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Statistical Analysis of the Variability in Shotcrete Strength

By Atef Badr

University of Portsmouth, United Kingdom

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Statistical Analysis of the Variability in Shotcrete Strength

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Keywords: strength variation; sprayed concrete; shotcrete; in-situ strength, concrete cores; fibre-reinforced-concrete; statistical analysis; coefficient of variation; standard deviation; quality control.

I. Introduction

Sprayed concrete, also known as shotcrete, is a cement-based mixture which is projected pneumatically at a high velocity onto a target surface. Compared to cast- in-place concrete, the sprayed concrete offers significant advantages. It reduces the amount and time for formwork installation and removal. Indeed, in many cases it eliminates the need for formwork altogether when shooting against existing surface. This advantage is extremely valuable in situations when formwork is cost prohibitive or deemed impractical [1-2].

Sprayed concrete has traditionally been used for repair works and for temporary construction in mining and tunneling to ensure the safety of workers. However, technological advancements, made it a viable construction material for new construction [2-3].

The utilisation of fibre reinforcement in concrete and sprayed concrete is rapidly expanding due to the potential economic and technical benefits. Many deficiencies of plain concrete and sprayed concrete could be alleviated by using fibre reinforcement. For example, polypropylene fibres are capable of improving the ductility of concrete by enhancing properties such as its flexural toughness, fatigue and impact resistance [4-10].

The physical and mechanical properties of properly applied sprayed concrete could be comparable or superior to those of conventionally cast concrete of same composition [2]. However, it is extremely difficult to produce sprayed concrete with the same composition of specified cast concrete due to the nature of the spraying process. The process of applying sprayed concrete generally ensures that most of the aggregates and cementitious materials combine to form a mixture, which adheres well to the substrate. Unfortunately, considerable amount of materials strikes the surface but does not adhere to the substrate. This is known as the rebound and it greatly influences the composition of the in-situ sprayed concrete. The latter could also be altered during the application process due to other variables such as using accelerator, fibre addition, poor application techniques, skills of the nozzleman and overwatering. Consequently, the properties of the placed sprayed concrete could have properties that are significantly different from the specified properties. Particularly, compressive strength [11-15].

Compressive strength is the primary material property specified for sprayed concrete. It is usually considered not only as a measure of its ability to carry loads but also as an indicator of its quality. Furthermore, the compressive strength of the placed sprayed concrete could be considered as the critical criterion used for design, and therefore needs to be accurately determined.

There are many testing methods available in the market for assessing the strength of in-situ sprayed concrete. Although each method has its advantages, most of them suffer from inherent negative aspects including limited range, inaccuracy and inconsistency. In addition, some of them are impractical [3, 16-17]. However, drilling cores from the in-situ sprayed concrete is considered one of the best methods to use in

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Author: PhD, MSc, BSc (Hons), PGCE, CEng, MICE, FHEA, Head of Civil Engineering Department, MTC, Muscat, Oman; PAL, University of Portsmouth, Portsmouth, UK. e-mail: atefbadr@hotmail.com

determining the compressive strength [12]. This technique is widely used since it is simple and economical. Guidelines and recommended procedures for coring, testing, and interpreting results of core specimens are well established and documented by several standards, codes and research reports such as ACI 214 R-02 [18], BS EN 13791 [19], ACI 214.4R-03 [20], ASTM C42 [21], BS 1881 [22], BS EN 12504-1 [23], The Concrete Society Technical Report CSTR 11 [24], Neville [25] and Chen et al. [26]. However, the results obtained from testing extracted cores are often noticeably scattered [14, 27]. The variation in the strength obtained for cores taken from sprayed concrete is often mentioned in the literature in general context but, unfortunately, it is rarely quantified on the basis of statistical analysis. Without significant statistical analysis the limited data available from placed sprayed concrete are regarded as unreliable [16]. The main objective of this research, therefore, was to investigate the variability in the strength of cores drilled into placed sprayed concrete and quantify it based on a statistical approach.

II. MATERIALS, MIX PROPORTIONS AND PRODUCTION OF SPECIMENS

a) Materials

The binder used in this investigation was Portland cement (CEM1), conforming to BS EN 197-1 (2000). The coarse aggregate was quartzite natural gravel of 10-mm nominal maximum size. It had a specific gravity of 2.64, bulk density of 1585 kg/m3 and water absorption of 0.60 percent. The fine aggregate was Quartzite sand complying to zone M of BS EN 12620 (2002), with specific gravity and water absorption of 2.68 and 0.10 percent, respectively. Fibrillated Polypropylene fibres (PPF) with a nominal length of 18mm and an average diameter of 55μm was used, where applicable. More information about this fibre is given elsewhere [4].

b) Mixes and mix proportions

Two types of concrete were sprayed in this study; plain and fibre reinforced concrete (FRC). The mixes were initially optimised from laboratory tests. The cast and pre-sprayed compositions of the mixes are given in Table 1. The water content for the lab-cast concrete was constant at 160 kg/m (i.e. w/c ratio of 0.40). However, for sprayed concrete it was decided during spraying by the nozelman according to the ease of 'shotability' of each mix.

