage.

The value of R^2 is always between 0 and 1, where 0 means that the model does not explain any variability in the variable (autogenous shrinkage in this case) and 1 meaning it explains full variability in the variable. The results of the lasso linear regressions are summarised in **Fig.7.** Models with less than 10 variables have a low R^2, models with 10 variables or more have higher R^2, but are likely overfitted because of relatively high number of variables in relation to the number of observations. The higher values of R^2 for similar GGBFS concrete than all observations is also probably caused by overfitting due to the limited number of observations (23 versus 110).

The variables that appeared in the different models were not consistent.

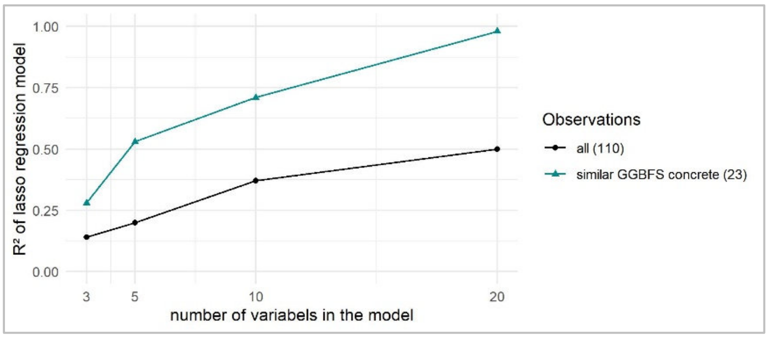

Fig.7 Summary of the results of lasso linear regression analysis.

4 Discussion

4.1 Variation of autogenous shrinkage in the database

In our database with mainly ordinary GGBFS concrete autogenous shrinkage at day 91 varies from -0.3 mm/m (shrinkage) to 0.1 mm/m (expansion). For a subset with similar GGBFS concrete autogenous shrinkage at day 91 varies from -0.2 mm/m to 0.0 mm/m. On the basis of Eurocode 2 [12], equations (3.11), (3.12) and (3.13), autogenous shrinkage at day 91 was calculated ranging from -0.04 to -0.07 mm/m for concrete strength classes C30/37 till C45/55, that match the concrete strengths in the database. The variation in autogenous shrinkage in the database and calculations according to Eurocode 2 can be seen in **Fig.8**. The measured autogenous shrinkage for concretes with a w/b ratio ≥ 0.45 can be larger than -0.1 mm/m, exceeding the calculated values and therefore cannot be neglected by definition.

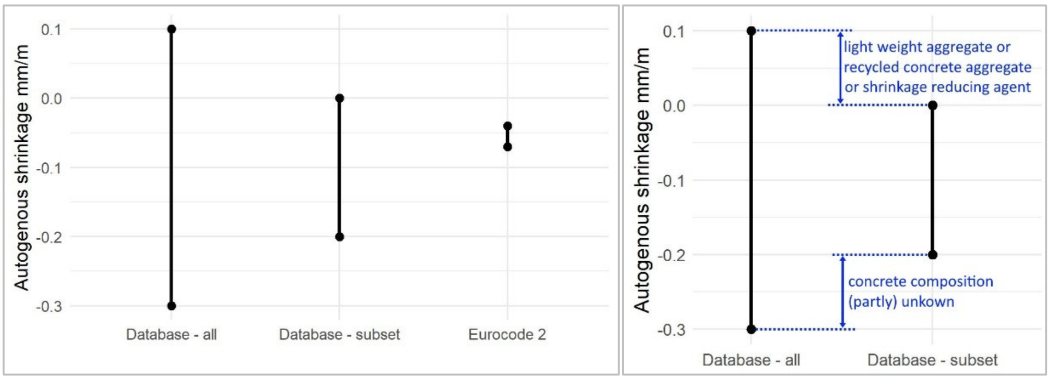

Fig.8 Variation in autogenous shrinkage in the database and calculations according to Eurocode 2 (left) and comparison of variations in all observations and the subset (right).

The observations with autogenous expansion (0.0 to +0.1 mm/m) contain light weight aggregate or recycled concrete aggregate, or a shrinkage reducing agent was used. The autogenous shrinkage decreasing effect of porous aggregates is consistent with previous research that reported that light weight aggregate can act as a water storage agent that mitigates the self-desiccation that is linked to autogenous shrinkage [4]. This effect will only manifest if the porous aggregates are absorbed with water before mixing.

The observations in the database with the highest shrinkage (-0.2 to -0.3 mm/m) are from clients of the tests that did not agree to reveal all data of the concrete composition and can therefore not be explained.

