RĪGAS TEHNISKĀ UNIVERSITĀTE
Būvniecības inženierzinātņu fakultāte
Būvražošanas institūts

RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Building Production

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Doktora studiju programma “Būvniecība”
Doctoral study programme “Civil Engineering”

Metodika mitruma sadalījuma noteikšanai gāzbetona konstrukcijās ar elektriskās impedances spektrometrijas metodi

Promocijas darba kopsavilkums
Dr. sc. ing. grāda zinātniskā iegūšanai būvzinātnes nozarē
būvmateriālu un būvtehnoloģiju apakšnozarē (P-06)

Methodology for Detection of Moisture Distribution throughout the Cross Section of Autoclaved Aerated Concrete Masonry Constructions by Application of EIS Method

Summary of the Doctoral Thesis
to Obtain the Degree of *Dr. sc. ing.* in Construction Science,
Subfield of Construction Materials and Technology (P-06)

Zinātniskie vadītāji/Scientific supervisors
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Saturs / Contents

Darba vispārējs raksturojums

Tēmas aktualitāte un pētījuma problēmas nostādne

Mūsdienu būvniecības tirgus ir orientēts uz ilgtspējīgu būvniecību, kā arī efektīvu energoresursu izmantošanu. Tādēļ arvien biežāk tiek izmantoti būvmateriāli, kas sevī apvieno pietiekami augstus spiedes stiprības parametrus un zemas siltumvadītspējas īpašības. Savukārt viena no negatīvākajām mūsdienu būvniecības tirgus tendencēm ir ļoti īsie termiņi, kas paredzēti būvniecības procesa īstenošanai un rada būtiskus riskus pareizas būvdarbu tehnoloģijas un būvmateriālu iestrādes tehnoloģijas īstenošanai. Tādēļ, lai nepieļautu būvdarbu tehnoloģijas un būtisku būvmateriālu iestrādes tehnoloģisko nosacījumu pārkāpšanu, arvien izplatītākas kļūst būvlaukuma apstākļos lietojamās negraujošās pārbaužu metodes, kas ļauj kontrolēt būtiskāko tehnoloģisko posmu ievērošanu būvdarbu izpildes laikā.

Gāzbetona mūra bloki ir viens no būvmateriāliem, kas sevī apvieno pietiekamu spiedes stiprību, lai to izmantotu slodzi nesošās būvkonstrukcijās, kā arī zemus siltumvadītspējas rādītājus. Tādēļ šis materiāls ir lietojams energoefektīvu būvju būvniecībā, kur arī konstruktīvais materiāls uzlabo kopējos norobežojošās konstrukcijas siltumtehniskos parametrus. Būtiskākais gāzbetona mūra bloku trūkums ir mitruma satura un tā sadalījuma pa materiāla šķērsgriezuma laukumu būtiskā ietekme uz gāzbetona situmtehniskajiem parametriem. Tādēļ ir būtiski kontrolēt mitruma saturu un tā sadalījumu pa gāzbetona mūra bloku šķērsgriezuma laukumu, lai novērstu neatbilstoši uzglabātu būvmateriālu iestrādi ēku konstrukcijās. Tikpat būtiski ir kontrolēt gāzbetona mūra konstrukciju žūšanas procesu būvdarbu izpildes laikā, lai novērstu pāragru apdares slāņu uzklāšanu uz gāzbetona bloku mūra konstrukcijām, pirms tās ir sasniegušas gaissausa materiāla stāvokli, tādējādi kavējot materiāla žūšanu un būtiski samazinot kopējos norobežojošās konstrukcijas siltumtehniskos parametrus. Pārlieku augsts mitruma saturs būvmaterialos var radīt situācijas, kad norobežojošās konstrukcijas nesasniedz saskaņā ar LVS EN ISO 6946:2009 L «Ēku būvkomponenti un būvelementi. Siltumpretestība un siltumapmaiņas koeficients. Aprēķināšanas metodika» aprēķinātos siltumtehniskos parametrus un attiecīgi netiek nodrošinātas būves energoefektivitātes prasības. Jebkura materiāla žūšanas process ir jāvērtē ilgtermiņā, tāpēc graujošas pārbaužu metodes, kas sevī ietver liela apjoma paraugu ņemšanu no pārbaudāmās konstrukcijas, nav efektīvi izmantojamas. Tādēļ ir nepieciešams attīstīt būvlaukuma apstākļos viegli lietojamas negraujošas pārbaužu metodes, kas ļautu noteikt mitruma saturu un sadalījumu gāzbetona konstrukcijās ar augstu ticamības pakāpi.

Virkne ražotāju piedāvā gāzbetona mūra blokus, un šo materiālu ķīmiskais sastāvs, kā arī ražošanas tehnoloģiskās īpatnības ir atšķirīgas. Tādēļ gāzbetona bloku blīvums un poru sadalījumus pa materiāla tilpumu savstarpēji atšķiras, kas savukārt var ietekmēt atsevišķu negraujošo pārbaužu metožu precizitāti mitruma sadalījuma noteikšanai gāzbetona konstrukcijās. Šajā pētījumā ir izskatīta iespēja lietot elektriskās impedances spektrometriju mitruma sadalījuma noteikšanai pa dažāda tipa gāzbetona bloku škērsgriezuma laukumu.

Darba mērķis

Darba mērķis ir izstrādāt negraujošu pārbaužu metodiku mitruma sadalījuma noteikšanai pa gāzbetona mūra bloku šķērsgriezuma laukumu būvlaukuma apstākļos, lietojot elektriskās impedances spektrometrijas metodi. Lai noteiktu izpildāmos darba uzdevumus, tika analizēti iepriekš veiktie pētījumi par negraujošu metožu izmantošanu mitruma satura un tā sadalījuma noteikšanai pa materiālu šķērsgriezuma laukumu cieta agregātstāvokļa materiāliem

Darba uzdevumi

Lai sasniegtu promocijas darba mērķi, tika noteikti šādi darba uzdevumi:

1. noteikt matemātiskas sakarības starp mitruma saturu gāzbetona bloku mūra konstrukcijās un elektriskās impedances spektrometrijas mērījumu rezultātiem attiecīgajā materiālā;
2. noteikt kontaktvirsmas blīvuma starp mērījumu zondi un gāzbetonu ietekmi uz veikto mērījumu precizitāti;
3. noteikt kontaktvirsmas starp mērījumu zondi un gāzbetonu pārklājuma ietekmi uz veikto mērījumu precizitāti;
4. noteikt attāluma starp mērījumu zondēm ietekmi uz iegūto rezultātu precizitāti;
5. noteikt mūra šuvju un materiāla plaisu ietekmi uz mērījuma rezultātu precizitāti.

Pētījuma zinātniskā novitāte

Izstrādāta negraujoša pārbaužu metodika mitruma sadalījuma noteikšanai gāzbetona konstrukcijās lietošanai būvlaukuma apstākļos, izmantojot elektriskās impedances spektrometrijas metodi. Noteiktas korelācijas sakarības starp elektriskās impedances spektrometrijas mērījumu rezultātiem un mitruma saturu dažāda tipa gāzbetona konstrukcijās.

Metodikas aprobācijas laikā ir pārbaudīta metodikas lietojamība mitruma sadalījuma noteikšanai dažāda blīvuma (375 kg/m^3 līdz 500 kg/m^3) un dažādu ražotāju (pētījumā veikti eksperimenti ar piecu dažāda tipa/ražotāju gāzbetona blokiem) gāzbetona mūra konstrukcijās.

Sagatavoti mācību stendi mitruma sadalījuma izmaiņu noteikšanai ar elektriskās impedances spektrometrijas metodi un *Z-meter III* iekārtu gāzbetona mūra konstrukcijās.

Promocijas darba praktiskais nozīmīgums

Būvdarbu veicēju nepilnīga izpratne par fizikālajiem procesiem, kas noris būvmateriālos, var radīt būtiskas problēmas būvju ekspluatācijas laikā. Sevišķi būtiski ir nepieciešams veicināt izpratni par mitruma migrācijas procesiem norobežojošās konstrukcijās. Gāzbetona mūra konstrukcijām gaissausā stāvoklī (5 % mitruma saturs no materiāla sausas masas saskaņā ar *RILEM* vadlīnijām gāzbetona konstrukcijām – *RILEM recommended practice. Autoclaved aerated concrete – Properties, testing and design. E&FN SPON, 1993*) ir zemi siltumvadītspējas parametri (λ = 0,09…0,12), tomēr ražošanas procesā gāzbetona blokos uzkrājas liels mitruma daudzums (līdz 50 % no materiāla sausas materiāla masas). Paaugstināts mitruma saturs gāzbetona konstrukcijās līdz pat 10 reizēm paaugstina materiāla siltumvadītspējas parametrus. Gan norobežojošo konstrukciju siltumtehniskajos aprēķinos, gan arī materiālu ražotāju sniegtajā tehniskajā informācijā par gāzbetona fizikālajām īpašībām tiek sniegta informācija par sausa materiāla īpašībām, tāpēc ir būtiski izstrādāt būvlaukuma apstākļos lietojamas kontroles metodikas, kas ļautu noteikt mitruma saturu būvkonstrukcijās un tā sadalījumu pa norobežojošās konstrukcijas šķērsgriezuma laukumu.

Šajā promocijas darbā ir izstrādāta negraujoša pārbaužu metodika mitruma sadalījuma noteikšanai gāzbetona konstrukcijās ar *Z-meter III* iekārtu, kuras darbība ir balstīta uz elektriskās impedances spektrometriju.

Izmantotie materiāli un pētīšanas metodika

Pētījumā ir noteikts mitruma sadalījums gāzbetona konstrukcijās ar elektriskās impedances spektrometrijas metodi un mērierīci *Z-meter III*. Pētījuma veikšanai ir izmantoti gāzbetona mūra bloki (1. tabula) no dažādu ražotāju piedāvātā sortimenta, kas visbiežāk tiek lietoti būvniecībā Latvijā.

1. tabula

Pētījumā izmantotie gāzbetona bloku veidi

Gāzbetona bloku veids	Materiāla siltumvadītspējas koeficients sausam materiālam λ W/mK	Materiāla blīvums kg/m³
AEROC Universal	0,090	375
Ytong PP2/0,4	0,105	375
Rocklite	0,11	500
Texoblock classic	0,12	500
Texoblock Lite	0,096	400

Mērierīce *Z-meter III*, kas izstrādāta projekta *EUREKA* E!4981 ietvaros Brno Tehnoloģu universitātes Būvniecības Inženierzinātņu fakultātes Ūdens resursu institūtā.

1. attēls. *Z-meter III* iekārta ar mērījumu zondēm.

Kontroles mērījumu veikšanai gravimetriskās metodes ietvaros tika izmantoti elektroniskie svari ar mērījumu precizitāti ±5g.

Rezultātu apstrādei izmantota datorprogramma *MS Excel*, kā arī *Z-meter III* programmnodrošinājums.

Z-meter III mērījumu rezultātu nolasījumu paraugs atspoguļots 2. tabulā.

2. tabula

Z-meter III mērījumu datu paraugs

Sākums 12.11.2014 9:12:30							
No	f [Hz]	date [dd.mm.yyyy]	time [hh:mm:ss]	ch	range	Rx [ohm]	Xx [ohm]
1	1000	12.11.2014	09:12:30	0	1	101,3	-47,4
2	1000	12.11.2014	09:12:30	1	1	101,4	-47,3
3	1000	12.11.2014	09:12:30	2	1	101,3	-47,3
4	1000	12.11.2014	09:12:31	3	1	101,3	-47,2
5	1000	12.11.2014	09:12:31	4	1	101,4	-47,2

Pētījuma teorētiskā un metodoloģiskā bāze

Promocijas darbs balstās uz šādām zinātņu nozarēm un apakšnozarēm:

- būvfizika;
- būvmateriāli un būvtehnoloģija;
- elektrotehnikas teorētiskie pamati;
- materiālzinātne;
- vides inženierzinātne.

Pētījuma diapazons un iegūto rezultātu lietojuma robežas

Izstrādātā metodika mitruma sadalījuma noteikšanai pa gāzbetona konstrukciju šķērsgriezuma laukumu ar *Z-meter III* iekārtu, kā arī noteikti vienādojumi sakarībām starp elektriskās impedances reālās komponentes vērtībām, kas noteiktas ar *Z-meter III* iekārtu un gāzbetona konstrukciju mitruma saturu, ir spēkā, izpildoties šādiem nosacījumiem:

1. mitruma sadalījuma mērījumi tiek veikti viena gāzbetona bloka robežās, zonā starp mērījumu zondēm nav mūra šuves vai plaisas, kas pārsniedz 0,1mm;
2. attālums starp mērierīces zondēm nepārsniedz 300 mm;
3. zondes un tās ievietošanai paredzētā urbuma diametru starpība nepārsniedz 2 mm;
4. mērījumi tiek veikti 8000 Hz frekvencē.

Aizstāvēšanai izvirzītie darba rezultāti

1. Metodika mitruma sadalījuma noteikšanai gāzbetona konstrukcijās, izmantojot elektriskās impedances spektrometriju un *Z-meter III* iekārtu.

