Technical Advisory Group (TAG):

Roller Compacted Concrete (RCC)

Investigating the Possibility of Developing a TAG Guideline to use RCC as a Liner Under the *Agricultural Operation Practices Act*

December 2020

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Executive Summary

The literature did not provide sufficient scientific information to support, or oppose, the development of a Technical Advisory Group (TAG) guideline for the use of roller compacted concrete (RCC) as a liner under the *Standards and Administration Regulation*. Key information includes the following:

- Feedlot operators are interested in RCC and would like to use this product as a pen liner. Currently, feedlots have installed RCC as a pen amendment, right over their existing liners.
- Alberta Cattle Feeders Association would like to work with researchers to address the gaps to further the potential of RCC as a liner.
- An RCC installation company said most of the RCC they install is on top of existing, AOPA approved liners. They believe the confined feeding industry will continue to be interested in RCC and will also want to install it in manure storage and collection areas and other associated facilities.
- At this point in time there is a gap in approved standards (provincially, nationally, or internationally) to ensure water tightness, such as water stops, for RCC.
- In the absence of concrete industry approved RCC standards, the installation company interviewed has developed their own best management practices for design, mix and installation. Installed product testing is completed and measured against existing approved concrete standards.
- Research has been conducted in many geographical locations, however, no research has been completed in Alberta or anywhere with similar climates and soil types.
- Groundwater protection studies, hydraulic conductivity and permeability, with RCC were not found in the available scientific research. A TAG guideline would require evidence that RCC provides equal or greater protection to uppermost groundwater resources than other approved AOPA liners.
- The available scientific literature has not yet reported the longevity of RCC.
- Of the available scientific studies, none researched design criteria of RCC to maintain structural integrity or ensure its durability.
- The concrete industry has not yet developed structural design, construction processes or curing standards for specific applications.

Based on the potential application of RCC and its gaining popularity within the scientific community, it is likely design standards for specific applications will be developed and may provide the specifications required to meet AOPA standards. However, at this time, there is insufficient evidence to demonstrate RCC would meet, or not meet, the requirements necessary in the development of a TAG guideline.

Objective

To determine if there is sufficient scientifically based information to support the development of a TAG guideline for the construction and maintenance of RCC as a liner under the Standards and Administration Regulation of AOPA. To meet this objective, a literature review, interviews with available RCC suppliers and installers as well as confined feeding operators who have applied RCC, and the identification of information gaps regarding RCC are within scope.

Defining RCC

RCC is a term used to describe a concrete mixture that is compacted by vibratory rollers (Tayabji & Okamoto, 1987; Rahmani et al., 2020). While the primary components of RCC are similar to traditional concrete, RCC is mixed in different proportions than concrete (Calis & Yildizel, 2019). RCC typically consists of a higher proportion of fine aggregates compared to concrete (Harrington et al., 2010). However, the composition and proportions of these materials can vary considerably.

Alberta RCC providers agree with the literature in that RCC is an umbrella term for a wide range of concrete products that are installed with compaction. Unlike traditional concrete, it is constructed without the use of rebar/reinforcements, forms or dowels (Harrington et al., 2010). Additionally, the amount of cement in RCC is typically reduced and is sometimes replaced with a percentage of supplementary cementitious mineral admixtures, such as silica fume or fly ash (Debbarma et al., 2020). Hazaree (2010) provides a comparison between RCC and conventional concrete in Table 1.

Table 1. RCC versus conventional concrete

Point	Conventional Concrete	RCC
Consistency	Measured by slump test, flow test, etc. Vebe test is not helpful	Measured by Vebe method. Value depends on the type of Vebe and application of RCC
Cement content	Decided by the water demand of the aggregate system and water to cement ratio	Generally includes low cement content

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Moisture Content	Given by the water to cement ratio by weight	Given by optimum moisture content
Aggregate grading	Comparatively less well graded	Very well graded
Fresh concrete property determination	Slump and temperature based methods	Vebe consistency, optimum moisture content and maximum fresh (dry) density
Concrete Mixing	Mostly mixers	Mixers or pug mulls depending on the application
Transportation	Usually through transit mixers	By scraper, conveyor, bottom and rear dump trucks or large front end loaders
Spreading and laying	By pumps, slip form paving machines, and/or manually	By backhoe, loader, asphalt paving machine, etc.
Compaction	Internal or external vibrators	Rollers or compactors
Strength	Relatively low	Relatively high
Permeability	Relatively less than RCC	Relatively higher than conventional
Surface finish	Smooth	Rough texture

RCC can be used as concrete pavement replacement, generally referred to as roller compacted concrete pavement (RCCP). RCCP use has grown due to the high cost and environmental concerns of asphalt pavement (Ashrafian et al., 2020). The RCCP in these studies was either compared to traditional asphalt or asphalt blended pavements, or the RCCP included recycled pavement as part of the mixture design, making the results not applicable to this review.