Table 1: Lab-cast and pre-sprayed mix proportions (kg per m^3)

Mixes	*Method*	*CEM1*	*Gravel*	*Sand*	*Fibre*
Cast-N	Lab-cast	400	948	948	-
Shot-N	Sprayed	400	948	948	-
Cast-F	Lab-cast	400	948	948	2.0
Shot-F	Sprayed	400	948	948	2.0

III. PRODUCTION AND TESTING OF SPECIMENS

a) Lab-cast concrete specimens

A conventional rotary drum concrete mixer was used for mixing. The coarse aggregate, cement and sand were first mixed in dry state for one minute before adding about half of the mixing water. After two minutes of mixing, the remaining mixing water was added. Mixing was continued for another three minutes before adding the polypropylene fibres, where applicable, carefully into the running mixer to avoid clumping. Mixing was continued for a further five minutes to achieve uniform mixture. After casting, the lab-cast concrete specimens were compacted using a vibrating table. The specimens were, then, finished and covered with wet hessian and polyethylene sheets overnight. They were then de-moulded after 24 hours and cured in a fog room with curing conditions conforming to BS 1881: Part 111: 1983 (20±2°C and RH 97±3%) until testing.

b) Sprayed concrete specimens

Sprayed concrete panels were produced by dry process, which was more appropriate for this study due to economical and practical reasons. A dry-process pneumatic spraying machine with rotary feed wheels, 38-mm nozzle and material hose was used.

All ingredients except water were first mixed in dry state in a conventional concrete mixer. Where applicable, PPF fibre was added after two minutes of dry mixing, which then continued for another two minutes. The dry mix was then fed through the hopper of the spraying machine, which conveyed the mix pneumatically through the material hose to the nozzle where water was added through the water ring.

Wooden square moulds of 1200-mm side and 100-mm depth, shown in Figure 1, were manufactured specially for this project. Before spraying, the moulds were positioned as vertically as possible (within 5 to 10°). Every effort was made to minimise the variations in the spraying process. For example, the spraying distance between the nozzle and the target-surface and the spraying angle were kept around one meter and 90°, as shown in Figure 2.

Figure 1: Wooden moulds for sprayed concrete panels

After completing spraying, each panel was marked and covered with polyethylene sheet for 2 days, after which the panels were loaded carefully on trucks and transported to the laboratory for curing, coring and testing. On arrival, all sprayed panels were kept in the fog room to be cured, in the same conditions as the counterpart lab-cast concrete.

Figure 2: Production of sprayed concrete panels

By the age of 14 days, cores were taken from the panels of each type of concrete for compressive strength testing. Cores were inspected for any imperfect parts or sand pockets, marked and kept cured in the same fog room.

Twenty cores were drilled from each type of sprayed concrete. The number has been decided to minimise the effect of variation. Celik et al. [16] suggested that sample sizes of 18 or more are preferred for statistically significant data sets for minimizing the effect of variation within the results of compressive strength.

c) Compressive strength tests

Compressive strength of the drilled cores from the sprayed concrete and the hardened concrete cubes was determined according to BS 1881: Part 116: 1983, at the age of 28 days. The tests were carried out using a digital automatic testing machine of a 3000 kN capacity. The results of the compression tests are given in Table 2.

Table 2: Results from compressive strength test (MPa)

Sample	**Plain**		**Fibre reinforced**		**Overall**	
	Shot-N	Cast-N	Shot-F	Cast-F	Shot	Cast
1	29.96	69.28	25.30	76.35	-	-
2	32.82	70.42	26.59	77.89	-	-
3	33.74	74.51	26.72	79.54	-	-
4	36.13	75.30	30.51	80.47	-	-
5	38.78	76.24	32.69	82.69	-	-
6	38.89	77.11	36.12	83.29	-	-
7	39.95	77.86	37.55	83.54	-	-
8	40.79	78.17	38.46	83.84	-	-
9	41.97	78.43	39.34	84.09	-	-
10	44.07	78.45	40.68	85.37	-	-
11	44.26	79.74	42.31	86.41	-	-
12	45.58	80.68	42.83	86.45	-	-
13	46.37	81.24	44.92	87.02	-	-
14	46.95	81.25	45.82	87.23	-	-
15	47.41	81.96	47.53	88.30	-	-
16	49.35	82.33	52.16	89.01	-	-
17	50.06	82.52	52.97	89.51	-	-
18	53.76	82.73	53.11	90.52	-	-
19	55.48	84.05	64.15	91.54	-	-
20	69.59	85.25	70.01	92.08	-	-
Mean (MPa)	44.3	78.9	42.5	85.3	43.4	82.1
SD (MPa)	9.0	4.2	12.0	4.4	10.5	5.4
CoV (%)	20.4	5.4	28.1	5.2	24.2	6.5

SD= Standard Deviation; CoV= Coefficient of Variation

IV. RESULTS AND DISCUSSION

a) Variability in sprayed and lab-cast concrete

The average 28-day strength of all sprayed concrete specimens was 43.4 MPa. The calculated standard deviation (SD) was 10.5 MPa and the coefficient of variation (CoV) was 24.2%. The corresponding values for the lab-cast concrete were 82.1 MPa, 5.4 MPa and 6.5% for the average strength, SD and CoV, respectively.