2. Vienādojumi sakarībai starp elektriskās impedances reālo komponenti un mitruma saturu gāzbetona konstrukcijās.

Promocijas darba rezultātu aprobācija

Promocijas darba rezultāti ziņoti un apspriesti 14 starptautiskajās konferencēs. Galvenie darba rezultāti izklāstīti 16 zinātniskajās publikācijās. Piecas no tām ir indeksētas *Scopus* datubāzē.

Dalība starptautiskajās konferencēs

1. «EUREKA 2013 1st conference and working session, Karolinka, Čehijas Republika, Brno Tehniskā universitāte, GEOTest. 2013. gada 30. oktobris–1. novembris (Rubene S., Vilnītis M. Application of Electrical Impedance Spectrometry for Determination of Moisture Distribution in Aerated Concrete Constructions);
2. RTU BF 150 gadu jubilejai veltīta starptautiska konference «Innovative Materials, Structures and Technologies», Rīga, Latvija, 2013. gada 8. novembris (Rubene S., Noviks J., Vilnītis M. Determination of Humidity Level In Aerated Concrete Constructions by Non Destructive Testing Methods);
3. «Cilvēks. Vide. Tehnoloģijas» 18. starptautiskā studentu zinātniski pētnieciskā konference, Rēzeknes Augstskola, Rēzekne, Latvija. 2014. gada 23. aprīlis (Rubene S., Noviks J., Frequency analysis of electrical impedance spectrometry);
4. «Advanced Construction», 4th international conference, Kaunas, Lietuva, Kauņas Tehniskā universitāte, 2014. gada 9.–10. oktobris (Rubene S., Vilnītis M., Noviks J. Monitoring of the Aerated Concrete Construction Drying Process by Electrical Impedance Spectrometry);
5. EUREKA 2014 2nd conference and working session, Pasohlavky, Brno, Čehijas Republika, Brno Tehniskā universitāte, GEOTest. 2014. gada 30. oktobris–1. novembris (Rubene S., Vilnītis M. Monitoring of Humidity Distribution Changes in Aerated Concrete Masonry Construction by EIS);
6. 5th European Conference of Civil Engineering, Florence, Italy, 2015. gada 22.–24. novembris (Rubene S., Vilnītis M. Correlation between EIS Measurements and Relative Humidity Distribution in Aerated Concrete Masonry Constructions);
7. 1st International Conference on Civil Engineering, Water Resources, Hydraulics and Hydrology (CEWHH 2014), Athens, Greece, 2015. gada 28. novembris–1. decembris (Rubene S., Vilnītis M., Noviks J. Impact of Contact Surface on

Accuracy of Humidity Distribution Measurements in Autoclaved Aerated Concrete Constructions by EIS);

8. 17th International Conference on Civil, Structural and Geoenvironmental Engineering, London, United Kingdom, 2015. gada 19.–20. janvāris (Rubene S., Vilnītis M., Noviks J. Impact of Masonry Joints on Detection of Humidity Distribution in Aerated Concrete Masonry Constructions by Electric Impedance Spectrometry Measurements);
9. Vide. Tehnoloģija. Resursi, Rēzeknes Augstskola, Rēzekne, Latvija, 2015. gada 18.–19. jūnijs (Rubene S., Vilnītis M., Noviks J. Impact of density and special features of manufacturing process on drying of autoclaved aerated concrete masonry blocks);
10. 7th Scientific-Technical Conference Material Problems in Civil Engineering (MATBUD'2015), Crakow University of Technology, Krakow, Poland, 2015. gada 22.–24.jūnijs (Rubene S., Vilnītis M., Noviks J. Frequency Analysis for EIS Measurements in Autoclaved Aerated Concrete Constructions);
11. Creative Construction Conference 2015, Krakow, Poland, 2015. gada 21.–24.jūnijs (Rubene S., Vilnītis M., Noviks J. Frequency Analysis and Measurements of Moisture Content of AAC Masonry Constructions by EIS);
12. 2nd International Conference «Innovative Materials, Structures and Technologies» (IMST 2015), Riga, Latvia, September 30 – October 2, 2015 (Rubene S., Vilnītis M., Noviks J. Impact of External Heat Insulation on Drying Process of Autoclaved Aerated Concrete Masonry Constructions);
13. EUREKA 2015 3rd conference and working session, Jaromerice nad Rokytnou, Brno, Čehijas Republika, Brno Tehniskā universitāte, GEOTest. 2015. gada 15.–16.oktobris (Rubene S., Vilnītis M. Accuracy of Humidity Distribution Measurements in Autoclaved Aerated Concrete Constructions by Electrical Impedance Spectrometry. No: EUREKA 2015 Proceedings, Čehija, Jaromerice nad Rokytnou, 15.–16. oktobris, 2015. Brno: 2015, 156.–164. lpp. ISSN 2464-4595.);
14. 6th European Conference of Civil Engineering, Budapest, Hungary, 2015. gada 12.–14. decembris (Rubene S., Vilnītis M. Monitoring of Water Infiltration in Autoclaved Aerated Concrete Masonry Construction Blocks by Electrical Impedance Spectrometry).

Publikācijas

1. Rubene S., Vilnītis M. Application of Electrical Impedance Spectrometry for Determination of Moisture Distribution in Aerated Concrete Constructions. In: EUREKA 2013: 1st Conference and Working Session: Proceedings, Czech Republic, Karolinka, 30 Oct–1 Nov., 2013. Brno: VUTIUM, Brno University of Technology, 2013, pp. 124–131. ISBN 978-80-214-4735-6.
2. Rubene S., Vilnītis M., Noviks J. Impact of Contact Surface on Accuracy of Humidity Distribution Measurements in Autoclaved Aerated Concrete Constructions by EIS. In: Proceedings of 1st International Conference on Civil Engineering, Water Resources, Hydraulics and Hydrology (CEWHH 2014), Greece, Athens, 28–30 November, 2014. Athens: EUROPMENT, 2014, pp. 99–104. ISBN 978-1-61804-253-8.
3. Rubene S., Vilnītis M. Correlation between EIS Measurements and Relative Humidity Distribution in Aerated Concrete Masonry Constructions. In: Recent Advances in Civil Engineering and Mechanics. Mathematics and Computers in Science and Engineering Series 35, Italy, Florence, 22–24 November, 2014. Florence: WSEAS Press, 2014, pp. 67–72. ISBN 978-960-474-403-9. ISSN 2227-4588.
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Promocijas darba sastāvs un apjoms

Promocijas darbā ir anotācijas angļu un latviešu valodā, ievads, trīs galvenās nodaļas, kas sadalītas apakšnodaļās, secinājumi, viens pielikums un literatūras avotu saraksts.

Darbā iekļautas 112 lapaspuses, 107 attēli, četras tabulas, 114 literatūras avoti.

Promocijas darba ievadā formulēta problēmas aktualitāte, darba mērķi, uzdevumi, kā arī darba zinātniskā novitāte un pētījuma rezultātu lietojums.

Pirmajā nodaļā apskatītas gāzbetona kā būvmateriāla galvenās īpašības, tā ražošanas procesa tehnoloģiskās īpašības. Veikta eksistējošo negraujošo pārbaužu metožu, kas lietojamas cietu vielu mitruma satura noteikšanai, darbības pamatprincipu analīze. Pirmajā nodaļā veikts elektriskās impedances spektrometrijas kā negraujošas pārbaužu metodes darbības pamatprincipu apskats, analizēti iepriekš veiktie pētījumi elektriskās impedances spektrometrijas lietošanai materiālu mitruma satura noteikšanai.

Otrajā nodaļā aprakstīti eksperimenti, kas veikti, lai sasniegtu promocijas darba ievadā noteiktos mērķus, kā arī lai aprobētu izstrādāto metodiku mitruma sadalījuma noteikšanai gāzbetona konstrukcijās ar elektriskās impedances spektrometriju un *Z-meter III* iekārtu.

Trešajā nodaļā veikts otrajā nodaļā veikto eksperimentu rezultātu kopsavilkums un iegūto rezultātu analīze.

Secinājumu daļā ir apkopota pētījuma rezultātā iegūtā informācija, formulētas aizstāvēšanai izvirzāmās tēzes.

Promocijas darba saturs

Ievads

Promocijas darba ievadā formulēta problēmas aktualitāte, darba mērķi, uzdevumi, kā arī darba zinātniskā novitāte un pētījuma rezultātu pielietojums.

1. Materiāli un metodes

Gāzbetons ir kaļķu java ar sasmalcinātām smiltīm vai rūpniecības atkritumiem, piemēram, pelniem kā pildvielām, kurā ar mehāniskām vai ķīmiskām metodēm ir iesaistīts gaiss, tādā veidā būtiski samazinot materiāla blīvumu.

Gāzbetona fizikālās īpašības, īpaši siltumtehniskās un higrometriskās īpašības, ir atkarīgas no gāzbetona mikrostruktūras un makrostruktūras. Gāzbetona poru veidošanās procesam ir būtiska ietekme uz tā mikrostruktūru un tātad – uz tā fizikālajām īpašībām. Gāzbetona struktūra ir raksturojama ar tā mikroporu matricu un makroporām. Poru daudzums un izvietojums pa materiāla tilpumu tieši ietekmē arī gāzbetona fizikālās īpašības, kā arī negraujošās metodes, ar kuru palīdzību ir iespējams noteikt mitruma saturu un sadalījumu gāzbetonā.

Visprecīzākā metode mitruma satura noteikšanai cietos materiālos ir gravimetriskā metode, kas sevī ietver materiāla masas izmaiņu noteikšanu starp materiāla masu sausā stāvoklī (attiecīgi, veicot materiāla piespiedu žāvēšanu, līdz tiek sasniegts absolūti sauss stāvoklis) un stāvoklī, kādā paraugs ir sagatavots mitruma satura noteikšanai. Tomēr šīs metodes trūkums ir tajā, ka šādā veidā ir nosakāms tikai vidējais mitruma saturs visā paraugā. Ja papildus ir nepieciešams noteikt mitruma sadalījumu pa parauga tilpumu, tad ir nepieciešams veikt parauga sadalīšanu sīkākos segmentos un veikt iepriekš aprakstīto žāvēšanas un masas izmaiņu aprēķina procedūru. Šāda metodika ir darbietilpīga un tādēļ nav plaši lietojama mitruma sadalījuma noteikšanai pa būvkonstrukciju šķērsgriezumu, tomēr tā ir izmantojama, lai veiktu negraujošo pārbaužu metožu precizitātes kontroli.

Pastāv virkne negraujošu pārbaužu metožu, kas ļauj noteikt cietu materiālu mitruma saturu un tā sadalījumu materiāla šķērsgriezumu laukumu. Kā precīzākās no šīm metodēm ir jānosauc radioloģiskās pārbaužu metodes, piemēram, gamma staru blīvuma mērīšana, neitronu radiogrāfija, atomu magnētiskā rezonanse, datortomogrāfija un elektromagnētiskā mikroviļņu radiācijas mērīšana. Iepriekš uzskaitīto metožu vislielākais trūkums ir tajā, ka attiecīgās metodes nav iespējams vai ir ļoti sarežģīti lietot būvlaukuma apstākļos un veikt daudzus atkārtotus mērījumus dažādiem paraugiem īsā laikā.

Mitruma satura noteikšana gāzbetona konstrukcijās, balstoties uz siltuma plūsmas mērījumiem, ir vēl viena pieeja, kas ļauj noteikt mitruma saturu un tā sadalījumu gāzbetona konstrukcijās. Šīs pieejas ietvaros ir izmantojamas vairāku zinātnieku noteiktās sakarības starp siltuma un mitruma pārneses procesiem cietos materiālos. Kā plašāk izplatītie šajā gadījumā ir jānosauc *Philip* un *DeVries* modeļi, kas izmanto temperatūras un mitruma satura gradientus kā pārvietošanas potenciālus (*Philip JR, DeVries DA (1975) Moisture movement in porous materials under temperature gradients. Trans Am Geophys Union 2:222–232*). Tomēr, kā zināms, pastāv pārtraukums mitruma satura profilos, kas atrodas starp diviem porainiem materiāliem. Tādēļ Luikovs (*Luikov AW (1966) Heat and mass transfer in capillary-porous bodies. Pergamon Oxford, UK*) ir piedāvājis precīzāku matemātisko modeli mitruma un masas pārvietojuma modelēšanai. Lietojot apskatītos matemātiskos modeļus un siltuma plūsmas mērījumus materiāla mitruma satura noteikšanai, ir nepieciešams noteikt virkni apkārtējās vides parametrus (apkārtējās vides, pētāmā materiāla temperatūra, gaisa relatīvais mitrums), kā arī balstīties uz materiāla ražotāja noteiktajām gāzbetona fizikālajām īpašībām. Tik daudzu mainīgo esamība, kā arī pietiekami sarežģīto aprēķinu apjoms padara attiecīgo pieeju gūti izmantojamu plašam lietojumam būvlaukuma apstākļos.

Pastāv metodika materiāla mitruma satura noteikšanai, novērtējot tā higrometriskās (ūdens uzsūces) īpašības. Šī pieeja arī ir balstīta uz matemātiskiem modeļiem, ko izstrādājis H. Kunzels (*Künzel, H. M. (1995), 'Simultaneous Heat and Moisture Transport in Building Components – One- and two-dimensional calculation using simple parameters', IRB Verlag, Stuttgart*), tomēr arī šī metodika sevī ietver apjomīgu datu apstrādi un apkārtējās vides parametru noteikšanu, kā tas ir nepieciešams arī iepriekš aprakstītajai pieejai mitruma sadalījuma noteikšanai ar siltuma plūsmas mērījumu palīdzību.