RCC Performance

Research has been and is currently being conducted globally on RCC. It has been studied in a variety of applications. The common challenges, explored in this section, associated with RCC include mixture design, structural design details, and construction or installation process. Until recently, due to a lack of approved testing standards, these studies have used a variety of testing procedures to prepare RCC laboratory specimens to represent in-situ, or field applications of RCC. The installation of RCC in the field has variety as well and changed over time.

Testing Standards

Standards to test and evaluate concrete mixtures are imperative to ensure their mechanical properties and safety. High correlation between laboratory and in-field applications is necessary to have confidence in the applicability of laboratory research. In Alberta, one of the biggest challenges in determining how mixture design and field construction processes will impact RCC is the lack of standard laboratory testing methodologies. In 2019, there was no specific compaction methodology developed to simulate the site conditions in the laboratory (Sengün et al., 2019).

To demonstrate the importance of RCC mechanical properties in differently prepared methods, LaHucik and Roesler (2017) performed an investigation to compare the compressive strength of laboratory versus field core specimens. They found the field core density decreased with depth and near edges of the RCC installation to as low as 80% compared to lab testing results. Statistical different densities result in different compressive strength and fracture properties of RCC. LaHucik and Roesler (2017), as well as Şengün et al. (2019), found a decrease of 4% in density resulted in a 45% decrease in compressive strength. In those studies, the density was higher in the laboratory prepared specimens. Additionally, Breakah et al. (2019) reported that a loss of 1% in the density of RCC could cause an average reduction of 10% in compressive strength.

ASTM International, formerly known as American Society for Testing and Materials (ASTM), is one of the world’s largest international standards developing organizations. ASTM’s cement and concrete standards are instrumental in the evaluation and testing of concrete. Development of laboratory testing standards is recent and ongoing, evident in the dates of the ASTM standards, Table 2. The methods in these standards apply impact based compaction, which is different from roller compaction used in Alberta’s commercial applications. Therefore the applicability of these standards is limited to impact based compaction and may not assist our understanding of RCC in agricultural settings.

Table 2. ASTM standards for testing RCC

Date	Title
Oct 16, 2020	ASTM C1176/C1176M-20 Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table
May 15, 2020	ASTM C1435/C1435M-20 Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer
May 13, 2020	ASTM C1170/C1170M-20 Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
Jun 15, 2017	ASTM C1849/C1849M-17 Standard Test Method for Density and Air Content (Pressure Method) of Freshly Mixed Roller-Compacted Concrete
Jul 1, 2016	ASTM C1800/C1800M-16 Standard Test Method for Determining Density of Roller-Compacted Concrete Specimens Using the Gyratory Compactor

Mixture Design and Mechanical Properties

The mixture design, sometimes called the recipe, is variable in terms of ingredients used as well as the quality and quantity of those ingredients. The geographic location, access to materials or ingredients, and the application of the final product influences the mixture design. The attributes and properties of RCC vary by changing materials such as aggregate size, binders, and water content. It is necessary to select the appropriate materials and proportions to achieve desired strength and product workability (Chhorn et al., 2018). This information was verified by John and Tim Both of Rock Solid Concrete who prepare and install RCC in Alberta.

Workability is a significant criterion for RCC as it influences compactability, and in turn, the material's compressive strength (Hazaree, 2010). Therefore, it requires significant attention during the mixing and installation phases. Workability is mainly dependent on aggregate gradation, water content (Chhorn et al., 2018), fibre addition (Ghahari et al., 2017; Adamu et al., 2018), the cement paste quality (Hazaree, 2010) and the pozzolan content (Shamsaei et al., 2017). Additional factors such as air entrapment can adversely affect workability and the stability of RCC (Wu et al., 2020).

The *strength, durability* and *performance* of RCC is dependent on the mixture design. Calis and Yıldızel (2019) reported that RCC contains approximately 12% cementitious material by weight, while Portland cement concrete (PCC) has 15%. This influences strength development and the rate of hydration (Calis & Yıldızel, 2019). Additionally, the quality of the aggregate and the quantity of water within the mixture affect the strength and performance of RCC (Hazaree, 2010).

The compressive strength of RCC is primarily dependent on the aggregate framework, as shown in Appendix A (Hazaree, 2010). Due to the variability in mixture design, studies have found the laboratory compressive strength of RCC can range from 8 MPa to 57 MPa, a 148% difference. Agriculture and Forestry (2019) found the mean compressive strength of feedlot pens and silage pad retrofitted with RCC in 2015 showed significant variability; compressive strength for RCC ranged between 10.6 MPa and 16 MPa, compared to 19.9 MPa and 26.5 MPa, for the pens retrofitted with RCC in 2017 and 2018, respectively. Overall, a compressive strength difference of 85%. The RCC in this study used a soil-fly ash mixture of 15-20%, with one installation as high as 28%, the addition of soil is different from RCC in the available literature and from RCC currently installed in Alberta feedlots.