The value of the CoV for the lab-cast concrete observed in this study (6.5%) is between the 5.5% and 7.0% limits of the fair class recommended by ACI 214 R-02 [18] for concretes with strength of more than 35MPa, but outside 4.5% to 5.5% band for good concrete for lab trial batches. However, the CoV value reported in this study is similar to what Cussigh et al. [28] reported for high-performance concrete. Indeed, the CoV recorded for the lab-cast concrete compare favourably to the values reported by Aït-Mokhtara et al. [29] for high performance concretes with strength range between 68 and 84 MPa. The standard deviation of the results of the lab-cast concrete indicates good quality control over the production of the concrete specimens, as it falls nicely 20 between 4 to 6 MPa, which is considered acceptable in the UK [30]. The values of the coefficient of variation show further evidence of good quality control. The coefficient of variation of 6.5% is at the lower end of the range (between 5 and 10%) suggested by Day et al. [30] for concrete with a reasonable quality control.

On the other hand, the standard deviation and coefficient of variation of the results of the sprayed concrete not only are much higher than those of the counterpart lab-cast concrete, but also are much higher than the acceptable values for good quality concrete. Considering the upper limits suggested by Day et al. [30], the SD of 10.5 MPa is about 75% higher than the upper limit of 6 MPa. In addition, the CoV of the sprayed concrete (24.2%) is double the upper limit of 10%. Even when compared to more relaxed limits, the 24.2% overall CoV is about 60% higher than the 15% suggested by Swamy and Stavrides [31] for good quality control of concrete. When compared to the limits given by ACI 214 R-02 [18] for concretes with strength of more than 35MPa, the CoV of the sprayed concrete is 70% higher than the maximum limit of 14% for general construction testing.

The observed variability in the compressive strength of cores taken form in-situ sprayed concrete could be attributed to several factors that might possibly affect the compressive strength either during sampling or testing procedures. For example, concrete cores are susceptible to damage caused by the drilling operation or removing the cored specimens. This damage could be in the form of macro or microcracking and/ or weakening the bond between the cement matrix and aggregate particles at the surface of the core. It is also inevitable that drilling cuts through coarse aggregate particles, resulting in them being not fully bonded to the concrete matrix [16, 32-35].

Indeed, the effect of any aggregate loosened by the cutting operation could explain the lower average strength obtained for sprayed concrete cores in this study. Particularly, when compared to that of the counterpart lab-cast concrete.

The lower average strength obtained for concrete cores is also observed for concrete placed using conventional placing methods and, thus, it is not necessarily a result of the spraying process. De Stefano et al. [36] reported that the in-situ concrete not only usually has low strength, but it is also highly variable, even within a single building.

Fig. 3 presents the histogram of all results obtained from the compressive strength tests for lab-cast and sprayed concrete. The figure shows that the results are almost normally distributed and fit well with the superimposed normal distribution curves of the same mean and standard deviation as the compressive strength results of each type of concrete; i.e. lab-cast and sprayed. However, the distribution of the latter is spread over a wider range of about 40 MPa (30 to 70 MPa) compared to only 20 MPa for the lab-cast concrete (70 to 90 MPa). This would be particularly significant when considered in the light of the values of the average strength in both cases. In addition, the curve in the case of lab-cast concrete is steep due to the low standard deviation (5.4 MPa) whereas for the sprayed concrete, it is flat because of its higher standard deviation (10.5 MPa).

The difference in the shapes of the two curves demonstrates that the strength results are more spread for sprayed concrete, indicating that less strength values fit within one standard deviation from the mean strength; i.e. confirming higher variations. Thus, sprayed concrete has a higher probability that measured strength values could be far from the mean strength.

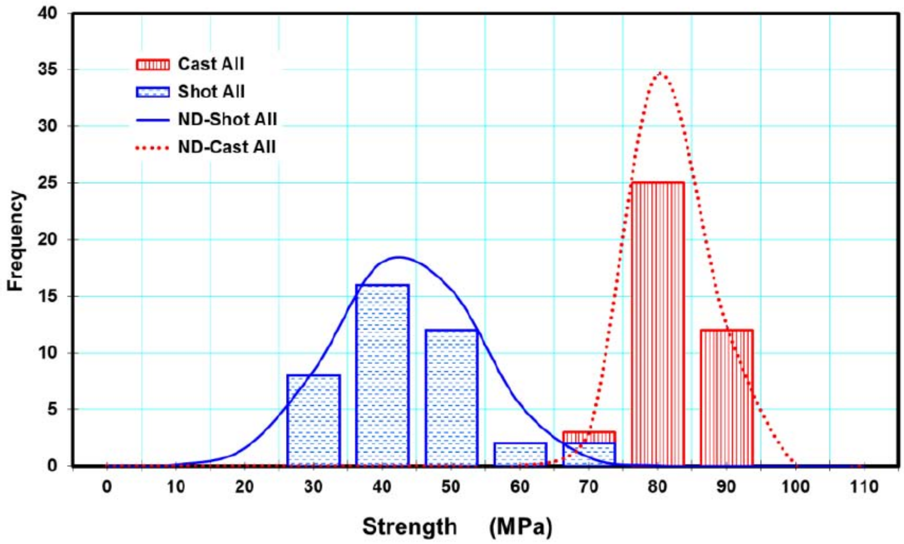


Figure 3: Distribution of strength (All results)