Šobrīd kā vienas no visplašāk izmantojamajām metodēm mitruma satura noteikšanai tiek izmantotas elektriskās metodes. Šīs metodes balstās uz dažādu elektrisko raksturlielumu noteikšanu materiāliem, kas vēlāk tiek korelēti ar mitruma saturu attiecīgajos materiālos. Parasti šo metožu ietvaros tiek izmantoti konstrukcijā iebūvējami sensori vai arī sensori, kas nosaka materiāla virsmas mitruma saturu, neparādot datus par mitruma sadalījumu konstrukcijā.

Elektriskās impedances spektrometrija ir viena no elektriskajām metodēm, kas tiek izmantota, lai raksturotu materiālu fizikālās īpašības. Metodes pirmsākumi ir meklējami 20. gadsimta 70. gados, kad attiecīgā metode tika izmantota, lai raksturotu dažādu elektronisku iekārtu parametrus (*Barsoukov, E., McDonald, R., Impedance Spectroscopy Theory, Experiment, and Applications, John Wiley & Sons, New York, USA, 2005, ISBN: 0-*

471-64749-739). Elektriskā impedance raksturo maiņstrāvas ķēdes īpašības, un tā vienmēr ir lielāka vai vienāda ar ķēdes reālo pretestību R (Ω). Ķēdes imaginārā pretestība X ir lielums, kas atkarīgs no frekvences, kā arī ķēdes elementu īpašībām (imagināro pretestību veido ķēdes elementu kapacitāte un induktivitāte). Elektriskā impedance matemātiskā formā var tikt izteikta ar Oma likumu maiņstrāvas ķēdei.

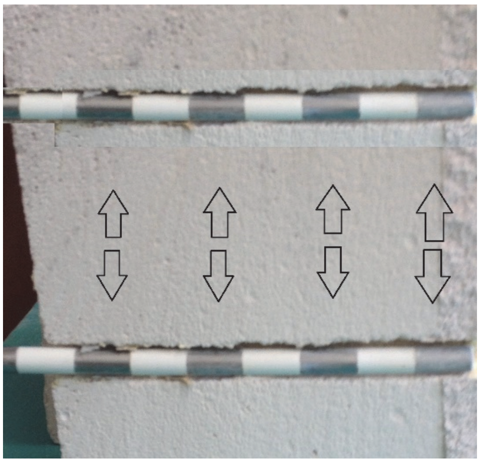
Elektriskās impedances metode ir izmantojama, lai raksturotu materiālu fizikālās īpašības, tāpēc attiecīgā materiāla un mērierīces savstarpējā iedarbība ir modelējama ar ekvivalentām ķēdēm.

Elektriskās metodes ir vienas no plašāk lietotajām negraujošo pārbaužu metodēm, tāpēc ir veikti pētījumi, lai attiecīgās metodes izmantotu betona konstrukciju mitruma satura noteikšanai. Elektriskie mērījumi ļauj noteikt virkni materiāla mikrostruktūras īpašību: poru lielumu un apjomu, poru savstarpējo savienojumu apjomu, jonu difuzitāti u. tml. (*Rajabipour F (2006) In situ electrical sensing and material health monitoring of concrete structures, Ph.D. Dissertation, Purdue University, West Lafayette, Indiana*). Tomēr ir jāņem vērā, ka elektrisko mērījumu precizitāti betona konstrukcijās vienlaikus var ietekmēt vairāki faktori, tādēļ ir jāizstrādā metodika, kas ļautu nodalīt atšķirīgu faktoru ietekmi uz veiktajiem mērījumiem, lai padarītu elektriskos mērījumu par precīzu metodi mitruma satura noteikšanai betona konstrukcijās (*Schmit T, Rajabipour F, Weiss WJ (2005) Investigating the use of a diffuse measurement interpretation for analyzing in situ electrical measurements. In: 3rd international conference on construction materials: ConMat'05, Vancouver, Canada*).

Gāzbetona porainā struktūra rada papildu traucējošus apstākļus, lai lietotu elektriskos mērījumus tā mitruma satura noteikšanai. Tomēr, veicot virkni eksperimentu, ir noskaidrots, ka, izmantojot maiņstrāvas ķēdes pretestības mērījumus, ir iespējams ne tikai noteikt mitruma sadalījumu gāzbetona konstrukcijās, bet arī citas materiāla fizikālās īpašības (piemēram, porainība).

Promocijas darbā tika izmantota *Z-meter III* iekārta, kas izstrādāta projekta *EUREKA* programmas E!4981 ietvaros Brno Tehnoloģu universitātes Būvniecības Inženierzinātņu fakultātes Ūdens resursu institūtā un kuras darbība ir balstīta uz elektriskās impedances spektrometrijas metodes. Iekārta ir neliela, mobila un ar to ir iespējams veikt lielu daudzumu atkārtojamu mērījumu īsā laika periodā, kā arī tā sniedz dalītus impedances datus (atsevišķi impedances reālo un imagināro komponenti), tāpēc tika veikta virkne eksperimentu, lai izstrādātu metodiku attiecīgās iekārtas izmantošanai mitruma sadalījuma noteikšanai gāzbetona konstrukcijās.

Pētījumā tika izmantotas konstrukcijā ievietojamas zondes ar pieciem mērījumu kanāliem (impedances mērījumi tika veikti vienlaikus piecos dažādos dziļumos), kas nosaka impedanci iecirknī starp attiecīgajiem zondes mērījumu kanāliem (1. attēls).



1. attēls. Mērījumi starp *Z-meter III* zondēm.

2. Veiktie eksperimenti

Pētījuma gaitā tika veikta virkne savstarpēji saistītu eksperimentu, kuru mērķis bija noskaidrot elektriskās impedances spektrometrijas lietojamības iespēju mitruma sadalījuma noteikšanai gāzbetona konstrukcijās, kā arī aprobēt izstrādāto mitruma sadalījuma noteikšanas metodiku pielietošanai būvlaukuma apstākļos.

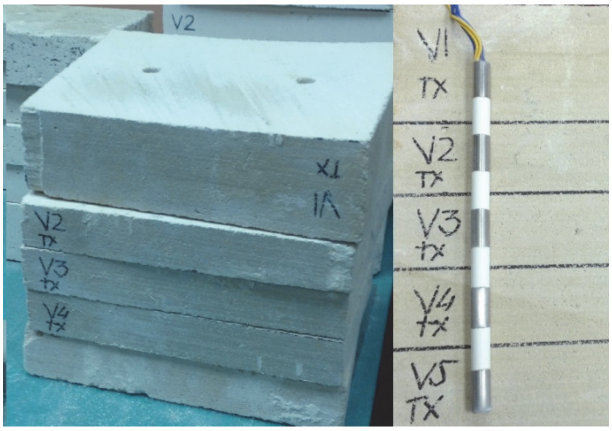
Gāzbetons ir porains materiāls, bet elektriskā impedance ir atkarīga no materiāla struktūras elektriskajiem parametriem (šajā gadījumā – kapacitātes, ko rada gāzbetona poru struktūra), tāpēc kā pirmais pētījumu posms tika noteikta impedances mērījumu frekvences noteikšana turpmāko impedances mērījumu veikšanai.

Eksperimentā tika izmantoti piecu dažādu veidu gāzbetona paraugu komplekti (gāzbetona veidi aprakstīti 1. tabulā). Eksperimentā tika noteikts frekvenču apgabals, kas ir piemērots turpmākiem elektriskās impedances spektrometrijas mērījumiem. Piemēroto frekvenču apgabalu ietekmē materiāla blīvums un poru struktūra, tādēļ katram no paraugu komplektiem tika noteikts atsevišķs turpmākiem mērījumiem piemērots frekvenču apgabals. Tomēr, lai iegūtu savstarpēji salīdzinājums datus, turpmākie eksperimenti visiem apskatītajiem gāzbetona tipiem tika veikti vienā frekvencē, kas ietilpa visu apskatāmo gāzbetona tipu piemēroto frekvenču intervālā.

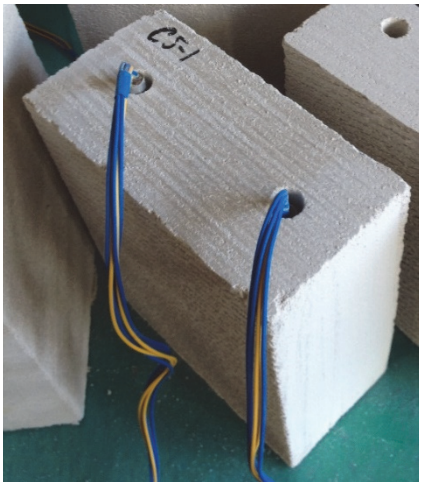
Eksperimenta laikā tika noskaidros, ka frekvenču analīzes rezultātus ietekmē arī mitruma saturs un tā sadalījum pa gāzbetona parauga šķērsgriezumu, jo mitrākajos (un attiecīgi arī blīvākajos) gāzbetona iecirkņos, piemēroto frekvenču intervāls ir plašāks nekā sausam materiālam noteiktais. Tāpat tika noskaidrots, ka gāzbetona anizotropijai, kas rodas tā ražošanas laikā, ir ietekme uz frekvenču analīzes rezultātiem, tādēļ, lai paaugstinātu elektriskās impedances spektrometrijas metodes precizitāti mitruma sadalījuma noteikšanai gāzbetona konstrukcijās, būtu jāņem vērā arī materiāla anizotropija.

Kā nākamais eksperiments tika veikta sakarību starp elektriskās impedances reālās komponentes un mitruma satura gāzbetona konstrukcijās noteikšana. Arī šajā eksperimentā tika izmantoti piecu dažādu tipu gāzbetona paraugu komplekti, kuru žūšanas laikā tika noteiktas korelācijas sakarības starp elektriskās impedances spektrometrijas mērījumu rezultātiem un mitruma saturu paraugos.

Kā mitruma sadalījuma kontroles metodika eksperimenta gaitā tika izmantota gravimetriskā metode atbilstoši Akitas pieejai mitruma sadalījuma noteikšanai (*Akita, H., Fujiwara, T. and Ozaka, Y.." A practical procedure for the analysis of moisture transfer within concrete due to drying." Magazine of Concrete Research 48 (6), 1996, p.129-137.*) atbilstoši 2. attēlā parādītajam sadalījuma piemēram.

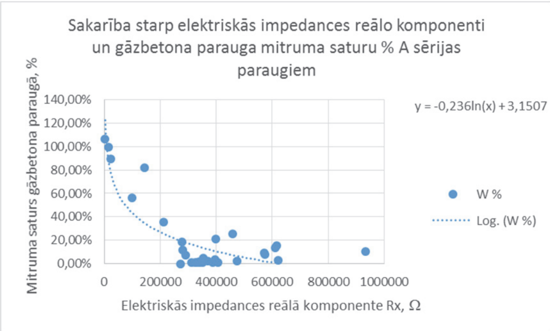


2. attēls. Gāzbetona parauga sadalījums.

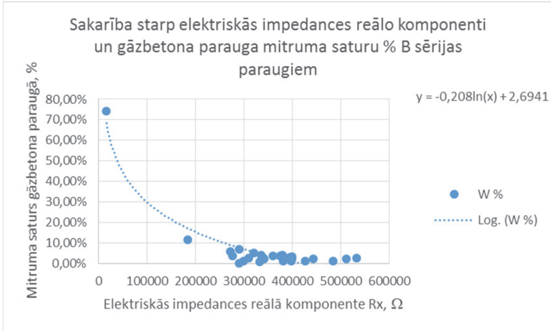


3. attēls. Gāzbetona bloks ar mērījumu zondēm.

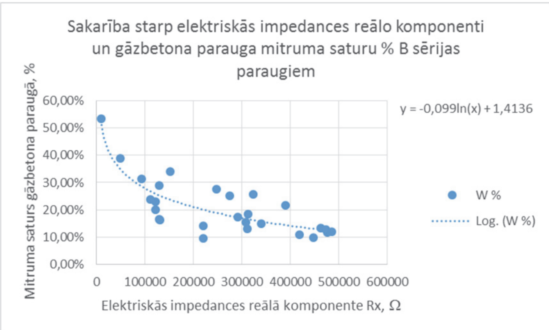
Eksperimenta rezultātā tika noteiktas matemātiskas sakarības starp mitruma saturu gāzbetona paraugos un elektriskās impedances reālās komponentes vērtību, kā arī tika izveidotas korelācijas līknes iegūto sakarību grafiskai attēlošanai.



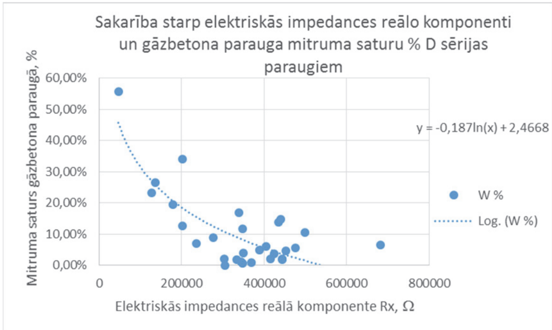
4. attēls. Sakarība starp elektriskās impedances reālo komponenti un gāzbetona parauga mitruma saturu (%).