Chhorn et al. (2018) reported compressive strength of RCC was higher than conventional concrete, yet the tensile strength of the RCC was less than conventional concrete. Adequate tensile strength is necessary to resist fatigue cracking. It is necessary to understand the relationship between compressive and tensile strengths of RCC installed in Alberta.

Permeability has been studied to determine permeability coefficients and it was found to be highly dependent on the mix design and strength of the RCC lab specimens (Heidarnezhad et al., 2019; Chhorn et al. 2018). Varying the water to cement ratio had the highest effect on the permeability coefficient and mechanical properties (Heidarnezhad et al., 2019).

Admixtures and Additives

The use of admixtures and additives in modern concrete technology is standard. The use of these additives also influences the material’s mechanical properties (Gruszczyński & Lenart, 2020). Common additives and/or replacements include fly ash, limestone, water reducers, silica fume, furnace slag and nano-silica [silica, nano-silica and furnace slag are forms of pozzolanic material].

Fly ash is a waste by-product coming from coal-based thermal power plants (Kourti & Cheeseman, 2010) and has been used to replace Portland cement in PCC (Cetin et al., 2010). Fly ash acts as an artificial pozzolana, which has cementitious properties and contributes in reducing the quantity of Portland cement in the mixture (Debbarma et al., 2020). Fly ash is generally used as it benefits fluidity, promotes concrete density, and reduces cost (Pavan & Rao, 2014).

The impact of using fly ash as an admixture in traditional concrete, collected from peer reviewed research as described below, show a reduction in concrete strengths at most substitution rates and ages of the concrete.

- Yao et al. (2015) demonstrated that fly ash caused a reduction in compressive strength of concrete at early ages, especially under cold weather conditions or when more than 40% of the cement was replaced with fly ash.
- Mardani-Aghabaglou et al. (2013a), Mardani-Aghabaglou and Ramyar (2013b) and Rao et al. (2015) reported when cement was replaced by fly ash (20 to 60% weight substitution), increasing the fly ash content caused a reduction in compressive, split tensile and flexural strength values at all ages, even up to 180 days.

The benefits and impact of using fly ash as an admixture in RCC collected from peer reviewed research are described in the bullets below.

- Cheng Cao et al. (2000) concluded that the early age compressive strength of RCC with high volume fly ash decreases with the increase of fly ash volume, but it increases with the curing age.
- Pavan and Rao (2014) replaced 20, 40 and 60% fly ash for cement. Results indicated that mixtures with increasing fly ash content, (mixtures where cement was substituted with fly ash) caused reduction in compressive, splitting tensile and flexural strength values at all of the age up to 28 days.
- Mardani-Aghabaglou et al. (2013a) prepared RCC by replacing 20, 40 and 60% weight of cement and aggregate with fly ash and found the freeze-thaw mass loss increased for the mixtures where cement was replaced with fly ash and decreased for the mixtures where aggregate was replaced with fly ash. This effect was more pronounced when the replacement level of fly ash increased.

Limestone is used as an additive to improve durability (Shen et al., 2020). When used in conjunction with fly ash, it can weaken the secondary hydration effect of fly-ash and restrict long-term strength development (Shen et al., 2020). Studies suggest that excessive amounts of limestone can reduce frost performance in RCC (Shen et al., 2020).

Superplasticizers/water reducers are generally not used in RCC (Khayat & Libre, 2014). When used in RCC, water reducers improve the material's workability and helps avoid excessive air entrapment, which adversely affects the stability of RCC (Alnusair et al., 2020; Rahmani et al., 2020). Water reducers must be added in large quantities in RCC, which increases the cost of application (Alnusair et al., 2020).

Silica fume is used as an additive as it has a capillary filling effect, which improves pore structure (Shen et al., 2020). It improves tensile strength, compressive strength, frost resistance, and increases corrosion resistance (Shen et al., 2020). Nano-silica, when used as a cement substitute in traditional cement, decreases drying shrinkage and creep, and increases skid resistance, fatigue endurance, and elastic modulus (Pranav et al., 2020).

Furnace slag, ground-granulated blast slag, is used as a cement substitute as it decreases cost (Pranav et al., 2020). It adversely affects freeze-thaw resistance, tensile strength and modulus of elasticity (Pranav et al., 2020; Rooholamini et al., 2019). Electric arc slag is used as an aggregate substitution (Pranav et al., 2020). Studies demonstrate that it increases both tensile and compressive strength (Pranav et al., 2020).

Other less common additives and replacements include:

- Recycled aggregates, which cause a reduction in compressive strength (Courard et al., 2010).
- Fibres which influences structural performance of RCC. This performance is dependent on fibre type, dosage and geometry (LaHuick et al., 2017).

Structural Design, Construction Process & Verification

There are currently multiple methods used for RCC design (e.g., Corps of Engineers, RCC Dam Methods, Maximum Density Method, and High Paste Method (Calis and Yildizel 2019)). Beyond describing methods used, the literatures does not evaluate, compare and verify structural design or construction processes.