The SD and CoV obtained in this study are slightly higher than the values reported by Zhang [14] for cores taken form test panels in a tunnel shotcrete project. The reported SD and COV for compressive strength at 28 days were 8 MPa and COV of 17%, respectively. However, these values are for wet-mix sprayed concrete, which is known to have a better quality control of the produced sprayed concrete compared to the dry-mix used in the current study. Nonetheless, the values of coefficient of variation obtained in this study or reported in the literature for sprayed concrete are significantly higher the recommended values for compressive strength of concrete. These high values of coefficients of variation for sprayed concrete strength obtained in this study and reported studies in the literature - despite the difference in the materials and methods used- indicate higher variability in the strength of sprayed concrete when compared to limits that have been derived and set originally for cast concrete. Therefore, there could be a need to amend standards, regulations and code of practice to reflect this higher variability and account for it when judging the quality of sprayed concrete.

b) Plain lab-cast and sprayed concrete

The plain (i.e. no fibre reinforcement) sprayed concrete had an average 28-day strength of 44.3 MPa, with a SD of 9.0 MPa and a CoV of 20.4%. The lab-cast concrete, on the other hand, has corresponding values of 78.9 MPa, 4.2 MPa and 5.4% for the average strength, SD and CoV, respectively.

Fig. 4 presents the histogram of the results obtained from the compressive strength tests for lab-cast and sprayed plain concrete. As with the overall results (Fig. 3), the Figure shows that the results are almost normally distributed for both types of concrete. The distribution of the sprayed concrete strength, however, is dispersed over a wider range compared to the cast concrete. This is reflected in the shape of the superimposed normal distribution curve of each type of concrete. The curve of the lab-cast concrete is steeper due to the lower standard deviation (4.2 MPa) compared to that of the sprayed concrete (9.0 MPa), which has a flatter curve, indicating that less strength values fit within one standard deviation from the mean strength. The standard deviation of the sprayed plain concrete not only is higher than that of the counterpart lab-cast plain concrete but also is much higher than the acceptable values for good quality of concrete. The standard deviation of 9.0 MPa is 50% higher than the upper limit of 6 MPa, suggested by Day et al. [30]. Equally, the value of the CoV of the sprayed plain concrete (20.4%) is double the upper limit of 10% and almost four-times higher the 5.4% coefficient of variation of the lab-cast plain concrete. The latter, is just below the 5.5% limit given by ACI 214 R-02 [18] for good concrete produced in laboratory. However, the 20.4% CoV of the sprayed plain concrete is significantly higher than the maximum limit of 14% for general construction.

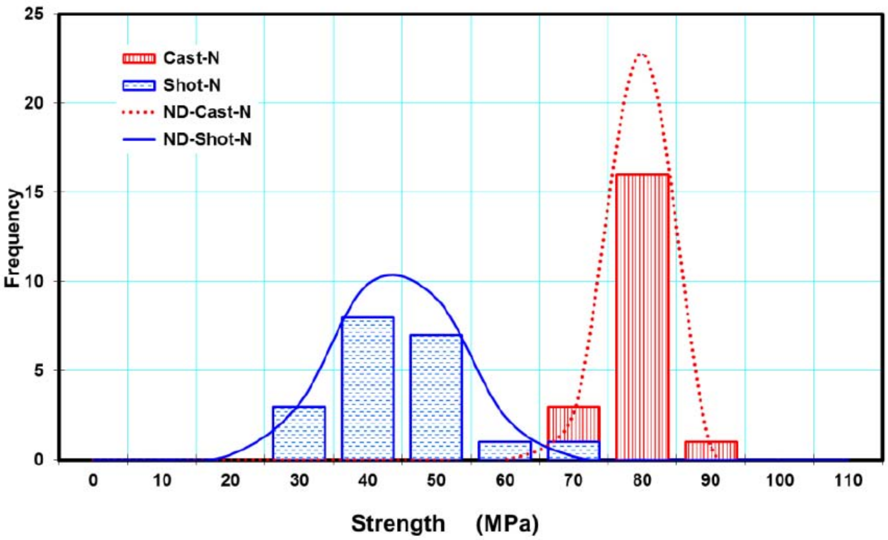


Figure 4: Distribution of strength of plain cast and sprayed concrete

c) *Fibre-reinforced lab-cast and sprayed concrete*

The fibre-reinforced concrete (FRC) produced using the spraying process had an average 28-day strength of 42.5 MPa, with a SD of 12.0 MPa and a CoV of 28.1%. The lab-cast concrete has corresponding values of 85.3 MPa, 4.4 MPa and 13 5.2%, respectively.