The variation in autogenous shrinkage in the subset with similar GGBFS (-0.2 to 0.0 mm/m) cannot be explained by variables in the database. This variation is larger than in most experimental studies. In [13] large composition variability is mentioned as uncertainty factor for random deviations. Most of the experimental research focusses on (ultra) high performance concrete (U)HPC [14][15][16]. In those studies the materials for the different samples often come from the same source. In addition the materials that are used for (U)HPC are generally from high, constant and controlled quality to be able to deliver the high performance. In our database, with ordinary concrete from construction projects, the source of materials is more divers. Another possible cause of variation is differences in working procedures that are followed to mix the concrete and make the samples.

4.2 Correlations in the database

A limited number and only weak to moderate correlations were found between autogenous shrinkage and other variables in the database. The variables that were found to have a statistical significant correlation with autogenous shrinkage are ‘Coarse aggregate average density (kg/m^3)’, ‘Water absorption (kg/m^3)’, ‘Contains recycled concrete aggregate’ and ‘Contains light weight aggregate’. All these variables relate to same underlying mechanism of porous aggregates that act as a water storage agent that mitigates the self-desiccation [4]. In a similar data-driven approach for autogenous shrinkage in UHPC, stronger correlations were found [16]. That not more or stronger correlations were found in our database can be explained by the high proportion of missing values. For the concrete strength, for example, 80 of 110 values are missing which makes it less likely that a correlation can be found.

The correlations that are found only explain part of the variability in autogenous shrinkage in the database, as can be seen from the considerable variability in vertical direction in **Fig.3**. Therefore it’s expected that the interaction of multiple variables play a role in autogenous shrinkage. Lasso linear regression with multiple variables was carried out to investigate this further, but did not provide more insight. This is probably due to the high proportion of missing values and the relatively small number of observations in relation to the high number of variables.

It was also considered whether variables may be missing from the database that have an important influence on autogenous shrinkage. Therefore, the database is compared with influencing factors mentioned in literature, but no obviously missing variables are identified.

4.3 Recommendations for future databases

Databases are set up to bring together scientific research on (autogenous) shrinkage of concrete [7][16]. The collection and analysis of data from practice can be a valuable addition to the scientific research. It can be used to validate experimental findings in practice. It is also an addition because scientific research is more focussed on new, innovative concrete types, while data from practice represents the concrete types that are most commonly used in the present. Also interesting is that unexpected relations or patterns may be found, because in data from practice the parameters and their variations are not preconceived and controlled and therefore less biased. Data from practice is useful but cannot be treated in the same way as peer reviewed scientific data. Therefore the source of the data shall always be clear if databases are formed.

The collection of data from multiple sources, whether scientific research or from practice, comes with challenge. Not the same testing procedures may be followed, the testing procedures may not be documented well, not the same data may be collected, the data may be registered differently and/or different interpretations of data occur. These challenges were also encountered in this study, leading to the high proportion of missing values. To face these challenges and make more rich and complete databases in the future, a standardised and widely adopted concrete data model is necessary. The concrete data model shall prescribe what data is collected and how it is structured. A data model for concrete composition shall be general applicable for all concrete research, for each type of testing a specific data model can be developed. It may be considered that some data in the data model is made obligatory or highly recommended to collect and register, even if this data is not necessary for the research itself. This will facilitate and promote the reuse of concrete research data. It is advised that the concrete strength will be made highly recommended in all concrete research, because it’s so widely used as a characteristic for concrete and a commonly used parameter in models and standards.

The International Federation for Structural Concrete (fib) has launched a wide and open initiative on test data management [17] including a standardised data model. The authors hope that this initiative will be widely adopted, that it will be used by concrete researchers worldwide and that it will be open for test data from practice too.

A standardised and widely adopted concrete data model will stimulate researchers to combine their own data with data from other researchers to gain more insights. It also creates a solid basis for the application of state-of-the-art data techniques, such as AI.

5 Conclusion

The results are given and discussed of the data analysis of an autogenous shrinkage database with data from practice of concrete with mainly GGBFS cement and w/b ratios of 0.45-0.50. The major findings are:

1) A standardised and widely adopted concrete data model, that is suited for scientific research as well as for data from practice, will facilitate and promote the use of data and state-of-the-art data techniques, such as AI, in the field of concrete research.
2) The collection and analysis of data from practice can be a valuable addition to experimental, scientific research, because it represents the concrete types that are most commonly used in practice in the present and not only the newest and most innovative concrete types.
3) If relevant for the structure, autogenous shrinkage cannot be neglected by definition for concrete with a w/b ratio $\geq$ 0.45. Autogenous shrinkage of more than -0.1 mm/m can occur for ordinary GGBFS concrete with w/b ratios of 0.45-0.50.
4) In practice the variation in autogenous shrinkage is considerable. A variation of -0.2 mmm to 0.0 mm/m was found for similar GGBFS concrete with w/b ratios of 0.45-0.50. The variation is attributed to the diversity in source of materials and working procedures in practice.