Gaps Identified within Research

Issues and gaps identified within the available research, for the applicability of RCC as a liner under the *Standards and Administration Regulation* include, but are not limited to:

- The lack of standards and testing related to RCC. There is no specific compaction methodology developed to simulate the site conditions in the laboratory (Sengun et al., 2019).
- Inconsistencies in RCC design, installation and curing of RCC, making the applicability/generalization of available research challenging.
- Literature is not consistent with its definition of RCC and RCCP and often does not specify quantities/mix and application method, making the applicability/generalization of available research challenging [caution: the mixture design of RCC across Alberta is also not consistent and varies from what is demonstrated in the literature].
- The lack of available research regarding the preparation of the foundation for RCC, its uniformity and placement, compaction and thickness, crack control and sealing around penetrations through RCC, such as pipes or fence posts.
- Limited research on the long term integrity of RCC.

- No field studies within Alberta, with the exception of AF's review, have been conducted regarding the challenges and possible solutions of RCC in environmental conditions (e.g., freeze/thaw environments) or in its application as a liner for manure storage and collection facilities.
- Limited studies review the effectiveness (not efficacy) of RCC.
- It is necessary to understand the relationship between compressive and tensile strengths of RCC installed in Alberta.
- The necessary permeability standard coefficients are not currently available for RCC, yet ASTM has conducted some research that could be in the works.
- There are currently multiple methods used for RCC design but the literatures does not evaluate, compare and verify structural design or construction processes.
- Installers agree with the scientific evidence that a lab specimen with a compressive strength of 40 MPa may only achieve 20 MPa in the field if it isn't compacted well. Although, the change in density (from compaction) has a drastic effect on the strength, they said this relationship is non-linear.

Current Status of Industry & Research

RCC has become popular due to the fact it is a simple material to produce, can be placed quickly, and produce a durable surface. In many cases it costs less than traditional concrete or asphalt. As such, RCC use is gaining traction, which is evident in the amount of grey literature that is available (Bellemare in Quebec; Beton Provincial in Quebec; Concrete Genius in Alberta; Concrete Saskatchewan in Saskatchewan; Lafarge in Canada; RCC Pavement Council in USA; RCC Surface Pro in USA; and PCA in USA).

- Cement and concrete organizations in North America include RCC on their websites and have demonstrated its use, typically as an asphalt pavement alternative (e.g. airport runways).
- Companies such as Lafarge have dedicated divisions for RCC and market it as an alternative to asphalt pavements.
- Construction and engineering websites, articles, and blogs speak highly of RCC and its potential.

The research and scientific communities see the value of RCC in many applications, as indicated by the number of peer reviewed publications in 2019 and 2020. In response to gaps identified in this research, standards are being developed, as shown in Table 2 by the October 16, 2020 ASTM Standard.

Alberta has also seen a number of RCC projects and an increase in the Alberta based companies advertising and promoting RCC. This includes advertising from Goldridge Sand and Gravel from Turin, Alberta; Lafarge across Alberta; and Concrete Genius from Barrhead, Alberta.

Based on potential applications and RCC gaining popularity within the scientific community, it is very likely design standards for specific applications will be developed and may be proven to meet AOPA standards.

Interviews

RCC Supply and Installation

Interviews with Rock Solid provided the following information:

- RCC suppliers and installers generally have concrete backgrounds and the RCC they provide is an additional product to conventional concrete.
- They believe the product and the installation practices have evolved over the last few years and have greatly improved.
- Rock Solid has found they produce a superior product when they are on the ground overseeing the mixing or manufacturing and installation. This process includes a proprietary quality assurance and quality control process.
- The Alberta RCC industry believes the performance characteristics are measureable and any reputable supplier would measure multiple characteristics of their product once installed. Currently, they are using the standards to measure traditional concrete.
- Every RCC will behave differently due to geography, climate, aggregates, concrete product, and the base preparation.
- Rock Solid explained they take quality assurance tests of the manufactured product multiple times per day to ensure the product created meets the design specification for the project. Onsite testing of the installed product is also completed to ensure moisture content and density are meeting project specifications. After 30 days, cores are taken and tested to verify the design criteria was met.
- They agree with the scientific evidence that a lab specimen with a compressive strength of 40 MPa may only achieve 20 MPa in the field if it isn't compacted well. Although, the change in

density (from compaction) has a drastic effect on the strength, they said this relationship is non-linear.

- Rock Solid has developed their own best practices for mixture design and installation processes as there currently aren't any provincially, nationally, etc. available. They have used Canadian Standards Association concrete protocols to build their practices upon.
- They believe crack control can be addressed through proper engineering, however, they did not divulge these details.
- The recommended path forward for TAG is to determine the permeability required to meet AOPA liner criteria and have the RCC industry design and build to that specification.
- The service providers are guarding their intellectual property, however, are willing to comply if it means the expansion of RCC use.