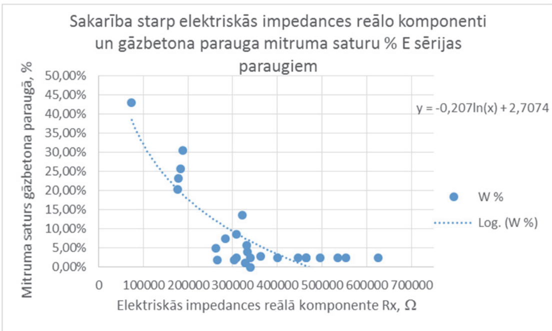
5. attēls. Sakarība starp elektriskās impedances reālo komponenti un gāzbetona parauga mitruma saturu (%).



6. attēls. Sakarība starp elektriskās impedances reālo komponenti un gāzbetona parauga mitruma saturu (%).

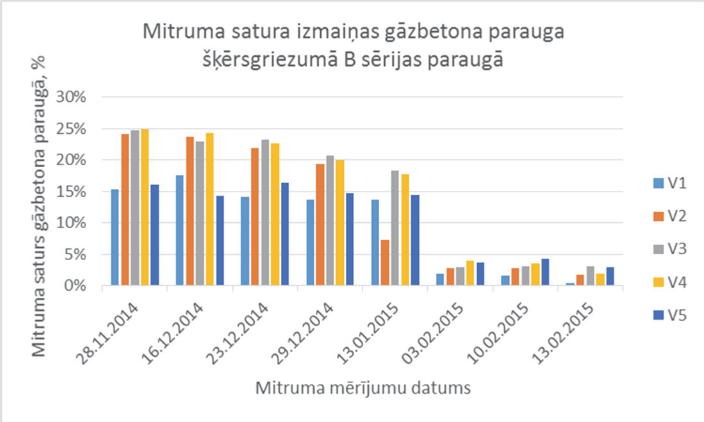


7. attēls. Sakarība starp elektriskās impedances reālo komponenti un gāzbetona parauga mitruma saturu (%).



8. attēls. Sakarība starp elektriskās impedances reālo komponenti un gāzbetona parauga mitruma saturu (%).

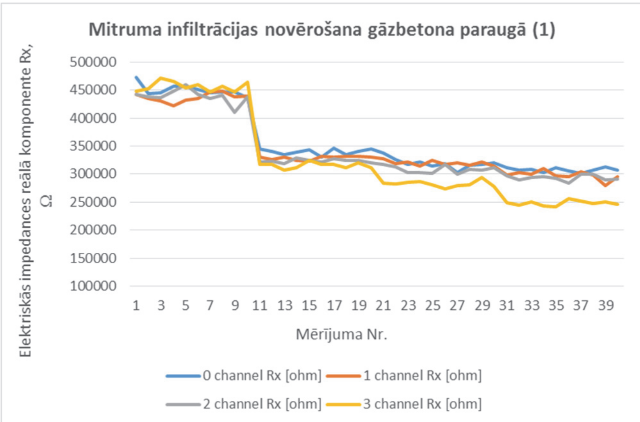
Izmantojot iegūtās sakarības, kļuva iespējams noteikt mitruma sadalījumu gāzbetona paraugos visos to žūšanas posmos atbilstoši 9. attēlā norādītajam piemēram.



9. attēls. Mitruma sadalījuma izmaiņas gāzbetona paraugā žūšanas procesa laikā.

Eksperimentālajā daļā tika noskaidrots, ka kontaktvirsmas ciešumam starp mērierīces zondēm un paraugu nav būtiskas ietekmes uz mērījumu precizitāti, tādēļ nākamais eksperimentālās daļas posms tika virzīts uz iegūto rezultātu aprobāciju turpmākam lietojumam būvlaukuma apstākļos.

Metodikas aprobācijas laikā tika veikta mitruma sadalījuma noteikšana ar elektriskās impedances spektrometrijas metodi un *Z-meter III* iekārtu gāzbetona paraugiem dažādu mitruma uzsūkšanas veidu gadījumos (infiltrācijas, kapilārās uzsūkšanas), kā arī sagatavotas mitruma uzsūkšanās līknes dažādos materiāla dziļumos.

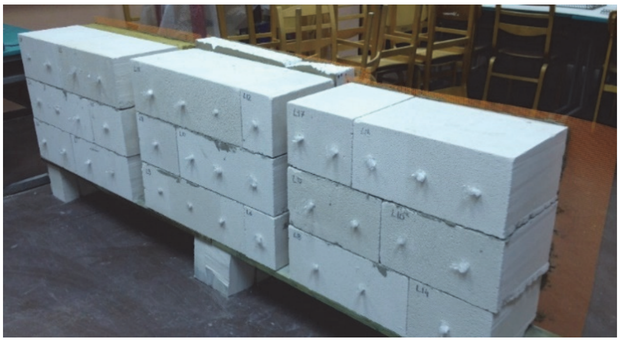


10. attēls. Elektriskās impedances reālā komponentes izmaiņas ūdenim infiltrējoties gāzbetona paraugā.

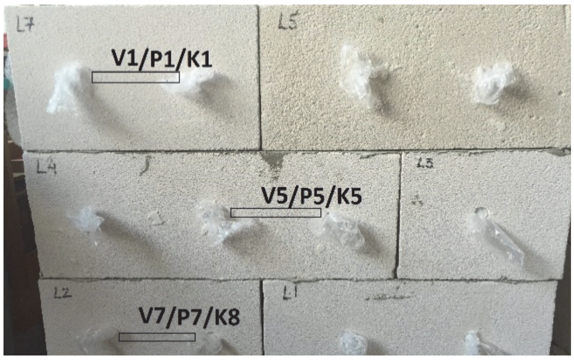
Kā nākamais posms metodikas aprobācijā tika noteikts mūra šuvju un plaisu ietekmes novērtējums uz elektriskās impedances spektrometrijas mērījumu rezultātu precizitāti. Šajā eksperimentā tika noskaidrots, ka mūra šuvēm un plaisām, kuru platums pārsniedz 0,1 mm, ir būtiska ietekme uz mērījumu rezultātu precizitāti, tādēļ šobrīd izstrādātā metodika ir lietojama tikai mitruma sadalījuma noteikšanai viena gāzbetona bloka robežās.

Eksperimentālajā daļā tika izveidoti mācību stendi mitruma migrācijas novērošanai gāzbetona sienu konstrukcijās ar atšķirīgiem apdares risinājumiem (akmens vates siltinājums, putupolistirola siltinājums, apmesta siena bez siltinājuma), kurām ar elektriskās impedances spektrometrijas metodi tiek veikta žūšanas procesa novērošana.

11. attēls. Sienu konstrukciju stendi.

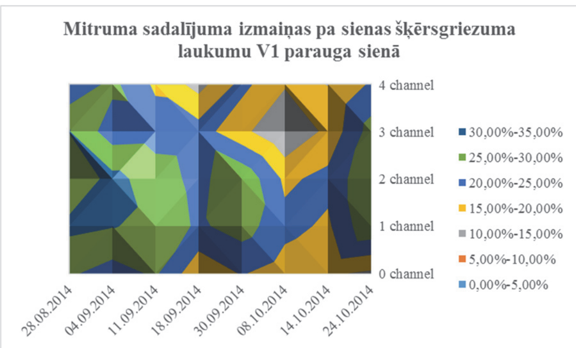


12. attēls. Sienu konstrukciju stendi.

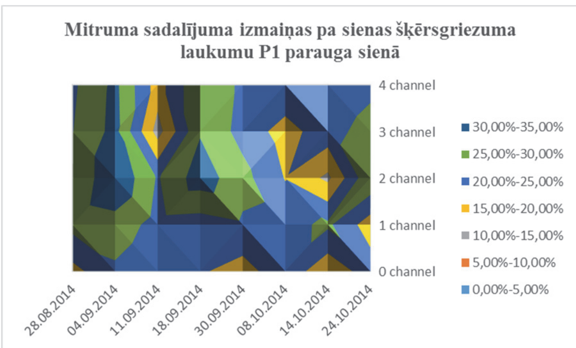


13. attēls. Sienu konstrukciju stendi.

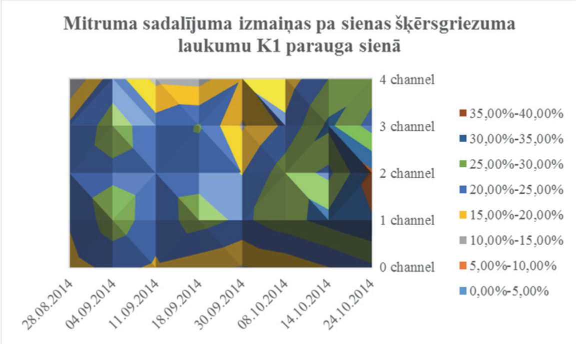
Žūšanas procesa novērošanas rezultātā tika sagatavotas mitruma migrācijas kartes (14.–16. attēls) pa konstrukcijas šķērsgriezumu, tādējādi maksimāli pietuvinot mērījumu veikšanas apstākļus būvlaukuma apstākļiem, kā arī iegūtos datus tiem datiem, kas tiek iegūti, lietojot apskatāmo metodiku būvlaukuma apstākļos.



14. attēls. Mitruma migrācijas karte šķēlumā V1 stendam ar akmens vates siltinājumu.



15. attēls. Mitruma migrācijas karte šķēlumā P1 stendam ar putupolistirola siltinājumu.



16. attēls. Mitruma migrācijas karte šķēlumā K1 stendam bez siltinājuma.

3. Rezultātu kopsavilkums

Promocijas darba otrajā nodaļā veikto eksperimentu dati un rezultāti tika apkopoti, lai izstrādātu turpmākas vadlīnijas elektriskās impedances spektrometrijas un *Z-meter III* mērierīces lietošanai mitruma sadalījuma noteikšanai gāzbetona konstrukcijās.

Elektriskās impedances spektrometrijas rezultātu precizitāti mitruma sadalījuma noteikšanai gāzbetona konstrukcijās būtiski ietekmē izvēlētā mērījumu frekvence, tādēļ pirms metodes lietošanas noteikti ir jāveic frekvenču analīze, lai noskaidrotu, vai mitruma sadalījums attiecīgajā konstrukcijā ir nosakāms relatīvās vērtībās, izmantojot elektriskās impedances spektrometrijas datus, kā arī vai noteiktās korelācijas sakarības ir lietojamas attiecīgā gāzbetona materiāla mitruma satura noteikšanai absolūtās vērtībās.

Mērījumu veikšanai piemērotās frekvences ietekmē materiāla blīvums, piesātinājuma pakāpe un poru struktūra. Attiecīgie parametri ar ietekmēt piemērotākās frekvences vērtību diapazonā līdz 2000 Hz.

Matemātiskā sakarība (1.), kas noteikta promocijas darbā veikto pētījumu rezultātā, ir lietojama visu tipu gāzbetona konstrukciju mitruma satura noteikšanai absolūtās vērtībās.

$$y = -0{,}201 \ln(x) + 2{,}6513 \tag{1.}$$

Lai paaugstinātu metodes precizitāti, katram apskatāmajam gāzbetona veidam tika izstrādāta arī individuāla sakarība starp mitruma saturu un elektriskās impedances spektrometrijas mērījumu rezultātu vērtību. Šādā gadījumā mērījumu rezultātu precizitāte paaugstinās vidēji par 10 %.

Secinājumi

Veicot promocijas darba rezultātu analīzi, var secināt, ka visi darba ievadā noteiktie mērķi ir izpildīti. Darba rezultātā ir izstrādāta metodika mitruma sadalījuma noteikšanai gāzbetona konstrukcijās ar *Z-meter III* iekārtu lietošanai būvlaukuma apstākļos. Ir noteikti metodi ierobežojoši faktori, kā arī apstākļi, kas jāņem vērā, lai nodrošinātu maksimāli augstu mērījumu rezultātu precizitāti.

Darba noslēguma ir iespējams izdarīt šādus secinājumus:

- elektriskās impedances spektrometrija var tikt lietota mitruma sadalījuma noteikšanai gāzbetona konstrukcijās ar vidējo precizitāti 70 %;
- pirms elektriskās impedances spektrometrijas metodes lietošanas ir nepieciešams veikt frekvenču analīzi, lai noskaidrotu mērījumiem piemērotāku frekvenci; Latvijas būvniecības tirgū biežāk sastopamajiem gāzbetona bloku veidiem piemērotākā mērījumu frekvence ir 8000 Hz;
- elektriskās impedances spektrometrijas mērījumu veikšanas laikā ir jānodrošina maksimāli cieša kontaktvirsma starp mērierīces zondi gāzbetona virsmu; gaisa šķirkārta, kas nepārsniedz 1 mm starp zondes un gāzbetona parauga virsmu, ietekmē mērījumu rezultātu precizitāti līdz 3 %;
- visprecīzākie elektriskās impedances spektrometrijas rezultāti ir sasniedzami, ja netiek izmantoti gāzbetona virsmas pārklājumi;
- elektriskās impedances spektrometrijas mērījumi var tikt veikti bez attāluma ierobežojuma starp mērierīces zondēm, tomēr attālums starp zondēm ietekmē frekvenci, kurā tiek veikti mērījumi; attālumam starp mērierīces zondēm, kas ir robežās 150–300 mm, piemērotākā mērījumu frekvence ir 8000 Hz;
- sakarība starp elektriskās impedances reālo komponenti un mitruma saturu gāzbetonā ir izsakāma ar logaritmisku sakarību;
- mūra šuvēm un plaisām, kas pārsniedz 0,1 mm platumu, ir būtiska ietekme uz mērījumu rezultātiem, tādēļ mērījumi būtu jāveic iecirkņos, kuros nav novērojamas plaisas vai mūra šuves.