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References

[1]. E. Tazawa, S. Miyazawa, Influence of cement and admixture on autogenous shrinkage of cement paste, Cem. Concr. Res. 25 (1995) 281–287

[2]. L. Wu, N. Farzadnia, C. Shi, Z. Zhang, H. Wang, Autogenous shrinkage of high performance concrete: a review, Construct. Build. Mater. 149 (2017) 62 – 75, https://doi.org/10.1016/j.conbuildmat.2017.05.064

[3]. Shengwen Tang, Desheng Huang, Zhen He, A review of autogenous shrinkage models of concrete, J. Build. Eng. 44 (2021) 103412, https://doi.org/10.1016/j.jobe.2021.103412

[4]. Zhichao Liu, Will Hansen, Aggregate and slag cement effects on autogenous shrinkage in cementitious materials, Construct. Build. Mater. 121 (2016) 429-436, https://doi.org/10.1016/j.conbuildmat.2016.06.012

[5]. K.M. Lee, H.K. Lee, S.H. Lee, G.Y. Kim, Autogenous shrinkage of concrete containing granulated blast-furnace slag, Cem. Concr. Res. 36, Issue 7 (2006) 1279-1285, https://doi.org/10.1016/j.cemconres.2006.01.005

[6]. Ei-ichi Tazawa, Shingo Miyazawa, Influence of cement and admixture on autogenous shrinkage of cement paste, Cem. Concr. Res. 25, Issue 2 (1995) 281-287, https://doi.org/10.1016/0008-8846(95)00010-0

[7]. Mija H. Hubler, Roman Wendner, Zdenek P. Bazant, Comprehensive database for concrete creep and shrinkage: analysis and recommendations for testing and recording, ACI Mat. J. 112.4 (2015) 547-558 http://www.civil.northwestern.edu/people/bazant/downloads.html

[8]. Tianshi Lu, Autogenous shrinkage of early age cement paste and mortar, Dissertation Delft University of Technology (2019), https://doi.org/10.4233/uuid:e06bd615-7fc4-481b-a334-37627f142e3d

[9]. CROW-CUR Rapport 1:2020 Scheurwijdtebeheersing van betonconstructies, https://www.crow.nl/publicaties/scheurwijdtebeheersing-betonconstructies-fase-1

[10]. CROW-CUR Beproevingsprotocol 1:2019 Autogene krimp fase 2, https://www.crow.nl/publicaties/crow-cur-beproevingsprotocol-1-2019

[11]. Hadley Wickham, Tidy data, The Journal of Statistical Software 59 (2014), https://www.jstatsoft.org/article/view/v059i10

[12]. EN 1992-1-1:2004, Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings

[13]. Hubler, M.H., Wendner, R. & Bažant, Z.P. Statistical justification of Model B4 for drying and autogenous shrinkage of concrete and comparisons to other models. Mater Struct 48, 797–814 (2015), https://doi.org/10.1617/s11527-014-0516-z

[14]. Ehsan Ghafari, Seyed Ali Ghahari, Hugo Costa, Eduardo Júlio, Antonio Portugal, Luisa Durães, Effect of supplementary cementitious materials on autogenous shrinkage of ultra-high performance concrete, Construct. Build. Mater. 127 (2016), 43-48, https://doi.org/10.1016/j.conbuildmat.2016.09.123

[15]. Peiliang Shen, Linnu Lu, Yongjia He, Meijuan Rao, Zedong Fu, Fazhou Wang, Shuguang Hu, Experimental investigation on the autogenous shrinkage of steam cured ultra-high performance concrete, Construct. Build. Mater. 162 (2018), 512-522, https://doi.org/10.1016/j.conbuildmat.2017.11.172

[16]. Yaqiang Li, Jiale Shen, Yue Li, Kai Wang, Hui Lin, The data-driven research on the autogenous shrinkage of ultra-high performance concrete (UHPC) based on machine learning, J. Build. Eng. 82 (2024) 108373, https://doi.org/10.1016/j.jobe.2023.108373

[17]. David Fernández-Ordóñez, Miguel Fernández Ruiz, Nikola Tošić, Roman Wan-Wendner, Albert de la Fuente, Rethinking databases: The fib project for a connected data repository. Struc. Concr.(2023) https://doi.org/10.1002/suco.202201023