Comments on their work conducted in feedlots:

- Most RCC installations have occurred on top of the existing pen floor. This has provided a good base to work on.
- Some feedlot operations have installed the product themselves but still hire Rock Solid to be onsite and oversee the installation for quality control.
- Feedlot operators are generally knowledgeable about concrete and understand failures are not always visible. Currently, three operators have taken their own cores and done break tests on those. This is evidence these customers want to have independent testing done to verify quality.

Feedlot Operators

The producer feedback provided their perspective, over time and is summarized below.

- The age of RCC ranged from new to 8 years old with installations between 2012 and 2020.
- RCC has been used primarily in cattle confinement areas. In some cases, producers have only used it in 2% of their pens and others have placed it in 100% of their feedlot.
    - Some producers identified that they have only used it in pens that are prone to standing water, which makes the surface structure susceptible to breakdown.
    - Another scenario described is to place RCC pads behind the concrete aprons in pens but leave the back half of the pen as clay.

- There is use beyond cattle confinement areas including alleyways and processing areas.

- Most interviewees commented that RCC will likely become commonplace over time and will be an Alberta Feedlot “game changer”.
  - It will provide feedlot floor protection and reduce maintenance cost, improve performance related elements of the livestock, and increase public trust.
  - Producers believe this product is the future of pen flooring for cattle feeding.
  - Others expressed they may need to increase animal density to make sense of the investment.
- Producers said they expect 15-20 years of performance from the RCC and so far it is better than anything the feedlot industry has used before.
- RCC installation varied from full contractor completion, hybrid, to installation by feedlot operators.
- Site preparation varied in the equipment used, design, skill and overall process, however followed a theme of consistently packed. Many reported doing some type of rolling test to identify soft areas that needed further levelling and compaction. In one case, a loaded gravel truck was driven over the prepared site as a deflection test.
  - Most interviewees said they installed the RCC over their existing pen liner, using it as a pen amendment, not a liner.
  - Sites where installation has occurred over time saw installation processes change. For example, one operator said their first RCC installer used one vibratory pass and one static pass yet during the next installation they passed the vibratory machine over the site twice and then used a static roller for one pass.
- RCC thickness varied from 6-8 inches. Many suggested that “enhanced” layers may be a good idea in high traffic areas such as gateways.
- Quality control received varying testing/validation during installation.
  - The thickness of RCC was frequently measured.
  - Some owners said nothing was done on in situ compressive strength.
  - Many reported the service providers are trusted and producers suggested the product and process have been improved from initial placements done in 2012.
  - One operator hired a third party to use a nuclear rod compaction test and took core samples to measure depth and compressive strength.

- Many interviewees stated the product has performed as expected or better. There have been minor problems that have been dealt with easily. Seams and fence lines are the primary areas of concern. Other operators said the problems usually show up within 60 days of installation.
    - Failures have been patched with traditional concrete as soon as noticed to avoid further damage thus protecting the investment.
    - Not all interviewees had a great experience with their RCC installer. One operator feels the product he received did not perform the way it was marketed.
- RCC has generally improved aspects relating to feedlot floor associated issues.
    - Initial capital cost is the only deterrent.
    - Provides better performance than any earthen liner.
    - Best is to install a large pad during new construction as it is much easier than placing RCC in existing confinement areas.
    - Need to hand pack fence lines and other obstructions.
    - Improved animal health and performance.
    - Reduced dust.
    - Easier to clean.
    - Better for staff.
    - Improved broad access to bunks (earthen floors often have trailing, etc.).
    - Site preparation is the key.
    - Holds large equipment well.
    - Patching with asphalt may be best (i.e., water line repair areas, etc.).
    - Leaving compacted (gleyed layer) on surface will protect RCC surface and fill cracking.

In conclusion, producers are very positive on the inclusion of RCC in feedlot floor situations and feel RCC will be a part of cattle feeding in the future. In their eyes, it has proven to be durable and effective over time from an anecdotal perspective. Placement processes remain somewhat variable, however, have been standardized over time due to industry collective experience.

The feedlot managers have primarily relied on the service providers for their expertise, however, it appears third party verification is increasing, as it was mentioned several times. As well, due to the large up front capital commitment, there is an increased need for confirmation “they are getting what they paid for," meaning they want verification they have received a prescribed quality they have paid for as the investment is quite large.

There seems to be no formal confirmation of design mixture and practices, rather a sense of industry understanding of "what is working and what is not" because the RCC industry is currently so small.

Concluding Comments

RCC is a concrete industry term used to cover a broad range of concrete products installed with compaction. This creates difficulty drawing evidence from existing scientific research as the products studied do not compare to the products currently installed in Alberta. The difference in compressive strength of the RCC presented was 148%. The permeability coefficient of RCC products is highly dependent on the mix design and not yet defined for products in Alberta.