Pētījumā ir sagatavoti priekšlikumi mērierīces *Z-meter III* uzlabošanai:

- jāizgatavo pašurbjošas mērījumu zondes, lai atvieglotu mērierīces lietošanu;
- iekārtas programmnodrošinājumā ir jāparedz automātiski veicama frekvenču analīzes funkcija;
- iekārtas programmnodrošinājums ir jāpapildina ar sakarībām starp elektriskās impedances reālo komponenti un mitruma saturu gāzbetonā, lai paātrinātu iegūto rezultātu apstrādi.

General Description of the Doctoral Thesis

Actuality of the Research and Formulation of the Problem

Contemporary construction trends are sustainable construction and effective use of construction materials; therefore, load bearing construction materials with high heat insulation parameters tend to become more popular. As an opposite trend, there are short construction terms, which fail to comply with all nuances of the material installation technology. Therefore, non-destructive testing methods have become more and more popular during the past years.

Autoclaved aerated concrete (AAC) masonry blocks are construction material with high heat insulation parameters. In the time of sustainable construction, this material can be used as a load bearing construction material for a range of buildings where it is necessary to obtain high heat insulation parameters of external delimiting constructions. The main problem of AAC masonry constructions is significant influence of moisture content and its gradient on heat resistivity properties of the AAC. It is important to monitor the drying process of AAC masonry constructions in order to avoid sealing of moisture inside the masonry by early application of finishing layers on the construction. Therefore, testing methods, which allow credible determination of moisture distribution throughout the cross section of the AAC masonry construction as well as moisture migration throughout the cross section of the construction, have to be developed. The drying process of the masonry is a long-term process; therefore, it is preferable to use non-destructive testing methods because a number of measurement series have to be performed in order to provide credible data of the changes in moisture content throughout the cross section of the masonry construction.

There is a variety of manufacturers who offer AAC masonry blocks, and the manufacturing process of the blocks slightly differs as well as the ingredients used for the manufacturing of the blocks. Thus, the porous structure, density as well as chemical composition of the AAC slightly differ. This research has been done to determine the possibility of application of electrical impedance spectrometry for in-situ non-destructive determination of moisture distribution throughout the cross section of AAC masonry constructions.

The Aim of the Research

The aim of the research is to develop a non-destructive testing methodology for detection of moisture distribution throughout the cross section of AAC masonry constructions under in-situ conditions. After the analysis of previous studies about non-destructive detection of moisture content and its distribution throughout the cross section in solid materials, the tasks of the research have been set.

The Tasks of the Research

1. To determine the correlation between EIS measurement results and moisture content in AAC.
2. To determine the impact of contact surface between measurement probe and AAC masonry construction on the accuracy of the obtained results.
3. To determine the impact of the coating on measurement contact surface on the accuracy of the measurement results.
4. To determine the impact of measurement distance on accuracy of measurement results.
5. To determine the impact of cracks and masonry joints on accuracy of EIS measurement results.

Scientific Novelty of the Research Results

Misunderstanding of the physical processes in construction materials can lead to misuse of effective construction materials and decrease the effectiveness of the properties of constructions designed in compliance with ISO 6946:2007 Building components and building elements - Thermal resistance and thermal transmittance - Calculation method. Therefore, a credible on-site control methodology of moisture distribution in AAC is necessary in order to reach the designed material properties and avoid mistakes during the installation stage of the material.

Previous studies have been focused on non-destructive detection of moisture content and its distribution in solid materials such as concrete. Non-destructive detection of moisture distribution in AAC has not been widely researched due to the uneven and porous structure of the material, which causes problems with repeatability of the measurement results and, therefore, excludes common use of the methodology. Therefore, in the present research an EIS methodology, which is usually applied for moisture detection of bulk materials (such as soil), has been adapted for application on AAC and has reached the aims stated in this research.

Application of the Research Results

The research results can be applied for on-site non-destructive detection of moisture distribution in AAC constructions as a part of quality control activities of the construction process.

Methodology of the Research

The research is based on determination of moisture distribution throughout the cross section of autoclaved aerated concrete (AAC) constructions with Z-meter III device. As a reference material, most commonly used AAC blocks of Latvian construction market were used (Table 1).

Table 1

AAC Blocks Used for the Research

Type of AAC	Thermal conductivity in dry state stated by manufacturer λ W/mK	Bulk density stated by manufacturer kg/m^3
AEROC Universal	0,090	375
Ytong PP2/0,4	0,105	375
Rocklite	0,11	500
Texoblock classic	0,12	500
Texoblock Lite	0,096	400

At the Laboratory of Water Management Research of the Institute of Water Structures at the Civil Engineering Faculty of Brno University of Technology, a measuring instrument with a Z-meter III device has been developed within the solution of an international project E!4981 of programme EUREKA.

Fig. 1. Z-meter III device with measurement probes.

For control measurements with gravimetric method, electronic scales with precision of ±5 g were used.

The results were operated by computer software MS Excel and Z-meter III software.

An example of Z-meter III output data has been displayed in Table 2.

Table 2

Z Meter III Output Data

Start at 12.11.2014 9:12:30							
No	f [Hz]	date [dd.mm.yyyy]	time [hh:mm:ss]	ch	range	Rx [ohm]	Xx [ohm]
1	1000	12.11.2014	09:12:30	0	1	101,3	-47,4
2	1000	12.11.2014	09:12:30	1	1	101,4	-47,3
3	1000	12.11.2014	09:12:30	2	1	101,3	-47,3
4	1000	12.11.2014	09:12:31	3	1	101,3	-47,2
5	1000	12.11.2014	09:12:31	4	1	101,4	-47,2

Theoretical and Methodological Basis of the Research

The Thesis has been based upon the following disciplines:

- Construction physics;
- Construction materials and technologies;
- Theoretical base of electrotechnics;
- Materials science;
- Environmental science.

Scope of the Study

The methodology developed for detection of moisture distribution throughout the cross section of AAC by EIS with *Z-meter III* device as well as the developed correlation equations are valid if the following criteria are met:

1. The EIS measurements are performed within borders of one masonry block, no cracks exceeding 0.1 mm thickness are present in the measurement distance;
2. The distance between measurement probes does not exceed 300 mm;
3. The distance between the measurement probe and AAC does not exceed 1 mm;
4. The measurements are performed in frequency of 8000 Hz.

Results Presented for Defence

- A following methodology for non-destructing detection of moisture distribution throughout the cross section of AAC masonry constructions with Z-meter device has been established:
    1. Choice of measurement points within the AAC masonry construction;
    2. Preparation of measurement bores, cleaning of internal surface of the measurement bores by compressed air;
    3. Frequency analysis of the AAC material (if high accuracy of the EIS measurement results is required);
    4. EIS measurements of the moisture distribution with Z-meter device;
    5. Processing of the measurement results.
- Correlation between EIS measurement results and moisture content in AAC is equal to: $y = a \ln(x) + C$;
- Distribution of pores throughout the volume of AAC has impact on the accuracy of EIS measurement results; therefore, it is advisory to detect expansion direction of the AAC prior the EIS measurements.

Approbation of the Results

The results of the Doctoral Thesis have been reported and discussed in 14 international conferences. The main results of the study have been presented in 16 scientific publications. Five of them have been indexed in SCOPUS database.

List of International Conferences

1. EUREKA 2013, 1st conference and working session, Karolinka, Czech Republic, Brno University of Technology, GEOTest. 30 October – 1 November 2013 (Rubene, S., Vilnītis, M. Application of Electrical Impedance Spectrometry for Determination of Moisture Distribution in Aerated Concrete Constructions);
2. "Innovative Materials, Structures and Technologies", Riga, Latvia, 28 November – 30 November 2013 (Rubene, S., Noviks, J., Vilnītis, M. Determination of Humidity Level In Aerated Concrete Constructions by Non Destructive Testing Methods);
3. The 18th International Student Scientific and Practical Research Conference "Cilvēks.Vide.Tehnoloģijas", Rezekne Higher Education Institution, Rezekne, Latvia. 23 April 2014 (Rubene, S., Noviks, J. Frequency Analysis of Electrical Impedance Spectrometry);
4. The 4th International Conference "Advanced Construction", Kaunas, Lithuania, Kaunas University of Technology, 9–10 October 2014 (Rubene, S., Vilnītis, M., Noviks, J. Monitoring of the Aerated Concrete Construction Drying Process by Electrical Impedance Spectrometry);
5. EUREKA 2014, 2nd conference and working session, Pasohlavky, Brno, Czech Republic, Brno University of Technology, GEOTest. 30 October – 1 November 2014 (Rubene, S., Vilnītis, M. Monitoring of Humidity Distribution Changes in Aerated Concrete Masonry Construction by EIS);
6. 5th European Conference of Civil Engineering, Florence, Italy, 22–24 November 2015 (Rubene, S., Vilnītis, M. Correlation between EIS Measurements and Relative Humidity Distribution in Aerated Concrete Masonry Constructions);
7. 1st International Conference on Civil Engineering, Water Resources, Hydraulics and Hydrology (CEWHH 2014), Athens, Greece, 28 November – 1 December 2015 (Rubene, S., Vilnītis, M., Noviks, J. Impact of Contact Surface on Accuracy of Humidity Distribution Measurements in Autoclaved Aerated Concrete Constructions by EIS);
8. 17th International Conference on Civil, Structural and Geoenvironmental Engineering, London, United Kingdom, 19–20 January 2015 (Rubene, S., Vilnītis, M., Noviks, J. Impact of Masonry Joints on Detection of Humidity Distribution in Aerated Concrete Masonry Constructions by Electric Impedance Spectrometry Measurements);

9. “Vide.Tehnoloģija.Resursi”, Rezekne Higher Education Institution, Rezekne, Latvia, 18–19 June 2015 (Rubene, S., Vilnītis, M., Noviks, J. Impact of Density and Special Features of Manufacturing Process on Drying of Autoclaved Aerated Concrete Masonry Blocks);
10. The 7th Scientific and Technical Conference on Material Problems in Civil Engineering (MATBUD’2015), Crakow University of Technology, Krakow, Poland, 22–24 June 2015 (Rubene, S., Vilnītis, M., Noviks, J. Frequency Analysis for EIS Measurements in Autoclaved Aerated Concrete Constructions);
11. Creative Construction Conference 2015, Krakow, Poland, 21–24 June 2015 (Rubene, S., Vilnītis, M., Noviks, J. Frequency Analysis and Measurements of Moisture Content of AAC Masonry Constructions);
12. The 2nd International Conference “Innovative Materials, Structures and Technologies” (IMST 2015), Riga, Latvia, 30 September – 2 October 2015 (Rubene, S., Vilnītis, M., Noviks, J. Impact of External Heat Insulation on Drying Process of Autoclaved Aerated Concrete Masonry Constructions);
13. EUREKA 2015, 3rd conference and working session, Jaromerice nad Rokytnou, Brno, Czech Republic, Brno University of Technology, GEOTest. 15–16 October 2015 (Rubene, S., Vilnītis, M. Accuracy of Humidity Distribution Measurements in Autoclaved Aerated Concrete Constructions by Electrical Impedance Spectrometry);
14. The 6th European Conference of Civil Engineering, Budapest, Hungary, 12–14 December 2015 (Rubene, S., Vilnītis, M. Monitoring of Water Infiltration in Autoclaved Aerated Concrete Masonry Construction Blocks by Electrical Impedance Spectrometry).

List of Scientific Publications on the Subject of the Doctoral Thesis

1. Rubene, S., Vilnītis, M. Application of Electrical Impedance Spectrometry for Determination of Moisture Distribution in Aerated Concrete Constructions. In: EUREKA 2013: 1st Conference and Working Session: Proceedings, Czech Republic, Karolinka, 30 October – 1 November 2013. Brno: VUTIUM, Brno University of Technology, 2013, pp. 124–131. ISBN 978-80-214-4735-6.
2. Rubene, S., Vilnītis, M., Noviks, J. Impact of Contact Surface on Accuracy of Humidity Distribution Measurements in Autoclaved Aerated Concrete Constructions by EIS. In: Proceedings of 1st International Conference on Civil Engineering, Water Resources, Hydraulics and Hydrology (CEWHH 2014), Greece,

Athens, 28–30 November 2014. Athens: EUROPMENT, 2014, pp. 99–104. ISBN 978-1-61804-253-8.