The histograms of the results obtained for lab-cast and sprayed FRC are presented in Fig. 5. The figure shows that the results are almost normally distributed for both types of concrete. Again, the distribution for sprayed concrete is dispersed over a wider range compared to the cast concrete. The 4.2 MPa standard deviation of the lab-cast concrete caused its curve to be steeper than that of the sprayed concrete, which has a 12.0 MPa standard deviation. The latter, is almost 3 times higher than that of the counterpart FRC produced in the lab (i.e. lab-cast) and is much higher than the acceptable values for good quality of concrete. The standard deviation of 12.0 MPa doubles the upper limit of 6 MPa, suggested by Day et al. [30]. Furthermore, the value of the coefficient of variation of the sprayed FRC (28.1%) would appear huge when compared to the upper limit of 10%, recommended by Day et al. [30] or the 15% limit suggested by Swamy and Stavrides [31]. Indeed, the 28.1% CoV of sprayed FRC is more than double the 14% limit in ACI 214 R-02 [18] for concrete produced in general construction conditions.

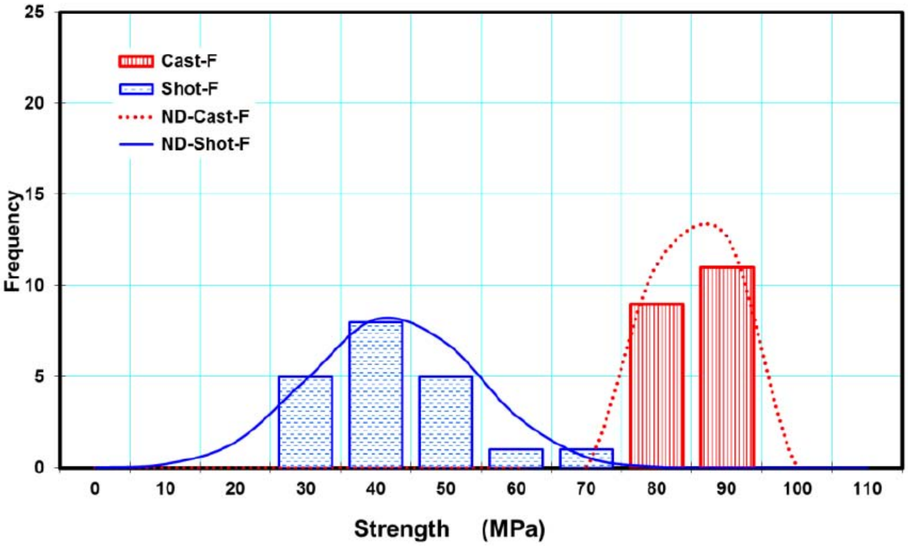


Figure 5: Distribution of strength of fibre reinforced cast and sprayed concrete

Comparing Figures 4 and 5 for sprayed plain and FRC revealed similarity in the characteristics of histograms and the superimposed normal distribution curves for both types. However, there have been distinct differences between the statistical parameters calculated for sprayed plain and FRC. The SD and CoV obtained for the sprayed FRC were higher than those of the sprayed plain concrete. The standard deviation of

12.0 MPa for sprayed FRC is 33% higher than the 9.0 MPa for the sprayed plain concrete. Similarly, the value of the coefficient of variation of the sprayed FRC (28.1%) is about 40% higher than that of the sprayed plain concrete. Coupling these two statistical parameters together it could be suggested that the results indicate higher variability in the results of the sprayed FRC when compared to sprayed plain concrete. This can be attributed to the inclusion of the fibre into the mixture, which could be seen as an introduction of additional variable. Indeed, the introduction of the fibre into sprayed concrete could impart several other variables, such as fibre rebound, local fibre de-bonding and collated fibre spots. Thus, adding fibres increased sources of variability in the strength results of sprayed concrete.

d) Normal probability plots

Figs. 6 and 7 present the normal probability plots of the strength results for lab- cast and sprayed concrete for the two types of concrete used in this study; i.e. plain and FRC, respectively. In each Figure, two straight lines representing best fit trends, have been drawn through the plotted points. It can be seen that the vast majority of the points representing the results for lab-cast and sprayed concrete are close to straight lines, indicating that the results are close to normal distribution with small departure. However, the departure from the normal distribution is clearer in the case of sprayed concrete. This is also reflected in the calculated coefficient of correlation for the best fit lines presenting cast and sprayed concrete. In the case of the latter, the coefficient of correlation for sprayed plain and FRC are 0.94 and 0.96, respectively. The corresponding coefficient of correlation for lab-cast concrete are 0.96 and 0.98, respectively. Relationships with coefficient of correlation over 0.95 is usually acceptable [11].