Despite current scientific gaps, RCC is a popular product as it is simple to produce, can be placed quickly, and typically costs less than traditional concrete or asphalt. This excitement is stimulating global research, development of testing and design standards for applications, and concrete industry leaders to develop/participate in cutting edge RCC projects. In Alberta, cattle feeders are equally excited about the product and have begun installing it as a pen floor amendment, not in place of a liner. Many have worked with Alberta based suppliers and installers to collaboratively develop processes and investigate RCC attributes.

In conclusion, at this time, December 2020, there is insufficient scientifically based information to support, or reject, the development of a TAG guideline for construction and maintenance of RCC as a liner under the Standards and Administration Regulation of AOPA. It is likely that design standards for specific applications will be developed and may provide the specifications required to meet AOPA standards.

References

Agriculture and Forestry (2019). Impact of amended feedlot pen surface on cattle health and welfare, environmental and economic sustainability.

Adamu, M., Mohammed B.S., Shafiq, N. and Liew, M.S. (2018). Effect of crumb rubber and nano silica on the fatigue performance of roller compacted concrete pavement. *Cogent Engineering 5,* 1436027. https://doi.org/10.1080/23311916.2018.1436027.

Alnusair, A. H., Katman, H. Y., Ibrahim, M. R., & Abd Rahman, N. (2020). The effect of superplasticizer on performance of roller compacted concrete pavement containing high volume fly ash*. International Journal of Recent Technology and Engineering (IJRTE)*. http://dspace.uniten.edu.my/jspui/handle/123456789/15173.

Ashrafian, A., Gandomi, A.H., Rezaie-Balf, M., and Emadi, M. (2020). An evolutionary approach to formulate the compressive strength of roller compacted concrete pavement. *Measurement,* https://doi.org/10.1016/j.measurement.2019.107309.

ASTM C1435 / C1435M-20, Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer, ASTM International, West Conshohocken, PA, 2020, https://www.astm.org/.

ASTM C1170 / C1170M-20, Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table, ASTM International, West Conshohocken, PA, 2020, https://www.astm.org/.

ASTM C1176 / C1176M-20, Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table, ASTM International, West Conshohocken, PA, 2020, https://www.astm.org/.

ASTM C1800 / C1800M-16, Standard Test Method for Determining Density of Roller-Compacted Concrete Specimens Using the Gyratory Compactor, ASTM International, West Conshohocken, PA, 2016, https://www.astm.org/.

ASTM C1849 / C1849M-17, Standard Test Method for Density and Air Content (Pressure Method) of Freshly Mixed Roller-Compacted Concrete, ASTM International, West Conshohocken, PA, 2017, https://www.astm.org/.

Breakah et al. (2019). Correlating field to laboratory compaction for roller compacted concrete. *International Journal of Engineering Research and Innovation*, 11(2).

Calis, G. & Yıldızel, S. (2019). Investigation of roller compacted concrete: Literature review. *Challenge Journal of Concrete Research Letters, 10*, 63-74.

Cao, C., Sun, W., and Qin, H. (2000). The analysis on strength and fly ash effect of roller-compacted concrete with high volume fly ash. *Cement and Concrete Research 30*, 71-75.

Chhorn and Lee (2017). Consistency control of roller-compacted concrete for pavement. *KSCE Journal of Civil Engineering, 21(5),* 1757-1763. https://doi.org/10.1007/s12205-016-0820-y.

Chhorn, C., Hong, S.J., and Lee, S.W. (2018). Relationship between compressive and tensile strengths of roller-compacted concrete. *Journal of Traffic and Transportation Engineering, 5(3),* 215-223.

Cetin, B., Aydilek, A.H., and Guney, Y. (2010). Stabilization of recycled base materials with high carbon fly ash. *Resources, Conservation and Recycling 54*, 878-892.

Courard, L., Michel, F., & Delhez, P. (2010). Use of concrete road recycled aggregates for roller compacted concrete. *Construction and Building Materials, 24(3),* 390-395. https://doi.org/10.1016/j.conbuildmat.2009.08.040.

Debbarma, S., Ransinchung, G.D., Singh, S., Sahdea, S.K. (2020). Utilization of industrial and agricultural wastes for productions of sustainable roller compacted concrete pavement mixes containing reclaimed asphalt pavement aggregates. *Resources, Conservation and Recycling, 152,* 104504.

Ghahari, S.A., Mohammadi, A., and Ramezanianpour, A.A. (2017). Performance assessment of natural pozzolan roller compacted concrete pavements. *Case Studies in Construction Materials* 7, 82-90.

Gruszczyński, M., & Lenart, M. (2020). Durability of mortars modified with the addition of amorphous aluminum silicate and silica fume*. Theoretical and Applied Fracture Mechanics, 107*, 102526. https://doi.org/10.1016/j.tafmec.2020.102526.

Harrington, D., Abdo, F., Adaska, W., Hazaree, C.V., Ceylan, H., and Bektas, F. (2010). Guide for roller-compacted concrete pavements*. InTrans Project Reports*, 102. https://lib.dr.iastate.edu/intrans_reports/102/.