3. Rubene, S., Vilnītis, M. Correlation between EIS Measurements and Relative Humidity Distribution in Aerated Concrete Masonry Constructions. In: Recent Advances in Civil Engineering and Mechanics. Mathematics and Computers in Science and Engineering Series 35, Italy, Florence, 22–24 November 2014. Florence: WSEAS Press, 2014, pp. 67–72. ISBN 978-960-474-403-9. ISSN 2227-4588.
4. Rubene, S., Vilnītis, M. Monitoring of Humidity Distribution Changes in Aerated Concrete Masonry Construction by EIS. In: EUREKA 2014: 2nd Conference and Working Session Proceedings, Czech Republic, Brno, 30–31 October 2014. Brno: VUTIUM Brno University of Technology, 2014, pp. 124–130. ISBN 978-80-214-4883-4.
5. Rubene, S., Vilnītis, M., Noviks, J. Monitoring of the Aerated Concrete Construction Drying Process by Electrical Impedance Spectrometry. In: Proceedings of 4th International Conference "Advanced Construction 2014", Lithuania, Kaunas, 9–10 October 2014. Kaunas: Kaunas University of Technology, 2014, pp. 216–220. ISSN 2029-1213.
6. Rubene, S., Noviks, J., Vilnītis, M. Determination of Humidity Level in Aerated Concrete Constructions by Non Destructive Testing Methods. In: Proceedings of the International Conference "Innovative Materials, Structures and Technologies", Latvia, Riga, 28-30 November 2013. Riga: RTU Press, 2014, pp. 141–146. ISBN 978-9934-10-583-8. e-ISBN 978-9934-10-584-5. Available from: doi:10.7250/iscconstrs.2014.23
7. Rubene, S., Vilnītis, M., Noviks, J. Impact of Masonry Joints on Detection of Humidity Distribution in Aerated Concrete Masonry Constructions by Electric Impedance Spectrometry Measurements. International Journal of Civil, Architectural, Structural and Construction Engineering, 2015, Vol. 9, No. 1, pp. 1089–1094. e-ISSN 1307-6892.
8. Rubene, S., Vilnītis, M., Noviks, J. Impact of External Heat Insulation on Drying Process of Autoclaved Aerated Concrete Masonry Constructions. IOP Conference Series: Materials Science and Engineering, 2015, Vol. 96, conference 1, pp. 1–8. ISSN 1757-8981. e-ISSN 1757-899X. Available from: doi:10.1088/1757-899X/96/1/012059 (SCOPUS indexed).

9. Rubene, S., Vilnītis, M., Noviks, J. Frequency Analysis and Measurements of Moisture Content of AAC Masonry Constructions by EIS. Procedia Engineering, 2015, Vol. 123, pp. 471–478. ISSN 1877-7058. Available from: doi:10.1016/j.proeng.2015.10.096 (SCOPUS indexed).
10. Rubene, S., Vilnītis, M., Noviks, J. Frequency Analysis for EIS Measurements in Autoclaved Aerated Concrete Constructions. Procedia Engineering, 2015, Vol. 108, pp. 647–654. ISSN 1877-7058. Available from: doi:10.1016/j.proeng.2015.06.194 (SCOPUS indexed).
11. Rubene, S., Vilnītis, M. Application of Electrical Impedance Spectrometry for Measurements of Humidity Distribution in Aerated Concrete Masonry Constructions. International Journal of Mechanics, 2015, Vol. 9, pp. 213–219. ISSN 1998-4448. (SCOPUS indexed).
12. Rubene, S., Vilnītis, M., Noviks, J. Impact of Density and Special Features of Manufacturing Process on Drying of Autoclaved Aerated Concrete Masonry Blocks. In: Environment. Technology. Resources. Rezekne, Latvia: Rezekne Higher Education Institution, 2015, pp. 186–192. ISSN 1691-5402. (SCOPUS indexed).
13. Rubene, S., Vilnītis, M. Frequency Analysis and Measurements of Moisture Content of AAC Masonry Constructions by EIS. In: Proceedings "Creative Construction Conference 2015". Budapest, Hungary: Diamond Congress Ltd., 2015, pp. 147–147. ISBN 978-963-269-491-7.
14. Rubene, S., Vilnītis, M. Monitoring of Water Infiltration in Autoclaved Aerated Concrete Masonry Construction Blocks by Electrical Impedance Spectrometry. In: Recent Advances in Mechanical Engineering Series 17 "Fluids, Heat and Mass Transfer, Mechanical and Civil Engineering", Hungary, Budapest, 12–14 December 2015. Budapest: WSEAS Press, 2015, pp. 106–111. ISBN 978-1-61804-358-0. ISSN 2227-4596.
15. Rubene, S., Vilnītis, M. Impact of Porous Structure of the AAC Material on Moisture Distribution throughout the Cross Section of the AAC Masonry Blocks. WSEAS Transactions on Heat and Mass Transfer, 2016, Vol. 11, pp. 13–20. ISSN 1790-5044. e-ISSN 2224-3461.
16. Rubene, S., Vilnītis, M. Accuracy of Humidity Distribution Measurements in Autoclaved Aerated Concrete Constructions by Electrical Impedance Spectrometry. In: EUREKA 2015 Proceedings, Czech Republic, Jaromerice nad Rokytnou, 15–16 October, 2015. Brno: 2015, pp. 156–164. ISSN 2464-4595.

Structure and Contents of the Doctoral Thesis

The Doctoral Thesis consists of abstract in English and Latvian, introduction, three main chapters, which have been divided into paragraphs, conclusion, bibliography comprising 114 reference sources and one appendix.

The volume of the Thesis is 112 pages. It has been illustrated by 107 figures and 4 tables.

In the introduction, the issue has been stated as well as the aims and tasks have been defined. The scientific novelty and application of the results has been stated in the introduction.

In the first chapter, the main properties of the AAC as well as the technology of its manufacturing process have been described. Review on existing non-destructive techniques of detection of moisture distribution throughout the cross section of solid materials has been provided in the first chapter.

In the second chapter, the author describes the experiments performed in order to reach the aims set in the Thesis. The procedure of approbation of the developed methodology for non-destructive detection of moisture distribution throughout the cross section of the AAC has been described in the second chapter.

In the third chapter, the author has provided a summary and brief analysis of the obtained results.

In the conclusion, the main results and finding have been summarized. Thesis statements to be defended have been stated.

Contents of the Doctoral Thesis

Introduction

In the introduction, the issue of the research has been stated as well as the aims and tasks defined. The scientific novelty and application opportunities of the results have been also stated in the introduction.

1. Materials and Methods

Aerated concrete is basically a mortar with pulverized sand or industrial waste like fly ash as filler, in which air is entrapped artificially by chemical (metallic powders like A1, Zn, and H_2O_2) or mechanical (foaming agents) means, resulting in a significant reduction in density. Aerated concrete falls into the group of cellular concrete (microporite being the other one). The main advantage of aerated concrete is its light weight, which optimises the design of supporting structures, including the foundation and load bearing walls. Aerated concrete provides a high degree of thermal insulation and considerable savings in material due to the porous structure. Aerated concrete can be obtained with a wide range of densities, e.g., 300 ± 1800 kg/m^3, thereby offering flexibility in manufacturing products for specific applications (structural, partition and insulation grades).

Physical properties, especially isolative and hygrometric properties, of aerated concrete depend on its microstructure and macrostructure.

In aerated concrete, the method of pore formation (gas release, foaming or combined) has significant impact on the microstructure and, thus, on its properties. The material structure of aerated concrete is characterised by its solid microporous matrix and macropores. The macropores are formed due to the expansion of the mass caused by aeration, and the micropores appear in the walls between the macropores.

The porous system of aerated concrete is also classified in terms of pore size distribution functions as artificial air pores, inter-cluster pores and inter-particle pores. The distribution of pores in the matrix has influence on its properties.

Aerated concrete is porous and there is a strong interaction between water, water vapour and the porous system; therefore, there are various moisture transport mechanisms. In the dry state, pores are empty and the water vapour diffusion dominates, while some pores are filled in higher humidity regions. Capillary suction predominates for an element in contact with water. These mechanisms make it difficult to predict the influence of pore size distribution and water content on moisture migration.

As AAC masonry constructions are porous, composed of solid matrix and pores. In porous materials heat transfer is often coupled strongly with moisture transfer. Accurate prediction of heat and moisture transfer in porous material is essential for optimization of building envelope with respect to energy consumption, hydrothermal performance, and indoor environment (Alexanderson J. Relations between Structure and Mechanical Properties of Autoclaved Aerated Concrete. Cem Concr Res 1979;9:507±14 5). The porous structure of the AAC has direct impact on the physical properties of the material as well as on non-destructive techniques, which can be applied for detection of moisture content and its distribution throughout the material.

The most precise and credible test method is a destructive measurement method, which is called a gravimetric method. Gravimetric method implies determining water content through weighting samples upon oven drying, encompassing absorbed and chemically bound water. This method is considered to be the most direct and reliable procedure despite the large number of specimens it requires, since different samples should be used for each measure, and only the average water content of each portion or slice should be obtained. It is also one of a few methods that can be employed at high moisture contents (Jana Selih, A. S. Moisture Transport in Initially Fully Saturated Concrete during Drying. Transport in Porous Media 24, 1996 pp. 81–106). Such an approach can provide credible results about humidity distribution throughout the cross section of the construction, but it is a long and laborious process, which is hard to repeat in a number of places on a construction site. However, this method can be used to control the non-destructive test results and prepare correlation equations between moisture content in specimen and EIS measurement results.

A number of studies have been performed in order to develop non-destructive test methods for the detection of humidity content in solid materials. These methods can be divided in several sub-groups such as radiological methods, electrical methods and heat flow measurement methods.

Radiological methods are the most precise methods from the range of non-destructive techniques for moisture detection. There are many radiological methods, e.g., gamma densitometry, neutron radiography, nuclear magnetic resonance (NMR), computer tomography, which can be applied for detection of moisture content in solid materials. When running a neutron radiography test, the drawback of these methods is related to safety arrangements and the need for specially trained personnel. It makes these methods rather unsuitable for in-situ use.

The moisture content on the construction can be performed by measuring its heat resistivity properties. Heat resistance of the material is directly dependent on its moisture content and its distribution throughout the cross section of the material.

The moisture distribution throughout the cross section of the element has significant impact on the heat conductive properties. A number of studies have been performed on the coupled heat and moisture transfer in porous media. One of the most disseminated and accepted models is the Philip and DeVries model, which uses the temperature and moisture content gradients as driving potentials (Philip, J.R., DeVries, D.A. (1975). Moisture Movement in Porous Materials under Temperature Gradients. Trans Am Geophys Union 2: 222–232). However, it is well known that there is discontinuity on the moisture content profile at the interface between two porous media. Luikov proposed a mathematical model for simultaneous heat and mass transfer in building porous materials (Luikov, A.W. (1966). Heat and Mass Transfer in Capillary-Porous Bodies. Pergamon Oxford, UK).

As it is a laborious process (including complicated calculations and measurements of surrounding constants) to obtain moisture distribution data from the heat resistance data, it is not widely used for detection of moisture distribution throughout the cross section of construction materials.

There are methods to calculate the moisture diffusivity at high moisture levels from the sorption coefficient. Such mathematical models for evaluation of moisture diffusivity at high moisture levels from a series of capillary water uptake tests and results from these methods are described in detail by Künzel (Künzel, H.M. (1995). Simultaneous Heat and Moisture Transport in Building Components – One- and Two-Dimensional Calculation Using Simple Parameters, IRB Verlag, Stuttgart). However, this approach also includes complicated calculations and measurements of surrounding constants; therefore, it is not easily applicable for in-situ measurements of moisture content in solid materials.

There are a number of non-destructive test methods, which are based on measurement of electrical parameters and corresponding them to humidity contents of construction materials. Electrical techniques are based on the relationship between the electrical properties of cement-based materials and their water content. Measurements of resistance, impedance, capacitance and the dielectric constant of porous materials are influenced by the water content and can be used as the basis of assessing water content. With appropriate attention to the condition of the material, electrical techniques can offer a quick, non-destructive method of identifying the extent of surface moisture by giving comparative measurements.

Method of electrical impedance spectrometry (EIS) enables detection of the distribution of impedance or other electrical variables (such as resistivity, conductivity etc.) inside a monitored object and, thus, the observation of its inner structure and its changes. This method ranks among indirect methods for detection of material properties through electrical measurements and it is used to measure properties of organic and inorganic substances. So far, EIS has been widely used in medicine as one of the most common testing methods in diagnostics where any kind of tissues are involved. It constitutes a very sensitive tool for monitoring phenomena that take place in objects (e.g., changes occurring in earth filled dams when loaded by water, in wet masonry sediments etc.), electrokinetic phenomena at boundaries (e.g., electrode/soil grain, between soil grains) or for describing basic ideas about the structure of an inter phase boundary (e.g., electrode/water) (Barsoukov, E., McDonald, R. (2005). *Impedance Spectroscopy Theory, Experiment, and Applications*. New York, USA: John Wiley & Sons, New ISBN: 0-471-64749-7 39).