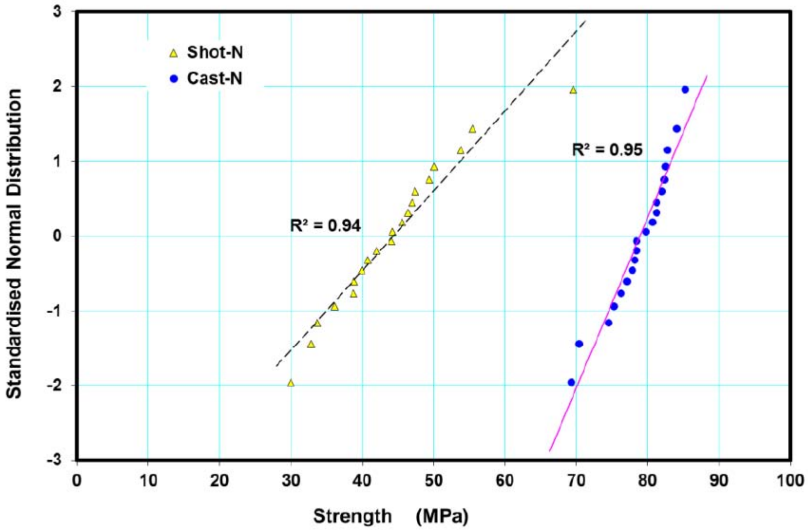


Figure 6: Normal probability plot of plain cast and sprayed concrete

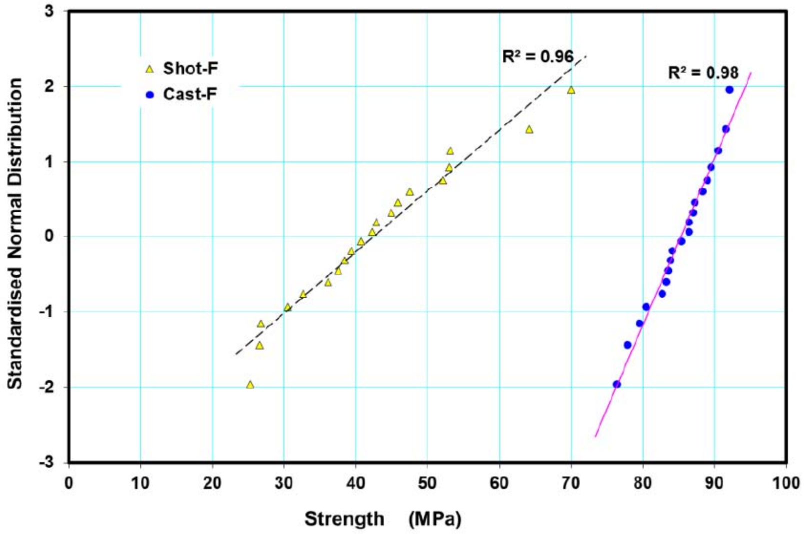


Figure 7: Normal probability plot of fibre reinforced cast and sprayed concrete

e) *Minimum number of test replications*

The statistical analysis of the strength of sprayed concrete indicated that the strength of the placed sprayed concrete had large variations. Therefore, for good practice, it might be necessary to increase the number of replications to ensure an acceptable error at certain level of confidence.

The CoV of the test results, shown in Table 2, could be used to determine the minimum number of replications, n, required in order to guarantee that the percentage error in the average strength is below a specified limit, e, at a specific level of confidence, as given by Equation 1 below [31, 37]:

$$n = t^2 v^2 / e^2 \qquad (1)$$

where:

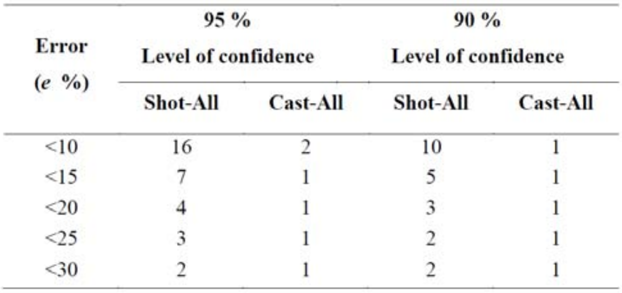
v = coefficient of variation

t = value of t-student distribution for the specified level of confidence and is dependent on the degree of freedom, which is related to the number of tests.

Considering a large sample size, the value of “t” approaches 1.645 and 1.282 at 95% and 90% levels of confidence, respectively [38-40]. The equation is used to calculate the number of samples required to keep the error under various limits between 10 and 30%, at 95% and 90% levels of confidence. The results is presented in Table 3.

It can be seen that the number of required replications increases as the level of confidence increases but, understandably, decreases if higher percentage error is accepted. However, the increase in the number of required replications in the case of sprayed concrete is significantly higher than that is required for lab-cast concrete.

Table 3: Number of replications required to keep the error under a specific limit



Error (*e* %)	95 % Level of confidence		90 % Level of confidence	
	Shot-All	Cast-All	Shot-All	Cast-All
<10	16	2	10	1
<15	7	1	5	1
<20	4	1	3	1
<25	3	1	2	1
<30	2	1	2	1

For example, two cubes of lab-cast concrete could be enough to keep the error below 10% at 95% confidence level, but 16 cores of sprayed concrete would be necessary to keep the error below 10% at the same confidence level. At least 7 specimens would be required to establish the strength of placed sprayed concrete with an error of less than 15%, at 95% level of confidence.

The European specification for sprayed concrete [41] recommend that the strength of placed sprayed concrete to be determined as the average value from 3 samples. It can be seen from Table 3 that if only three specimens of sprayed concrete were tested, then the percentage error could have been as high as 25% and 20% at 95% and 90% confidence levels, respectively. It is, therefore, suggested to review the current regulations and guidelines to increase the required number of replications to offset large variations and ensure higher confidence in the strength of the placed sprayed concrete. Alternatively, new limits for SD and CoV should be developed for good quality sprayed concrete, rather than relying on limits that have been originally derived from testing cast concrete specimens.