Hazaree, C. V. (2010). Workability and strength attributes of RCC: Effects of different chemical admixtures and resulting paste [Dissertation, Iowa State University]. https://lib.dr.iastate.edu/etd/11250/.

Hazaree, C., Ceylan, H., & Wang, K. (2011). Influences of mixture composition on properties and freeze–thaw resistance of RCC. *Construction and Building Materials, 25*(1), 313-319. https://doi.org/10.1016/j.conbuildmat.2010.06.023.

Heidarnezhad, F., Toufigh, V., and Ghaemian, M. (2021). Analyzing and predicting permeability coefficient of roller-compacted concrete (RCC). *Journal of Testing and Evaluation, 49*.

Khayat, K. H., & Libre, N. A. (2014). Roller compacted concrete: field evaluation and mixture optimization (No. NUTC R363). *Missouri University of Science and Technology. Center for Transportation Infrastructure and Safety*. https://rosap.ntl.bts.gov/view/dot/27986.

Kourti, I. and Cheeseman, C (2010). Properties and microstructure of lightweight aggregate produced from lignite coal fly ash and recycled glass. *Resources, Conservation and Recycling 54*, 769-775.

LaHucik, J., Dahal, S., Roesler, J., & Amirkhanian, A. N. (2017). Mechanical properties of roller-compacted concrete with macro-fibers. *Construction and Building Materials, 135*, 440-446. https://doi.org/10.1016/j.conbuildmat.2016.12.212.

LaHucik, J. and Roesler, J. (2017). Field and laboratory properties of roller-compacted concrete pavements. Transportation Research Record: *Journal of the Transportation Research Board, 2631(1)*, 33-40. https://doi.org/10.3141/2630-05.

Mardani-Aghabaglou, A., Andiç-Çakir, Ö, & Ramyar, K. (2013a). Freeze–thaw resistance and transport properties of high-volume fly ash roller compacted concrete designed by maximum density method. *Cement and Concrete Composites, 37*, 259-266. https://doi.org/10.1016/j.cemconcomp.2013.01.009.

Mardani-Aghabaglou, A., & Ramyar, K. (2013b). Mechanical properties of high-volume fly ash roller compacted concrete designed by maximum density method. *Construction and Building Materials, 38,* 356-364. https://doi.org/10.1016/j.conbuildmat.2012.07.109.

Mohammed, B. S., & Adamu, M. (2018). Mechanical performance of roller compacted concrete pavement containing crumb rubber and nano silica. *Construction and Building Materials, 159*, 234-251. https://doi.org/10.1016/j.conbuildmat.2017.10.098.

Pavan, S., & Rao, S. K. (2014). Effect of fly ash on strength characteristics of roller compacted concrete pavement*. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 11(6),* 04-08.

Pranav, S., Aggarwal, S., Yang, E. H., Sarkar, A. K., Singh, A. P., & Lahoti, M. (2020). Alternative materials for wearing course of concrete pavements: A critical review. *Construction and Building Materials, 236,* 117609. https://doi.org/10.1016/j.conbuildmat.2019.117609.

Rahmani, E., Sharbatdar, M. K., & Beygi, M. H. A. (2020). A comprehensive investigation into the effect of water to cement ratios and cement contents on the physical and mechanical properties of Roller Compacted Concrete Pavement (RCCP). *Construction and Building Materials, 253,* 119177. https://doi.org/10.1016/j.conbuildmat.2020.119177.

Rao, S. K., Sravana, P., & Rao, T. C. (2015). Strength and compaction characteristics of fly ash roller compacted concrete. *International Journal of Scientific Research in Knowledge, 3(10),* 260-269. http://dx.doi.org/10.12983/ijsrk-2015-p0260-0269.

Rooholamini, H., Sedghi, R., Ghobadipour, B., & Adresi, M. (2019). Effect of electric arc furnace steel slag on the mechanical and fracture properties of roller-compacted concrete. *Construction and Building Materials* 211, 88-98. https://doi.org/10.1016/j.conbuildmat.2019.03.223.

Şengün, E., Alam, B., Shabani, R., & Yaman, I. O. (2019). The effects of compaction methods and mix parameters on the properties of roller compacted concrete mixtures. *Construction and Building Materials, 228,* 116807. https://doi.org/10.1016/j.conbuildmat.2019.116807.

Shamsaei, M., Aghayan, I., Kazemi, K.A. (2017). Experimental investigation of using cross-linked polyethylene waste as aggregate in roller compacted concrete pavement. *Journal of Cleaner Production,* 165, 290–297.

Shen, L., Li, Q., Ge, W., & Xu, S. (2020). The mechanical property and frost resistance of roller compacted concrete by mixing silica fume and limestone powder: Experimental study. *Construction and Building Materials, 239,* 117882. https://doi.org/10.1016/j.conbuildmat.2019.117882.