Electrical impedance is a basic property characterising AC electrical circuits. It is always greater than or equal to the real electrical resistance R in the circuit. Imaginary resistance, i.e. inductance–reactance of inductor XL and capacitance–reactance of capacitor XC, creates variable and, therefore, frequency-dependent part of the impedance. Electrical impedance is evidently made up of real and imaginary parts. Resistance R creates real part and is frequency-independent. Imaginary part is created by reactance X, which is frequency-dependent. Electrical impedance can be expressed by Ohm's equation for AC circuits, i.e., by the ratio of electric voltage phasor U and electric current phasor I.

As the EIS is used for monitoring of material properties, the processes taking place in the material as well as interaction between the monitored object and the measurement device can be described with equivalent circuits.

Electrical measurements have shown promise as non-invasive methods to evaluate the material properties of concrete. For example, a range of microstructural properties can be evaluated, including porosity, pore connectivity, water permeability, and ion diffusivity (Christensen, B.J., Coverdale, R.T., Olson, R.A., Ford, S.J., Garboczi, E.J., Jennings, H.M., and Mason, T.O. (1994). Impedance Spectroscopy of Hydrating Cement-Based Materials: Measurement, Interpretation, and Application. *J Am Ceramic Soc 77(11)*, 2789–2802 75. Rajabipour, F. (2006). *In Situ Electrical Sensing and Material Health Monitoring of Concrete Structures*. Ph.D. Dissertation, Purdue University, West Lafayette, Indiana). One potential drawback associated with the use of electrical measurements is that several factors can simultaneously influence the measurement results and this may complicate the interpretations (Schmit, T., Rajabipour, F., and Weiss, W.J. (2005). Investigating the Use of a Diffuse Measurement Interpretation for Analyzing In Situ Electrical Measurements. *The 3rd International Conference on Construction Materials: ConMat'05*. Vancouver, Canada).

The porous structure of AAC causes obstacles for direct application of electrical measurements for detection of material moisture content. However, after a series of experiments a methodology for detection of moisture distribution throughout the cross section of material has been developed.

At the Laboratory of Water Management Research of the Institute of Water Structures at the Civil Engineering Faculty of Brno University of Technology, a measuring instrument with a Z-meter III device has been developed within the solution of an international project E!4981 of programme EUREKA. A prototype of the Z-meter III has been applied for all EIS measurements described in the present Thesis.

Z-meter III device consists of an electronic block and detachable measurement probes as displayed in Fig. 1. The measurement probe consists of active channels from stainless steel and insulator channels from plastics. The measurements have been performed between the active channels of the measurement probes.

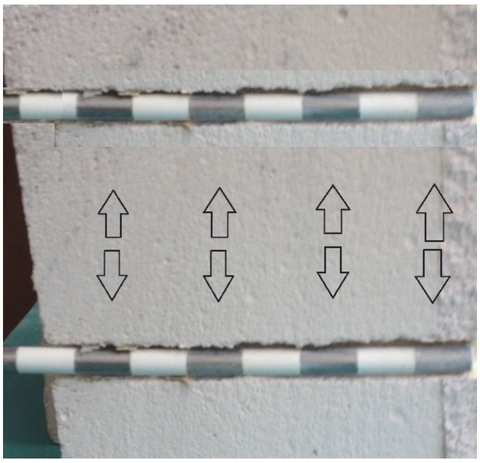


Fig. 2. Schematic picture of measurements with a probe pair of Z-meter III.

2. Experiments

The present Thesis has been based on comprehensive research conducted on a step-by-step basis taking into consideration all main issues that could affect the possibilities of application of EIS method for detection of moisture distribution in AAC masonry constructions. Every experiment has been performed in order to verify the influence of different issues, such as measurement frequency, quality of contact surface between measurement probe and AAC etc., on the accuracy of the obtained results. The further paragraphs provide the description of the experiments as well as the main results.

The EIS method is based on measurements of resistance of AC circuit. Therefore, the measurement result is a frequency dependant value, which depends on a number of factors that characterise the properties (such as porous structure, density changes, moisture saturation rate, etc.) of the material measurements are taken upon.

The experiment was based on the monitoring of differences in the preferable measurement frequencies in AAC material due to the chemical and structural differences of the material.

For this experiment, five different AAC masonry block specimen were chosen. In order to compare the possibilities of the application of EIS on different types of AAC masonry constructions, five different specimen types of AAC were used for this test. The samples came from different manufacturers and had slightly different densities. Those facts allowed assuming that the porous structure as well as chemical structure of the samples slightly differed.

For frequency analysis, the X component of resistance is used because the optimal measurement frequency depends on the structure of AAC material. The complex impedance Z of the unsaturated porous material describes its properties – the solid part (grains) is formed by insulating materials characterised by their dielectric constants – and represents the imaginary part of the measured impedance, which is taken into consideration during the frequency analysis. Water containing mineral salts is a conductive material. The degree of saturation of the material strongly influences the real part of the measured impedance. However, it is impossible to exclude the impact of moisture on the results of frequency analysis, especially, if the saturation rate of the material is high. In such cases, moisture fills pores of the material increasing overall density of the material and reduces the impact of the pores on the results of frequency analysis. Therefore, it is important to perform the frequency analysis on specimen with a possibly low saturation rate and even moisture distribution throughout the cross section of the material. It can be observed that the regions of the samples with higher moisture content and, thus, with higher density have wider frequency ranges, which are suitable for EIS measurements. However, it should be taken into consideration that the samples with large differences of the moisture content throughout the cross section of the sample also had large differences of impedance measurement results. Therefore, the moisture distribution measurements should be performed on the specimen prior the frequency analysis in order to determine initial moisture distribution throughout the cross section of the sample in relative means using an average measurement frequency of 8–10 kHz, which has been detected as suitable for moisture distribution measurements in AAC.

When a suitable measurement frequency for the EIS measurements in AAC material has been detected, it is possible to apply EIS measurements for detection of moisture distribution throughout the cross section of the AAC material. However, these measurements have only relative character if a correlation between the EIS measurement result and a moisture content of the AAC sample is not known. As it is important to be aware of the moisture content in the construction materials in absolute means, a necessity of development of correlation equations between the EIS measurement results and the moisture content of the AAC samples arises. In order to develop correlation equations between the moisture content in AAC masonry constructions (moisture content in % upon weight of dry mass) and the result of EIS measurement of real part of electrical impedance (ohm), the research with a set of experiments has been conducted.

For the particular experiment, a set of five different types of AAC masonry blocks with different density and porous structure were used.

Specimen with density in range from 375 to 500 kg/m3 were chosen for the experiment in order to determine the impact of different AAC properties – such as density, speed of drying, porous structure – on the correlation between the EIS measurement results and moisture content in the AAC. One of the blocks from each type was split into several pieces according to the approach of Akita et al. (Akita, H., Fujiwara, T., and Ozaka, Y. (1996). A Practical Procedure for the Analysis of Moisture Transfer within Concrete due to Drying. *Magazine of Concrete Research 48(6)*, 129–137) in order to determine the moisture content of each segment in the masonry block by gravimetric method (Fig. 2). The monitoring of the changes in moisture content of each sample was performed by monitoring of mass changes in time for each specimen. Such an approach allowed determining the changes of moisture content in the specimen and the relevant changes of EIS measurement results upon the specimen.

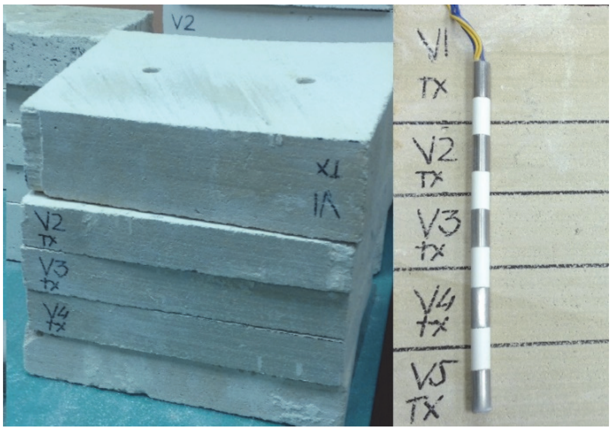


Fig. 2. AAC masonry block samples for determination
of humidity distribution by gravimetric method.

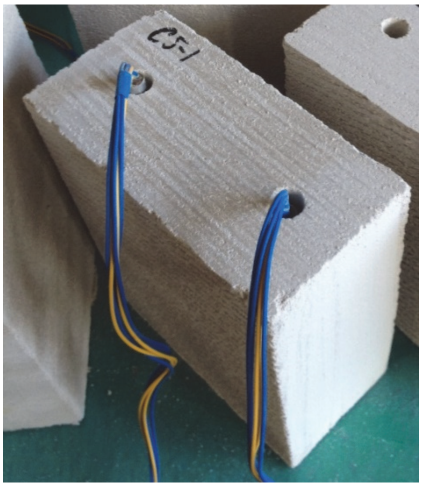


Fig. 3. Autoclaved aerated masonry block sample
with measurement probes.

As a result of the research, correlation graphs between the results of EIS measurements and absolute values of moisture content in cross section of the sample were prepared for each type of AAC samples.

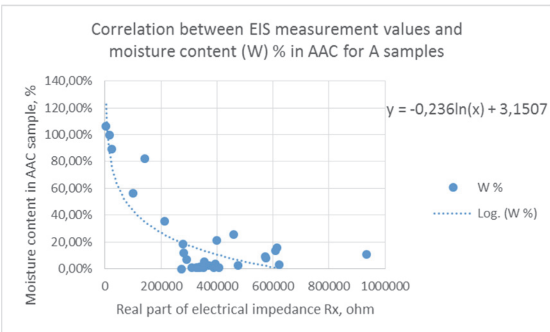


Fig. 4. Correlation between EIS measurement values and moisture content of the samples of A series in %.

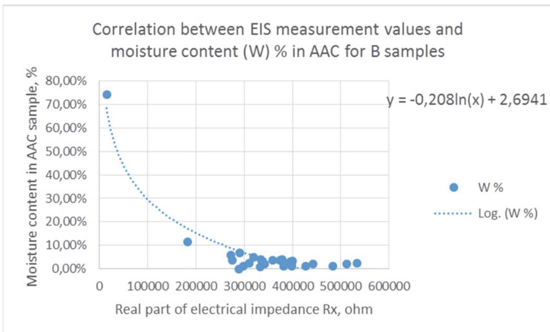


Fig. 5. Correlation between EIS measurement values and moisture content of the samples of B series in %.

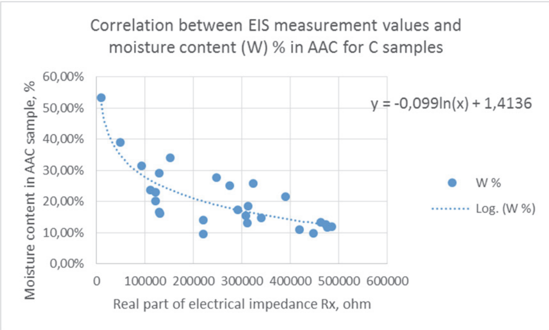


Fig. 6. Correlation between EIS measurement values and moisture content of the samples of C series in %.

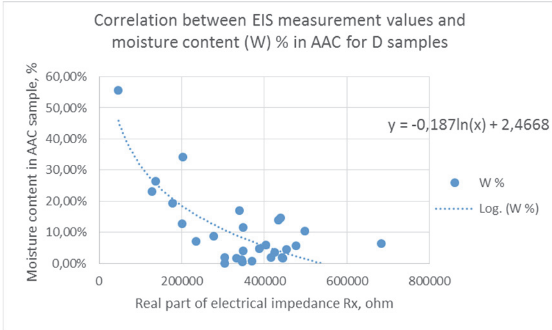


Fig. 7. Correlation between EIS measurement values and moisture content of the samples of D series in %.

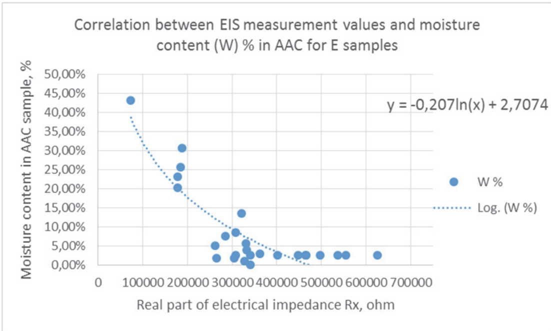


Fig. 8. Correlation between EIS measurement values and moisture content of the samples of E series in %.

EIS measurement results can be transformed into moisture content rate of the AAC material, and in such way the distribution of moisture content in the material sample can be determined by a non-destructive method (Fig. 9).

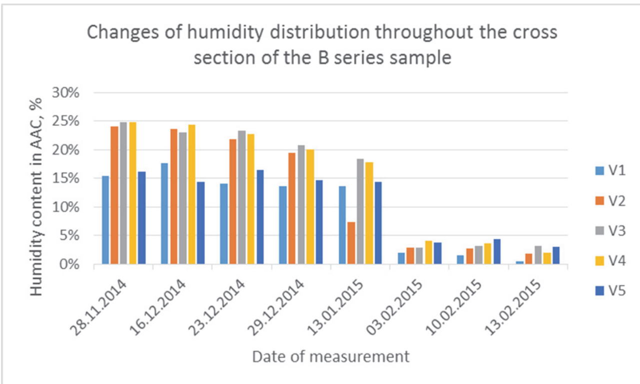


Fig. 9. Changes of moisture content throughout the cross section of the samples during drying process.