V. CONCLUSIONS

For the materials and techniques used in this investigation, the following conclusions could be made:

1. The variability in the strength of sprayed concrete was significantly higher than that of counterpart lab-cast concrete. The standard deviation and coefficient of variation of the results of sprayed concrete (10.5 MPa and 24.2%, respectively) not only were higher than those of the counterpart lab-cast concrete (5.4 MPa and 6.5%, respectively) but also were outside the common acceptable limits for good quality concrete.
2. Compared to the case of sprayed concrete, the histograms of the results obtained for lab-cast concrete is steeper due to lower standard deviation (5.4 MPa compared to 10.5 MPa) and narrower range. The strength results are more spread for sprayed concrete than those of lab-cast concrete, indicating that less strength values fit within one standard deviation from the mean strength; i.e. higher variations.
3. The normal probability plots for lab-cast and sprayed concrete were close to straight lines, indicating that the results are close to normal distribution with small departure. The departure, however, was clearer in the case of sprayed concrete.
4. For sprayed concrete, it could be necessary to increase the number of test replications to ensure an acceptable error at certain level of confidence.

While two cubes of lab-cast concrete were enough to keep the error below 10% at 95% confidence level, 16 cores were necessary for sprayed concrete.

5. It is recommended to review current regulations and guidelines in order to account for the large variability that exists intrinsically in the strength results of cores drilled into sprayed concrete. It is suggested that new acceptance levels should be developed for sprayed concrete rather than using limits that were originally derived from testing lab-cast concrete. Alternatively, the required number of replications could be increased to offset the large variations and ensure higher confidence in the strength of the placed sprayed concrete. The latter, however, could have practical and economical implications.

References Références Referencias

1. ACI Committee 506 (2005), "Guide to Shotcrete," ACI Manual of Concrete Practice, Part 5, ACI 506R-05.
2. Bernardo, G., Guida, A. & Mecca, I. (2015) "Advancements in shotcrete technology, Structural Studies, Repairs and Maintenance of Heritage Architecture," XIV, WIT Transactions on The Built Environment, Vol 153, 591-602
3. Mohajerani, A., Rodrigues, D., Ricciuti,C. & Wilson, C. (2015) "Early-Age Strength Measurement of Shotcrete," Journal of Materials, Vol 2015, pp 1-10.
4. Badr, A., Richardson, I.G. & Brooks, J.J. (2001) "Performance of Monofilament & Fibrillated Polypropylene FRC," 2nd 12 Intl Conf Engineering Materials, August 16-19, San Jose, CA, U.S.A., Vol. 1, pp. 735-744.
5. Patel, P.A., Desai, A.K. and Desai, K.A. (2012) "Evaluation of engineering properties for polypropylene fiber reinforced concrete," International Journal of Advanced Engineering Technology, 3(1), pp.42-45.
6. Ghallab, A. & Badr, A. (2006) "Flexural Behaviour of Polypropylen Fibres-Reinforced Concrete Beams," Housing & Building National Research Centre (HBRC) Journal, Egypt, Vol. 2, No. 3, pp. 50-63.
7. Eswari, S., Raghunath, P.N., Suguna, K. (2008) "Ductility Performance of Concrete with Dramix Steel Micro-reinforcement", Advances in Natural and Applied Sciences, 2(3), pp. 243-248.
8. Badr, A. (2007) "Fatigue of High-Strength Fibre-Reinforced Concrete," Indian Journal of Engineering & Materials Sciences, Vol. 27 14, No. 5, pp. 352-357.
9. Barros, J.A., Lourenço, L.A., Soltanzadeh, F. and Taheri, M. (2014) "Steel-fibre reinforced concrete for elements failing in bending and in shear," European Journal of Environmental and Civil Engineering, 31 18(1), pp.33-65.
10. Yin, S., Tuladhar, R., Riella, J., Chung, D., Collister, T., Combe, M. and Sivakugan, N., (2016) "Comparative evaluation of virgin and recycled polypropylene fibre reinforced concrete," Construction and Building Materials, 114, pp.134-141.
11. Beauprè, D., Dufour,J.F., Hutter, J. & Jolin, M (2005) "Variability of Compressive Strength of Shotcrete in a Tunnel-Lining Project," Shotcrete, V. 5, No. 2, pp. 22-25.
12. NIOSH (2014) "Shotcrete design and installation compliance testing: early strength, load capacity, toughness, adhesion strength, and applied quality," Martin et al. edit, National Institute for Occupational Safety and Health, Publication No. 2015-107, RI 9697.
13. Badr, A. & Brooks, J.J. (2008) "Rebound and Composition of in-Situ Polypropylene Fibre-Reinforced Shotcrete," 11th 6 Intl Conf Durability of Building Materials & Components, 11DBMC, Istanbul, Turkey, 11-14 May, Vol. 1, pp. 569-576.
14. Zhang, L. (2014) "Variability of Compressive Strength of Shotcrete in a Tunnel-Lining Project," Shotcrete, V. 14, No. 4, pp. 22-27.
15. Badr, A. (2010) "Fly Ash and Silica Fume for Green Shotcrete," Construction for a Sustainable Environment, Sarsby, R. & Meggyes, T. (Editors), CRC Press, Taylor & Francis Group; pp. 301-310.
16. Celik, A.O., Kilinc,KF., Tuncan, M. & Tuncan, A. (2012) "Distributions of Compressive Strength Obtained from Various Diameter Cores," ACI Materials Journal, 2012. V. 109, No. 6, pp. 597-606.
17. Uva, G., Porco, F., Fiore, A. and Mezzina, M. (2013) "Proposal of a methodology for assessing the reliability of in situ concrete tests and improving the estimate of the compressive strength," Construction and Building Materials, 38, pp.72-83.
18. ACI Committee 214 (2010) "Evaluation of Strength Test Results of Concrete," ACI Manual of Concrete Practice, Part 1, ACI 214 R-02.
19. BS EN 13791 (2007) "Assessment of in situ compressive strength in structures and precast concrete components," European Committee for Standardization, London. UK.
20. ACI Committee 214 (2003), "Guide for Obtaining Cores and Interpreting Compressive Strength Results," ACI Manual of Concrete Practice, Part 1, ACI 214.4R-03.
21. ASTM (2000) "Obtaining and testing drilled cores and sawed beams of concrete," ASTM C42, West Conshohocken, PA.
22. BS 1881-Part 120 (1983) "Method for determination of the compressive strength of concrete cores," British Standards Institution, London. UK.
23. BS EN 12504-1 (2009) "Testing Concrete in Structures-Part 1: Cored Specimens - Taking,