Tayabji, S. D., & Okamoto, P. A. (1987). Engineering properties of roller-compacted concrete (No. 1136). http://onlinepubs.trb.org/Onlinepubs/trr/1987/1136/1136-004.pdf.

Wu, Z., Libre, N. A., & Khayat, K. H. (2020). Factors affecting air-entrainment and performance of roller compacted concrete. *Construction and Building Materials, 259,* 120413. https://doi.org/10.1016/j.conbuildmat.2020.120413.

Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. *Earth-Science Reviews, 141,* 105-121. https://doi.org/10.1016/j.earscirev.2014.11.016.

Appendix A Compressive Strength

Study	Specifiers (if necessary, otherwise assume RCC)	Compressive Strength (MPa)		Mixture (kg/m^3)				Aggregate (kg/m^3)			Total Aggregate (kg/m^3)	Water to Cement Ratio	Other Additives (kg/m^3)				
		Field	Lab	Cement	Water	Fine Aggregate	Coarse Aggregate	0-5 mm	5-12 mm	12-19 mm			Silica	Filler	Crumb Rubber	Fly Ash	Limestone/ Dolomite
Breakah et al. (2019)	---	18-21	17-40	472.5	170	666.5	1087	---	---	---	---	0.32	---	---	---	---	---
Chhorn and Lee (2017)	“Optimal”; no superplasticizer	---	40	280	147.3	1285	864	---	---	---	---	0.52	---	---	---	---	---
	“Optimal”; superplasticizer PNS at 0.3%	---	42	280	147.3	1285	864	---	---	---	---	0.52	---	---	---	---	---
Hazaree et al. (2011)	---	---	57	350	122	---	---	---	---	---	1928	0.35	---	---	---	---	---
		---	15	100	127	---	---	---	---	---	2132	1.27	---	---	---	---	---
Mohammed and Adamu (2018)	---	---	50	268.69	98.24	1148.05	831.88	---	---	---	---	---	2.69	103.76	0	---	---
		---	25	268.69	98.24	803.64	831.88	---	---	---	---	---	8.06	103.76	344.67	---	---
Shen et al. (2020)	---	---	23.7	156	130	805	1280	---	---	---	---	---	0	---	---	52	52
		---	27.8	156	130	805	1280	---	---	---	---	---	13	---	---	91	0
		---	28.6	156	130	805	1280	---	---	---	---	---	13	---	---	39	52
Sengun et al. (2019)	---	---	8.4	200	74	---	---	1463	790	---	---	0.37	---	---	---	---	---
		---	22.8	200	156	---	---	1015	815	206	---	0.78	---	---	---	---	---
		---	17.5	400	74	---	---	1351	730	---	---	0.19	---	---	---	---	---
		---	45	400	158	---	---	928	745	188	---	0.4	---	---	---	---	---
Rao, Sravana and Rao (2015)	---	---	43	295	114	801	1209	---	---	---	---	0.39	---	---	---	0	---
		---	35	231	117	791	1194	---	---	---	---	0.4	---	---	---	58	---
		---	24	168	133	767	1158	---	---	---	---	0.48	---	---	---	112	---
		---	16.8	110	135	758	1144	---	---	---	---	0.49	---	---	---	165	---

Cao, Sun and Qin (2000)	---	---	55.4	210	113	773	---	---	---	---	---	0.377	---	---	---	134	1320
		---	32.5	110	133	678	---	---	---	---	---	0.443	---	---	---	285	1320
Tayabji and Okamoto (1987)	4" core	26.3	---	169	90	619	1622	---	---	---	---	---	---	---	---	0	---
		25.2	---	144	82	622	1631	---	---	---	---	---	---	---	---	28	---
		30.3	---	158	96	686	1516	---	---	---	---	---	---	---	---	32	---
		17.1	---	156	84	634	1606	---	---	---	---	---	---	---	---	27	---
	6" cylinder	30.6	---	169	90	619	1622	---	---	---	---	---	---	---	---	0	---
		27.6	---	144	82	622	1631	---	---	---	---	---	---	---	---	28	---
		33.2	---	158	96	686	1516	---	---	---	---	---	---	---	---	32	---
		25.6	---	156	84	634	1606	---	---	---	---	---	---	---	---	27	---
Mardani-Aghabaglou and Ramyar (2013)	---	---	41	250	97.5	---	---	1263	429	432	---	0.39	---	---	---	0	---
		---	38.9	200	100	---	---	1248	424	427	---	0.4	---	---	---	50	---
		---	35.6	150	105	---	---	1235	419	422	---	0.42	---	---	---	100	---
		---	31.8	100	115	---	---	1209	410	413	---	0.46	---	---	---	150	---
		---	44.4	250	123	---	---	1185	402	405	---	0.41	---	---	---	50	---
		---	46.6	250	150.5	---	---	1107	376	379	---	0.43	---	---	---	100	---
		---	49.5	250	188	---	---	1020	346	349	---	0.47	---	---	---	150	---

Studies that specified RCC are included above and studies that specified “RCCP” were excluded.