In-situ application of EIS method for detection of moisture content and its distribution throughout the cross section of AAC masonry constructions involves several issues, which should be taken into consideration. One of such issues is the quality of contact surface between the measurement probe and the AAC. The term *contact surface* involves not only the smoothness of the measurement surface but also the distance between the measurement probe and the AAC as well as the covering material of the measurement surface in order to obtain closer contact surface between the measurement probe and AAC. After series of measurements, where the distance between the measurement probe and contact surface varied in the range from 1 to 3mm, it was determined that the bore diameter did not have significant impact on measurement results.

Within the framework of approbation of the EIS method for non-destructive detection of moisture distribution in AAC, the monitoring of different liquid transport processes (seepage flow, capillary conduction) in AAC has been performed. Charts (Fig. 10) of moisture distribution throughout the cross section of the material have been prepared as a result of the approbation.

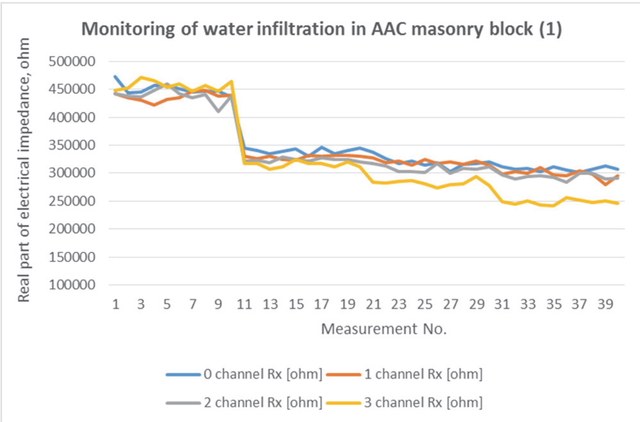


Fig. 10. EIS measurement results of moisture migration due to the seepage flow in the second set of the samples, measurements taken parallel to the manufacturing direction of AAC.

Application of EIS measurements for in-situ detection of moisture distribution in AAC masonry constructions can be expanded to the subject of non-destructive detection of moisture content in habitable buildings with finishing layers applied to masonry constructions. Therefore, a question of impact from masonry joints on the accuracy of the EIS measurement results arises. This subject is important because it is difficult to detect the masonry joints beneath the finishing layers without removing of finishing, which brings the EIS method out of range of easily applicable non-destructive methods as a number of on-site preparation works (e.g., removal of finishing layers, location of masonry joints) have to be done. This means that masonry joints have a significant impact on EIS measurement results. Therefore, results, which are obtained in wall segments without joints, are not directly comparable to results, which are obtained in wall segments with masonry joints.

In-situ AAC masonry constructions are usually insulated with a layer of heat insulation material (e.g., mineral wool or polystyrene). As a part of approbation of the methodology, the moisture transport processes in AAC masonry wall segments with different types of insulation have been monitored.

Fig. 11. Sample constructions on stand.

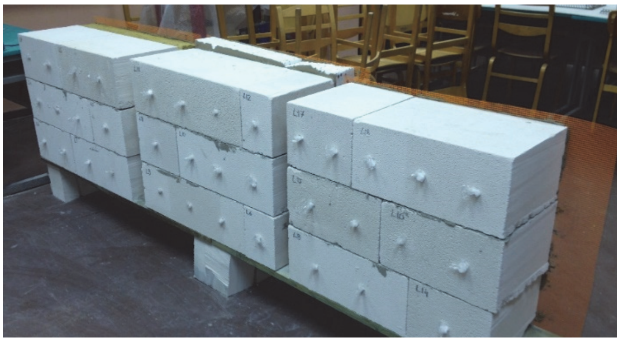


Fig. 12. Sample constructions on stand.

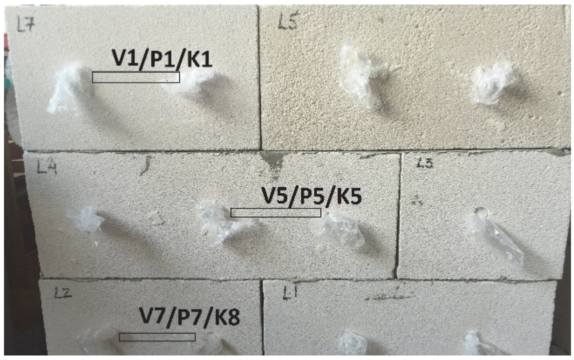


Fig. 13. Measurement points on specimen.

Further, the moisture distribution changes throughout the cross section of the specimen were monitored by application of EIS measurements three times a week and certain dynamics of drying process was established for each sample construction. Figures14–16 display the changes of moisture distribution throughout the cross section of the AAC samples with different external finishing. The obtained data were merged in one surface graph for each sample and the division of the data on x axis allowed following the changes of the moisture distribution throughout the cross section of the specimen during the whole period of the experiment.

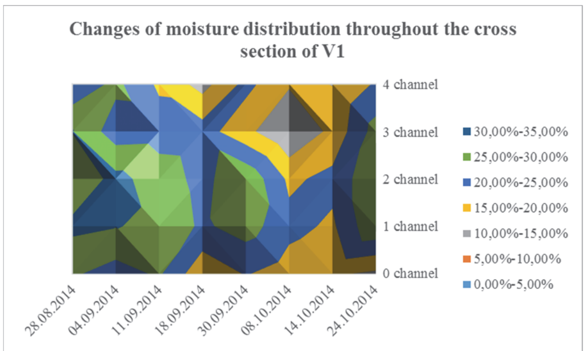


Fig. 14. Changes of moisture distribution throughout the cross section V1 of A specimen construction during the experiment.

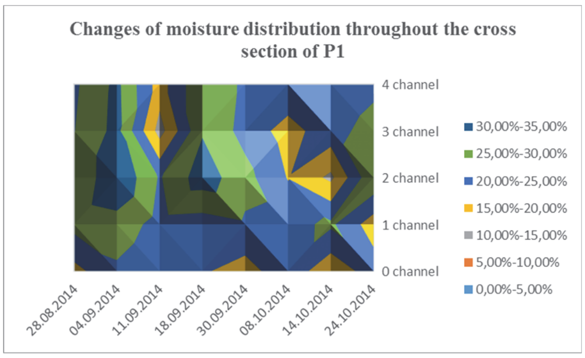


Fig. 15. Changes of moisture distribution throughout the cross section P1 of B specimen construction during the experiment.

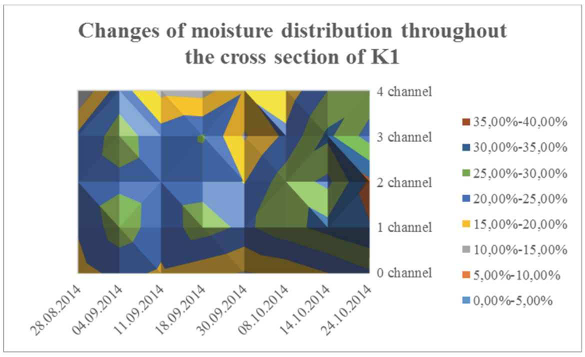


Fig. 16. Changes of moisture distribution throughout the cross section K1 of C specimen construction during the experiment.

3. Summary of the Results

The results and data obtained in experiments described in the 2nd chapter of the Thesis have been analysed and summarised in order to develop further trends for application of EIS and Z-meter III device for non-destructive on-site methodology for detection of moisture distribution in AAC masonry constructions.

The following issues have impact on the accuracy of the obtained results of moisture distribution throughout the cross section of AAC and should be taken into consideration during application of this method:

The frequency analysis has a significant impact on the accuracy of moisture content measurement results obtained by EIS and Z-meter III device. The results of frequency analysis depend on the density of the AAC material and the porous structure of the material. The results of frequency analysis can vary in the range of 2000Hz for the saturated and non-saturated specimen. Moreover, the porous structure of the AAC material has a significant impact on the results of frequency analysis. After comparing specimen with different porous structure and density, it can be concluded that the optimal frequency varies in the range of 2000 Hz as well. Therefore, it is strongly advisable to choose a measurement frequency, which is at least 2000 Hz higher than the minimal applicable measurement frequency for EIS.

Correlation equations between EIS measurement results and moisture content rate in AAC developed within the research can be applied for all types of AAC masonry blocks. The accuracy of the universal equation is 71 %, which is an acceptable result as the preferable moisture content in AAC masonry constructions is 5 % to 10 %. Therefore, in case of moisture content of 10 % the maximal deviation provided by this equation is 3 %. However, in order to increase the accuracy of the obtained results, it is necessary to determine the type of AAC and apply the equation developed for the relevant type of the AAC. The accuracy of the obtained equations varies in the range from 70 % to 81 % if an equation for the relevant type of AAC is used. If a universal equation is applied, then the accuracy of the obtained results can decrease up to 17.05 % in absolute values or 31 % in percentage rate. The AAC with high densities (higher than 500 kg/m^3) is the most deviant one. Other types of AAC with similar density have deviation in the range of 13 % in absolute values or 24 % in percentage rate.

Porous structure of the AAC has impact on the accuracy of EIS measurement results as well. In this case, not only the EIS measurement results vary by themselves, but also the correlation equation varies between the EIS measurement results and moisture content in AAC material. If the EIS measurements are taken in different directions vs the direction of expansion of AAC, the result can vary in the range of 3 %. The range is not too wide by itself; however, in combination with other factors, which cause deviations in measurement results, it can decrease the accuracy of the obtained data.

Conclusion

Comprehensive analysis of the results obtained during the experimental part of the research proves that the electrical impedance spectrometry can be applied to autoclaved aerated concrete masonry constructions for non-destructive measurements of moisture distribution throughout the cross section of the masonry construction. A methodology for application of EIS for non-destructive monitoring of moisture migration throughout the cross section of AAC masonry constructions with Z-meter device has been developed.

At the beginning of the research, the following tasks have been set:

1. To determine the correlation between EIS measurement results and moisture content in AAC.
2. To determine the impact of contact surface between measurement probe and AAC masonry construction on the accuracy of the obtained results.
3. To determine the impact of the coating on measurement contact surface on the accuracy of the measurement results.
4. To determine the impact of measurement distance on accuracy of measurement results.
5. To determine the impact of cracks and masonry joints on accuracy of EIS measurement results.

All the tasks stated above have been accomplished during the research. Accomplishing the tasks set at the beginning of the research, the following thesis statements can be made:

- EIS can be applied to AAC masonry constructions for non-destructive detection of moisture distribution throughout the cross section of the AAC masonry construction with average precision of 70 %;
- Prior the application of the EIS on AAC masonry constructions, the frequency analysis must be performed in order detect the most suitable EIS measurement frequency; for most common types of AAC the measurement frequency for EIS is 8000 Hz on the Latvian construction market;
- The contact surface between the measurement probe and AAC masonry construction should be as close as possible. However, the impact of the contact surface on the accuracy of the measurement results does not exceed 3 % of the reference result;
- The most precise measurement results can be obtained without any contact surface covering between the measurement probe and the AAC;
- EIS measurements can be performed in any range of measurement distances between measurement probes. However, the measurement distance between probes has impact on the determination of the measurement frequency. For measurement distance range from 150 mm to 300 mm, which complies with measurement distance within borders of one masonry block, the most suitable measurement frequency is 8000 Hz;
- Correlation equation between EIS measurement results and moisture content in AAC masonry constructions has been established. Correlation has logarithmic character and slightly differs depending on the type of AAC. The equation developed during the research is $y = a \ln(x) + C$;
- Large cracks and masonry joints have significant impact on the EIS measurement results; therefore, EIS should not be applied for the detection of moisture content in AAC sections with masonry joints in absolute means. However, EIS can be applied in such sections for non-destructive monitoring of moisture migration in relative means.

During the research conducted within the framework of the present Doctoral Thesis, the following proposals for the improvement of the Z-meter device have been developed:

- Self-drilling measurement probes should be manufactured;
- Software update for automatic frequency analysis should be developed;

- Software of the Z-meter device should be updated with the correlation equations between the EIS measurement results of the most common types of AAC and moisture content rate of AAC.

Promocijas darba literatūras atsauces / List of References of the Doctoral Thesis

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APSTIPRINĀJUMS / DECLARATION OF ACADEMIC INTEGRITY

Apstiprinu, ka esmu izstrādājusi šo promocijas darbu, kas iesniegts izskatīšanai Rīgas Tehniskajā universitātē inženierzinātņu doktora grāda iegūšanai. Promocijas darbs zinātniskā grāda iegūšanai nav iesniegts nevienā citā universitātē.

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Science is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Sanita Rubene

/26.08.2016/

Promocijas darbā ir ievads, trīs nodaļas, secinājumi, literatūras saraksts, 107 zīmējumi un ilustrācijas, kopā 112 lapaspuses, viens pielikums. Literatūras sarakstā ir 114 nosaukumi.

The Doctoral Thesis contains introduction, three chapters, conclusion, bibliography comprising 114 reference sources and one appendix. It has been illustrated by 107 figures. The volume of the Thesis is 112 pages.