Examining and Testing in Compression," European Committee for Standardization, London, UK.

24. The Concrete Society (1976). "Concrete core testing for strength," Technical Report No. 11, London, UK, 44 pp.
25. Neville, A. M. (2001) "Core Tests: Easy to Perform, Not Easy to Interpret," Concrete International, V. 23, No. 11, Nov. 2001, pp. 59- 68.
26. Chen, X., Wu, S. & Zhou, J. (2014a) "Compressive Strength of Concrete Cores with Different Lengths," Journal of Materials in Civil Engineering, ASCE 26(7): 04014027-7.
27. Chen, X., Wu, S. & Zhou, J. (2014b) "Variability of Compressive Strength of Concrete Cores," Journal of Performance of Constructed Facilities, ASCE 28(4): 06014001-6.
28. Cussigh, F., Bonnard,V., Carde, C. & Houdusse, O. (2007) "Rion- Antirion bridge project – concrete durability for prevention of corrosion risks," in: Toutlemonde et al. (Eds.), International Conference on Concrete Under Severe Conditions (CONSEC'07), Tours, France, pp. 839-850.
29. Aït-Mokhtara, A., Belarbia, R., Benboudjemab, F., Burlionc, N., Caprad, B. et al. (2013), "Experimental investigation of the variability of concrete durability properties," Cement and Concrete Research, V 45, pp. 21-36.
30. Day, K.W., Aldred J. and Hudson, B. (2013) "Concrete Mix Design, Quality Control and Specification," 4th 22 Edition. CRC Press, USA.
31. Swamy, R.N., Stavrides, H. (1976) "Some Statistical Considerations of Steel Fibre Reinforced Composites," Cement and Concrete Research, 6(2), 201 - 216.
32. Hanson, J. (2007) "Survey of practice to determine strength of in situ concrete from core tests," Journal of Performance of Constructed Facilities, ASCE 21:1(22), 22–25.
33. Kog, Y. C. (2012) "Sample size for determining in situ strength of concrete in structures," Magazine of Concrete Research, 64(11), 1045–1048.
34. Rojas-Henao, L., Fernandez-Gomez, J., and Lopez-Agui, J. C. (2012) "Rebound hammer, pulse velocity, and core tests in self-consolidating concrete," ACI Mater. J., 109(2), 235–243.
35. Unanwa, C., and Mahan, M. (2014) "Statistical analysis of concrete compressive strengths for California highway bridges," Journal of Performance of Constructed Facilities, ASCE, pp. 157–167.
36. De Stefano, M., Tanganelli, m. & Viti, S. (2013) "On the variability of concrete strength as a source of irregularity in elevation for existing RC buildings: a case study," Bull Earthquake Eng 11:1711–1726.
37. Badr, A., Ashour, A.F. & Platten, A.K. (2006) "Statistical Variations in Impact Resistance of Polypropylene Fibre-Reinforced Concrete," International Journal of Impact Engineering, Elsevier, UK, Vol. 32, No. 11, pp. 1907-1920.
38. Box, G.E.P., Hunter, J.S. & Hunter, W.G. (2005) "Statistics for Experimenters Design, Innovation, and Discovery," 2nd Edition. USA: Wiley & Sons Inc.
39. Walpole, R. E.; Myers, R. H.; Myers, S. L.; and Ye, K., (2007)"Probability & Statistics for Engineers & Scientists," eighth edition, Pearson-Prentice Hall, London, UK, 848 pp.
40. Gregersen, E. (2010) "The Britannica Guide to Statistics and Probability," First edition, Rosen Educational Services, New York, 17 333 pp.
41. EFNARC Sprayed Concrete Technical Committee (1996) "European specification for sprayed concrete," European Federation of Producers and Applicators of Specialist Products for Structures, Aldershot, UK.